NOYES' KNEE DISORDERS

Surgery, Rehabilitation, Clinical Outcomes

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Second Edition

Editor

Frank R. Noyes, MD
Chairman and CEO
Cincinnati SportsMedicine and Orthopaedic Center
President and Medical Director
Cincinnati SportsMedicine Research
and Education Foundation
Noyes Knee Institute
Cincinnati, Ohio

Associate Editor

Sue D. Barber-Westin, BS
Director, Clinical and Applied Research
Cincinnati SportsMedicine Research
and Education Foundation
Cincinnati, Ohio

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To JoAnne, my loving and precious wife, and to all our families.

CONTRIBUTORS

Thomas P. Andriacchi, PhD
Professor of Mechanical Engineering
Department of Orthopaedic Surgery
Stanford University
Stanford, California;
Professor
Joint Preservation Center
Palo Alto Veterans Administration
Palo Alto, California

John Babb, MD
Orthopedic Surgeon
Mid-America Orthopedics
Wichita, Kansas

Sue D. Barber-Westin, BS
Director, Clinical and Applied Research
Cincinnati SportsMedicine Research and Education Foundation
Cincinnati, Ohio

Asheesh Bedi, MD
Harold and Helen W. Gehring Professor
Chief of Sports Medicine
MedSport
Department of Orthopaedic Surgery
University of Michigan Hospitals
Ann Arbor, Michigan

Geoffrey A. Bernas, MD
Clinical Assistant Professor of Orthopaedic Surgery
Department of Orthopaedic Surgery
University at Buffalo
Buffalo, New York;
University Sports Medicine
Orchard Park, New York

Lori Thein Brody, PT, PhD, SCS, ATC
Senior Clinical Specialist
Sports and Spine Physical Therapy
UW Health
Madison, Wisconsin;
Professor
Orthopaedic and Sports Science
Rocky Mountain University of Health Professions
Provo, Utah

William D. Bugbee, MD
Attending Physician
Division of Orthopaedic Surgery
Scripps Clinic
La Jolla, California

Brian J. Cole, MD, MBA
Professor
Department of Orthopaedics
Department of Anatomy and Cell Biology
Section Head
Cartilage Restoration Center
Rush University Medical Center
Chicago, Illinois

A. Lee Dellon, MD
Professor of Plastic Surgery and Neurosurgery
Johns Hopkins University;
Director
The Dellon Institutes for Peripheral Nerve Surgery
Baltimore, Maryland

Alvin Detterline, MD
Orthopaedic Surgeon
Towson Orthopaedic Associates
Towson, Maryland;
Volunteer Faculty
Department of Orthopaedic Surgery
University of Maryland
Baltimore, Maryland

Eric Fester, MD
Assistant Professor of Surgery, Uniformed Services
University of the Health Sciences
Bethesda, Maryland;
Clinical Assistant Professor of Orthopaedic Surgery
Wright State University
Dayton, Ohio;
Chief, Orthopaedic Sports Medicine
Wright-Patterson Medical Center
Wright-Patterson Air Force Base, Ohio

Judd R. Fitzgerald, MD
Resident
Department of Orthopaedics and Rehabilitation
University of New Mexico
Albuquerque, New Mexico

Simon Görtz, MD
Department of Orthopaedic Surgery
Washington University in St. Louis
St. Louis, Missouri

Guilherme C. Gracitelli, MD
Department of Orthopaedic Surgery
Federal University of São Paulo
São Paulo, Brazil

Brian M. Grawe, MD
Assistant Professor
Sports Medicine & Shoulder Reconstruction
Department of Orthopaedic Surgery
University of Cincinnati Academic Health Center
Cincinnati, OH

Edward S. Grood, PhD
Director
Biomechanics Research
Cincinnati SportsMedicine Research and Education Foundation;
Professor Emeritus
Department of Biomedical Engineering
Colleges of Medicine and Engineering
University of Cincinnati
Cincinnati, Ohio

Joshua D. Harris, MD
Orthopaedic Surgeon
Orthopaedics & Sports Medicine
Houston Methodist Hospital
Houston, Texas;
Assistant Professor
Clinical Orthopaedic Surgery
Weill Cornell Medical College
Houston, Texas

Timothy Heckmann, PT, ATC
Clinic Supervisor, Physical Therapy
Mercy Health/Cincinnati SportsMedicine
Cincinnati, Ohio;
Clinical Instructor, Physical Therapy
Duquesne University
Pittsburgh, Pennsylvania;
Clinical Instructor, Physical Therapy
University of Kentucky
Lexington, Kentucky

Todd R. Hooks, PT, ATC, OCS, SCS, CSCS
Assistant Athletic Trainer/Physical Therapist
New Orleans Pelicans
Metairie, Louisiana

Frank R. Noyes, MD
Chairman and CEO
Cincinnati SportsMedicine and Orthopaedic Center
President and Medical Director
Cincinnati SportsMedicine Research and Education Foundation
Noyes Knee Institute
Cincinnati, Ohio

Michael M. Reinold, PT, DPT, ATC, CSCS
Rehabilitation Coordinator and Assistant Athletic Trainer
Boston Red Sox;
Coordinator of Rehabilitation Research and Education
Division of Sports Medicine
Department of Orthopedic Surgery
Massachusetts General Hospital
Boston, Massachusetts

Dustin L. Richter, MD
Fellow
Orthopaedic Surgery Sports Medicine
University of Virginia
Charlottesville, Virginia

Scott A. Rodeo, MD
Professor of Orthopaedic Surgery
Co-Director, Tissue Engineering, Regeneration, and Repair Program
Weill Medical College of Cornell University;
Co-Chief Emeritus, Sports Medicine and Shoulder Service
Attending Orthopaedic Surgeon
Hospital for Special Surgery;
Associate Team Physician
New York Giants Football
New York, New York

Sean F. Scanlan, PhD
Scientist
Cummings Scientific
Tallahassee, Florida

Robert C. Schenck Jr, MD
Professor and Chair
Department of Orthopaedic Surgery
University of New Mexico School of Medicine
Head Team Physician
Department of Athletics
University of New Mexico
Albuquerque, New Mexico

Justin Strickland, MD
Orthopedic Surgeon
Mid-America Orthopedics
Wichita, Kansas

Fumitaka Sugiguchi, BS
Weil Medical College of Cornell University
New York, New York

Robert A. Teitge, MD
Professor
Department of Orthopaedic Surgery
Wayne State University School of Medicine
Detroit, Michigan

Kelly L. Vander Have, MD
Assistant Professor
University of Michigan
Ann Arbor, Michigan

Daniel C. Wascher, MD
Professor
Department of Orthopaedics
University of New Mexico
Albuquerque, New Mexico

K. Linnea Welton, MD
Resident Surgeon
Department of Orthopaedic Surgery
University of Michigan Hospital and Health Systems
Ann Arbor, Michigan

Kevin E. Wilk, PT, DPT, FAPTA
Adjunct Assistant Professor
Marquette University
Milwaukee, Wisconsin;
Vice President of Education and Associate Clinical Director
Physiotherapy Associates;
Director of Rehabilitation Services
American Sports Medicine
Birmingham, Alabama

Edward M. Wojtys, MD
Professor & Service Chief
Department of Orthopaedic Surgery
University of Michigan
Ann Arbor, Michigan

PREFACE

I am grateful to all of the contributors to this textbook, *Noyes' Knee Disorders*, which is appropriately subtitled *Surgery, Rehabilitation, Clinical Outcomes*. The chapters reflect the writings and teachings of the scientific and clinical disciplines required for the modern treatment of clinical afflictions of the knee joint. Our goal is to present rational, evidence-based treatment programs based on published basic science and clinical data to achieve the most optimal outcomes for our patients.

The key to understanding the different disorders of the knee joint encountered in clinical practice truly rests on a multidisciplinary approach that includes a comprehensive understanding of knee anatomy, biomechanics, kinematics, and biology of soft tissue healing. Restoration of knee function then requires an accurate diagnosis of the functional abnormality of the involved knee structures, a surgical technique that is precise and successful, and a rehabilitation program directed by skilled professionals to restore function and avoid complications. Each chapter follows a concise outline of indications, contraindications, physical examination and diagnosis, step-by-step open and arthroscopic surgical procedures, clinical outcomes, and analysis of relevant published studies.

The second edition of *Knee Disorders* is the result of complete editing of each chapter, the addition of new chapters on partial knee replacements, updates on anterior cruciate ligament (ACL) and posterior cruciate ligament arthroscopic reconstructions as well as posterolateral reconstructions, the addition of clinical studies on meniscus transplants and meniscus repairs, and the addition of newer concepts on neuromuscular testing and conditioning. Importantly, each rehabilitation postoperative protocol for every surgical procedure has been updated because this textbook serves a readership of surgeons, physical therapists, athletic trainers, and exercise specialists. As a result, this textbook has 45 chapters, 30 authors, 1000 figures, 285 tables, and more than 4500 references, including 1500 new references (1050 clinical studies and 450 articles on biomechanics, anatomy, or basic science).

A special feature of second edition is the video library referenced in the chapters, allowing the reader to both read and see the content being presented. There are 45 videos totaling more than 11 hours of content: 11 surgical videos, 19 patient rounds focusing on surgical procedures and postoperative rehabilitation, and 15 presentations of knee content pertaining to certain selected book chapters.

The first two chapters comprise an anatomic description of the structures of the knee joint. The images and illustrations represent the result of many cadaveric dissections to document knee anatomic structures. It was a pleasure to have four of our fellows (class of 2008-2009) involved in these dissections, which resulted in two superb, award-winning instructional anatomic videos included with this book. Numerous anatomy textbooks and publications were consulted during the course of these dissections to provide, to the best of our ability, accurate anatomic descriptions, with the realization there is still ambiguity in the nomenclature used for certain knee structures.

Special thanks go to Joe Chovan, a wonderful and highly talented professional medical illustrator. Joe attended anatomic dissections and worked hand in hand with us to produce the final anatomic illustrations. Joe and I held weekly to bimonthly long working sessions for more than 2 years, resulting in the unique, highly detailed, and accurate anatomic and medical illustrations throughout this book.

All surgeons appreciate that operative procedures come and go as they are proved inadequate by long-term clinical outcome studies and replaced by newer techniques that are more successful. I am reminded that the basic knowledge of anatomy, biomechanics, kinematics, biology, statistics, and validated clinical outcome instruments always remain our lightposts for patient treatment decisions. For this reason, there is ample space devoted in the text to these scientific disciplines. Equally important are the descriptions of surgical techniques, presented in a step-by-step approach with precise details by experienced surgeons on the critical points for each technique to achieve successful patient outcomes. It is hoped that surgeons in training will appreciate the necessity for the basic science and anatomic approach that, combined with surgical and rehabilitation principles, are required to become a true master of knee surgery and rehabilitation.

There is a special emphasis placed in each of the 13 sections on rehabilitation principles and techniques, including preoperative assessment, postoperative protocols, and functional progression programs to restore lower limb function. The comprehensive rehabilitation protocols in this book have been used and continually modified over many years. My coauthor on these sections, Timothy Heckman, is a superb physical therapist. We have worked together treating patients in a wonderful harmonious relationship for more than 30 years. In addition, there are special programs for the female athlete to reduce the risk of ACL injury. Sportsmetrics, a nonprofit neuromuscular training and conditioning program developed at our Foundation, is one of the largest women's knee injury prevention programs in the world and has been in existence for more than 15 years. A number of scientists, therapists, athletic trainers, and physicians at our Foundation have been involved in the research efforts and publications of this program. All centers treating knee injuries in athletes are reminded of the importance of preventive neuromuscular and conditioning programs, whose need has been well established by many published studies. Recent studies show a high rate of repeat injury to the ACL-reconstructed knee or the opposite knee, approaching 12% to 30% with return to athletics. Our goals are not only to prevent or decrease the incidence of ACL injuries, but (of equal importance) also incorporate Sportsmetrics neuromuscular programs after ACL surgery before return to sports activities.

The entire staff at Cincinnati SportsMedicine and Orthopaedic Center and the Foundation functions as a team, working together in various clinical, research, and rehabilitation programs. The concept of a team approach is given a lot of attention; those who have visited our center have seen the actual programs in place. This team effort is appreciated by all, including patients, staff, surgeons, physical therapists, athletic trainers, administrative staff, and clinical research staff. Our administrative staff has been directed by a superb and highly effective clinical operations manager, Linda Raterman, whom I thank and express my gratitude for her dedication and time. As the President and CEO, I have been freed of many of the operational administrative duties because of this excellent staff, allowing time required for clinical and research responsibilities. I have been blessed to be associated with a highly dedicated group of orthopaedic partners who provide excellent patient care and are a vehicle for lively discussions and debate at our academic meetings and journal clubs.

Nearly all of the patients treated at the Noyes Knee Institute are entered into prospective clinical studies by a dedicated clinical research group directed by Sue Barber-Westin and Cassie Fleckenstein. The staff meticulously tracks patients over many years to obtain a 90% to 100% follow-up rate; I thank Jenny Riccobene for diligently keeping track of all our patients. I invite you to read the Preface by Sue Barber-Westin, who has performed such an admirable and dedicated job in bringing

our clinical outcome studies to publication. It is only through her efforts of more than 30 years that we have been successful in conducting large prospective clinical outcome studies. In each chapter, the results of these outcome studies are rigorously compared with other authors' publications. The research and educational staff work with fellows and students from many different disciplines, including physicians, therapists, trainers, and biomedical students. There have been 147 Orthopaedic and SportsMedicine Fellows who have received training and awarded their certification at our center. The scientific contributions of fellowship research projects working hand-in-hand with our teaching staff are acknowledged numerous times in this text. Our staff enjoys the mentoring process; from a personal perspective, this has been one of my greatest professional joys.

In regard to mentoring, one might ask where the specialty of orthopaedics (or any medical specialty) would be today without the professional mentoring system that trains new surgeons and advances our specialty, providing a continuum of patient treatment approaches and advances. The informal dedication of the teacher to the student, often providing wisdom and guidance over many years, is actually contrary to capitalistic principles because the hours of dedication are rarely (if ever) compensated; it is the gift from one generation to another. I mention this specifically, as I hope that I have been able to repay in part the mentors who provided this instruction and added time and interest for my career. I graduated from the University of Utah with a Philosophy degree, which provided an understanding of the writings and wisdom of the great scientists and thinkers of all time, taught by superb educators in premedical courses and philosophy. I received my medical degree from George Washington University and am thankful to the dedicated teachers who laid a solid medical foundation for their students and taught the serious dedication and obligation that physicians have in treating patients. I was fortunate to be accepted for internship and orthopaedic residency at the University of Michigan and remember the opportunity to be associated with truly outstanding clinicians and surgeons. Under the mentorship of the chairman, William S. Smith, MD, my fellow residents and I received training from one of the finest orthopaedic surgeons and dedicated teachers. Many graduates of this program have continued as orthopaedic educators and researchers, which is a great tribute to Bill Smith and his mentorship. My fellow residents know one of his many favorite sayings that reminded residents of the need for humility: After a particularly enthusiastic lecture or presentation by a prominent visiting surgeon who received glowing statements of admiration, Bill Smith would say with a wink and smile, "He puts his pants on one leg at a time, just like you do."

After orthopaedic residency, I accepted a 4-year combined clinical and research biomechanics position at the Aerospace Medical Research Laboratories with the United States Air Force in Dayton, Ohio. The facilities and veterinary support for biomechanical knee studies were unheralded. It was here that some of the first high-strain-rate experiments on the mechanical properties of knee ligaments were performed. I am indebted to Victor Frankel and Albert Burstein, the true fathers of biomechanics in the United States, who guided me in these formative years of my career. I was particularly fortunate to have a close association with Al Burstein, who mentored me in the discipline of orthopaedic biomechanics. This research effort also included professors and students at the Air Force Institute of Technology. I am grateful to all of them for instructing me in the early years of my research training. As biomechanics was just in its infancy, it was obvious that substantive research was only possible with a combined MD-PhD team approach.

One of the most fortunate blessings in my professional life is the relationship I have had with Edward S. Grood, PhD. I established a close working relationship with Ed, and we currently have the longest active MD-PhD (or PhD-MD) team that I know of, and we are currently conducting the next round of knee ligament function studies using sophisticated three-dimensional robotic methodologies. We worked together to establish one of the first biomechanical and bioengineering programs in the country at the University of Cincinnati College of Engineering, and I greatly appreciated that it was named the Noyes Biomechanics and Tissue Engineering Laboratory. This initial effort expanded with leadership and dedicated faculty and resulted in a separate Bioengineering Department within the College of Engineering, with a complete program for undergraduate and graduate students. Dr. Grood pioneered this effort with other faculty and developed the educational curriculum for the 5-year undergraduate program. Many students of this program have completed important research advances that are referenced in this book. David Butler, PhD, joined this effort in its early years and contributed important and unique research works that are also credited throughout the chapters. This collaborative effort of many scientists and physicians resulted in three Kappa Delta Awards, the Orthopaedic Research and Education Clinical Research Award, American Orthopaedic Society for Sports Medicine Research Awards, and the support of numerous grants from the National Institutes of Health, National Science Foundation, and other organizations. The publications from the clinical and translational research team have been recognized in bibliographic studies as some of the most quoted in the world, as referenced by a recent *Journal of Bone & Joint Surgery* publication of the 100 most quoted knee studies in the past 40 years. Thomas Andriacchi, PhD, collaborated on important clinical studies that provided an understanding of joint kinematics and gait abnormalities. It has been an honor to have Tom associated with our efforts throughout the years.

On a personal note, my finest mentors were my parents, a dedicated and loving father, Marion B. Noyes, MD, who was a true renaissance surgeon entirely comfortable doing thoracic, general surgery, and orthopaedics, and who, as a Chief Surgeon at academic institutions, trained decades of surgical residents. Early in my life, I read through classic Sobotta anatomic textbooks and orthopaedic textbooks that remain in my library with his writings and notations alongside the surgical procedures. Later in my training, I was fortunate to scrub with him on surgical cases. My loving mother, a nurse by training, was truly God's gift to our family. She provided unqualified love and sage and expert advice for generations, with knowledge, wisdom, and our admiration—all the way into her nineties. She expected excellence, performance, and adherence to a rigorous value system. These are also the attributes of the most wonderful gift of all, the opportunity to go through life with a loving and true soulmate, my wife JoAnne Noyes, to whom I remain eternally grateful and devoted. Our family includes a fabulous daughter and two wonderful sons and their families and five wonderful grandchildren. Together with JoAnne and all our brothers and sisters, we enjoy many family events together. As I look back on my career, it is the closeness of family and friends that has provided the greatest enrichment.

In closing, I wish to thank Laura Schmidt, Dolores Meloni, and the other Elsevier staff who are true professionals and were a joy to work with in completing this textbook. Given all the decisions that must be made in bringing a textbook to publication, at the end of the process the Elsevier team made everything work in a harmonious manner, always striving for the highest quality possible.

Frank R. Noyes, MD

PREFACE

Revising and updating *Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes* has been a stimulating experience, and I am extremely grateful to the medical community and Elsevier for providing us with this opportunity. Numerous advances have occurred in the treatment and published outcomes of knee injuries and problems in the 7 years since the first edition. This is reflected in the more than 1000 new references that are included in the chapters Dr. Noyes and I completed. Postoperative rehabilitation has also progressed, with more objective and functional measures used to determine when an athlete may safely resume sports participation. Paramount for a successful outcome is the restoration of normal proprioception, balance, coordination, and neuromuscular control for desired activities. These concepts are discussed in detail in chapters Dr. Noyes, Timothy Heckmann, and I revised, as well as in the two chapters contributed by Kevin Wilk.

My interest in conducting clinical research stemmed from my experience of undergoing open knee surgery as a collegiate athlete many years ago. Although the operation was done in an expert manner, it was followed by inadequate rehabilitation and a poor outcome. Three years later, the experience was repeated except that the patient education process was markedly improved, as was the postoperative therapy program, both of which contributed to a successful result. The tremendous contrast between these experiences prompted a lifelong interest in helping patients who face the difficulty of dealing with knee problems. Having undergone arthroscopic surgery more recently on my knee and shoulders, I can personally attest to the incredible advances sports medicine has achieved in the past 3 decades. However, it is important to acknowledge that there is still much to learn and understand regarding the complex knee joint.

My initial experience with research involved collecting and analyzing data from a prospective randomized study on the effect of immediate knee motion after anterior cruciate ligament allograft reconstruction with Dr. Noyes and our rehabilitation staff. The experience was remarkable for the time Dr. Noyes spent mentoring me on all aspects of clinical studies, including critical analysis of the literature, correct study design, basis statistics, and manuscript writing. The scientific methodology adopted by Drs. Noyes and Grood, along with our center's philosophy of the physician-rehabilitation team approach, provided an extraordinary opportunity to learn and work with those on the forefront of orthopaedics and sports medicine. My second major project, used as the thesis for my undergraduate work, involved the analysis of functional hop testing. Dr. Noyes and our statistical consultant at that time, Jack McCloskey, were invaluable in their assistance and efforts to see the investigations through to completion. I remain grateful for these initial stimulating experiences, which provided the basis and motivation for my research career.

The clinical outcomes sections of the chapters of this textbook represent a compilation of knowledge from studies involving thousands of patients from both our center and other published cohorts. We have attempted to justify the recommendations for treatment based in part on the results of our clinical studies, which consistently use rigorous knee rating systems to determine outcome. The development and validation of the Cincinnati Knee Rating System was a major research focus for Dr. Noyes and I for several years. As a result, we have long advocated that "outcome" must be measured by many factors, including patient perception of the knee condition along with valid functional, subjective, and objective measures such as radiographs, knee arthrometer testing, and magnetic resonance imaging when necessary. Simply collecting data from questionnaires does not, in our opinion, provide a scientific basis for treatment recommendations. Even more compelling is the necessity to conduct long-term clinical studies with at least a 10-year follow-up evaluation. These studies must also include these measures to determine the long-term sequelae of various injuries and disorders. At our center, we will continue to conduct clinical research in this manner in our efforts to advance knowledge of the knee joint and provide the best patient care possible.

Another area of particular research interest of mine over the years has been in the field of rehabilitation. In fact, the first clinical study I participated in was initiated while I worked on the physical therapy staff for 2 years. Having been a patient myself, I had a strong interest in studying the effects of different rehabilitation treatment programs on clinical outcomes. At our center, we have always held the belief that postoperative rehabilitation is just as important as the operative procedure for successful resolution of a problem. I have enjoyed working with Tim Heckmann in these studies for many years, as well as many other therapists, assistants, and athletic trainers vital to the success of our rehabilitation research and clinical programs.

Many individuals have contributed to the success of our clinical research program over 30-plus years, but it is not possible to name them all. However, I want to especially recognize Jennifer Riccobene, who for many years has doggedly tracked down and assisted hundreds of patients from all over the United States and beyond with their clinical research visits. Cassie Fleckenstein manages the studies in Cincinnati, keeping track of a multitude of tasks, including fellowship involvement in research, which has been a cornerstone of this program since the early 1980s. We are also very grateful for the statistical expertise provided by Dr. Marty Levy of the University of Cincinnati.

Finally, I'd like to thank my family—my husband Rick and my children Teri and Alex—for their support during this endeavor. I hope this textbook will be of value to many different types of health professionals for many years to come.

Sue D. Barber-Westin

FOREWORD TO THE FIRST EDITION

It has been my observation over the years that Frank Noyes has three fundamental beliefs, or organizing principles, around which he has dedicated his professional life and that explain the contents of this book. These are:

1. Diagnosis and treatment of patient disorders should be strongly informed by knowledge gained from basic science studies.
2. The outcome of surgical treatment is critically dependent on rehabilitation therapy.
3. Advancement of medical care, both surgical and nonsurgical, requires carefully conducted outcomes studies that account for differences in outcome caused by the type and intensity of a patient's activities and avoid bias due to the loss of patients to follow-up.

These core beliefs help explain the many research studies he and his colleagues have conducted. The results of these studies and their clinical correlations, along with the broader base of knowledge developed by numerous investigators, form the foundation of Dr. Noyes' approach to the diagnosis and treatment of knee disorders.

This book details the approaches Dr. Noyes has developed to the diagnosis and treatment of knee disorders, along with the scientific foundations on which his approaches are based. The result is a valuable reference book for both physicians and physical therapists who care for patients with knee disorders. The inclusion of supporting basic science data also makes this book an excellent reference for any investigator or student who is interested in improving the care provided to patients with knee disorders by further advancing knowledge of the normal and pathologic knee.

Although the title *is Noyes' Knee Disorders,* and the content in large part reflects his clinical approaches and research, it also includes the clinical approaches and research results of other leading surgeons and physical therapists. There is, however, a common thread in that the clinical approaches presented include the scientific foundations on which they are based. Furthermore, the reader will find that the chapters that present the research of Dr. Noyes and his colleagues also include results of other leading scientific investigators. The studies included were selected to fill in gaps and provide a broader perspective in areas where a consensus has not yet been developed.

The quality of the content of this book is complemented by the quality of its production. Each chapter has "Critical Points" boxes that focus the reader's attention on the main takeaway messages. There is extensive use of color to enhance readability, particularly in the presentation of data. Great care has been taken to make the anatomic drawings and medical illustrations accurate and to carefully label all illustrations and images. The care put into the production by Elsevier reflects the high standard of care Dr. Noyes brings to those projects he undertakes, including the care delivered to his patients and his dedication to advancing care through carefully conducted basic science and clinical research studies. Although one result of Elsevier's and Dr. Noyes' efforts is the book's visual appeal, it was not the goal. Rather, the visual appeal is a byproduct of their efforts to provide the reader with a useful text in which the content is easily understood and accessible.

This book presents much of the research conducted by Dr. Noyes and his collaborators, including much of my own research. I would like to take this opportunity to express my appreciation and gratitude to Frank Noyes for the opportunity of collaboration, for the time and energy he has devoted to our collaboration, and to the significant financial support he and his partners have provided our research. I first met Frank in 1973 when he was stationed with the 6570th Aerospace Medical Research Laboratory, located at Wright Patterson Air Force Base just outside Dayton, Ohio. I had recently received my PhD and was working at the University of Dayton Research Institute. It was there we met thanks to the efforts of a mutual friend and colleague, George "Bud" Graves. It was also in Dayton we did the first collaborations that led to our paper on the age-related strength of the anterior cruciate ligament. In 1975 we moved to the University of Cincinnati, thanks to the encouragement of Edward Miller, MD, then Head of the Division of Orthopaedics. This move was made possible by the generosity of Nicholas Giannestras, MD, and many other orthopaedic surgeons in the community who provided support to initiate a Biomechanics Laboratory. It was in Cincinnati where we initiated our first study on whole knee biomechanics and designed and initiated our first studies on primary and secondary ligamentous restraints. We were fortunate to have David Butler join our group in late 1976 and complete the study in progress on ACL and PCL restraints, a study for which he later received the Kappa Delta Award.

In addition to working with excellent colleagues, I have been fortunate to work with many engineering students, orthopaedic residents, postdoctoral students, sports medicine fellows, and visiting professors. Without their combined intellectual contributions and hard work, I would not have been able to complete many of the studies that are included in this text. They all have my sincerest appreciation for their support and contributions.

Edward S. Grood, PhD
Director, Biomechanics Research
Cincinnati SportsMedicine Research and Education Foundation
Professor Emeritus, Department of Biomedical Engineering
Colleges of Medicine and Engineering
University of Cincinnati
Cincinnati, Ohio

FOREWORD

The 1970s saw the beginning of dramatic changes in the diagnosis and treatment of knee injuries. Frank Noyes has remained in the forefront of this revolution. Frank Noyes, MD, and Edward Grood, PhD, together with coworkers at the University of Cincinnati and later Cincinnati SportsMedicine and Orthopaedic Center, were the first to perform sophisticated biomechanical studies that changed the way we think about knee instabilities. They were the first to perform three-dimensional analysis of knee motions. They wrote the software that characterized the three axes of knee motion, about which each axis has a rotation and a translation. This concept is used today in all robotic and computerized programs on knee motion analysis.

Noyes and his coworkers studied normal and abnormal knee kinetics and kinematics, specifically anterior and posterior cruciate ligament graft placement sites and tension, as well as strengths of knee ligaments and replacement grafts; they then introduced the flexion-rotation drawer test. They also developed a logical classification of knee ligament injuries. Noyes has published more than 50 articles that have characterized the scientific basis of knee ligament function. His laboratory received a Kappa Delta Award for this research program.

In particular, Dr. Noyes has demanded evidence to support treatments and published the results of many prospective randomized control outcome studies. Dr. Noyes developed and validated the Cincinnati Knee Rating System, considered the gold standard for outcome studies today. He stressed the importance of postoperative rehabilitation and pioneered innovative rehabilitation techniques. Dr. Noyes developed the first program to show that neuromuscular conditioning could decrease the incidence of ACL injuries. This nonprofit program is the largest ACL injury prevention program in the world; it is active at more than 1500 sites in the United States, Europe, Asia, Australia, and elsewhere.

In 1980 the American Orthopaedic Society for Sports Medicine, acting on Dr. Noyes' proposal, created a Research Committee with Dr. Noyes as its Chairman for 10 years. He was appointed the to the National Institutes of Health (NIH) Arthritis Advisory Panel and paved the way for the NIH awarding its first grants in sports medicine.

In "The 100 Classic Papers of Orthopaedic Surgery," Dr. Noyes is listed twice.[1] Only two other orthopaedic surgeons have more citations, none in sports medicine. Several other studies show Dr. Noyes to have the highest number of citations in the published orthopaedic literature.[2-4] Dr. Frank Noyes can unquestionably be called the "father of scientific sports medicine."

In 2010, Dr. Noyes published the culmination of his 40 years of clinical and research experience: *Noyes' Knee Disorders: Surgery, Rehabilitation, and Clinical Outcomes.* He has now prepared an updated and expanded second edition. This new book contains 45 chapters written by 30 authors. The edition also comes with 45 videos lasting 11 hours and has new chapters on unicompartmental knee arthroplasty.

Recently, questions have been raised regarding when athletes may safely return to sports after major knee surgery. The rehabilitation chapters in this new second edition include a detailed progression of exercises and parameters to be met before patients may be released to unrestricted activities.

This edition also contains some of the most comprehensive and advanced chapters on knee arthrofibrosis, complex regional pain syndrome, tibial and femoral osteotomies, and posterolateral reconstructions available in current published literature.

It would be difficult to imagine how the first edition of *Noyes' Knee Disorders* could be made better. But Dr. Noyes has done just that in this new and enhanced second edition.

Bertram Zarins, MD
Augustus Thorndike Clinical Professor of Orthopaedic Surgery
Harvard Medical School
Emeritus Chief of Sports Medicine
Massachusetts General Hospital

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FOREWORD

I am honored to write this forward for *Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes* by Dr. Frank Noyes. I would not have thought that the first edition could have been enhanced, but it certainly was with this edition. My compliments to the editors and authors of this insightful and wonderful textbook. It is truly a wealth of knowledge in one package.

The objective of this book was to produce an all-inclusive text on the knee joint that would include a multidiscipline approach to the evaluation and treatment of knee disorders. The textbook was designed to provide both basic and clinical sciences to enhance the reader's knowledge of the knee joint.

The knee joint continues to be one of the most researched, written about, and talked about subjects in orthopaedics and sports medicine. Even with the extensive literature available, Dr. Noyes and Ms. Barber-Westin have done a masterful job pulling a tremendous amount of information together into over 1200 pages, with over 4600 references and nearly 1000 figures in one comprehensive textbook. There are numerous chapters on the anatomy and biomechanics of various knee structures. There are specific and detailed sections on the evaluation and treatment of specific knee lesions, including the anterior cruciate ligament (ACL), posterior cruciate ligament, articular cartilage, patellofemoral joint, the menisci, and other structures. There are numerous chapters on the rehabilitation for each of the various knee disorders, and even a section on the gender disparity in ACL injuries. Furthermore, there are thorough sections on clinical outcomes—a much-needed area for clinicians to understand and utilize.

I have had the true pleasure of knowing Dr. Noyes for over 25 years, and he has always practiced medicine using several principles. These include a scientific basis (evidence) to support his treatment approach, a team approach to treatment, meticulous surgery, and the attitude to always do what is best for the patient. He has applied these key principles into this outstanding textbook. Dr. Noyes has always been a proponent of a team approach to the evaluation and treatment of patients with knee disorders. This book illustrates this point beautifully, with chapters written by biomechanists, orthopaedic surgeons, and physical therapists. Furthermore, Dr. Noyes has always searched for the best treatments for the patient, seeking clinical evidence to support the treatment.

As they have done more than one hundred times before in published manuscripts and chapters, Dr. Noyes and Ms. Barber-Westin have teamed up to provide us with an outstanding reference book. This text will surely remain on every knee clinician's desk for a very long time. It should be read and studied by physicians, physical therapists, athletic trainers, students, and anyone involved in treating patients with knee disorders. This book will surely be a favorite for all practitioners.

This is a truly great contribution to the literature. Thank you, Dr. Noyes, for the guidance you have given and continue to give us.

Kevin E. Wilk, PT, DPT, FAPTA
Adjunct Assistant Professor
Marquette University
Milwaukee, Wisconsin;
Vice President of Education and Associate Clinical Director
Physiotherapy Associates;
Director of Rehabilitation Services
American Sports Medicine
Birmingham, Alabama

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1

Medial and Anterior Knee Anatomy

Alvin Detterline, John Babb, Frank R. Noyes

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MEDIAL ANATOMY OF THE KNEE

The medial anatomy of the knee consists of several layers of structures that work together to provide stability and function.[39,59-61] Authors have used a variety of anatomic terms and descriptions that, unfortunately, have created ambiguity and confusion regarding this area of the knee. Two anatomic classifications or descriptions have been proposed to aid in the understanding of the relationships of the medial knee structures. These include a layered approach,[57] which describes the qualitative relationship of each medial structure, and a more quantitative description,[35] which details the exact attachment site and origin of each structure. In this chapter, both approaches will be presented; however, emphasis is on the precise anatomic relationships that provide a more thorough understanding of the structures compared with the layer approach.

Medial Layers of the Knee

The three-layer description of the medial anatomy of the knee was proposed by Warren and Marshall.[57] In this approach, layer 1 consists of the deep fascia or crural fascia; layer 2 includes the superficial medial collateral ligament (SMCL), medial retinaculum, and the medial patellofemoral ligament (MPFL); and layer 3 is composed of the distal medial collateral ligament (DMCL) and capsule of the knee joint (Fig. 1-1). For this chapter, the term *medial collateral ligament* (MCL) has been used instead of tibial collateral ligament because it represents the term most commonly used in the English language literature. The medial structures identified as important in preventing lateral patellar subluxation are the MPFL[2,19,20] and the medial patellomeniscal ligament, which inserts onto the inferior third of the patella to the anterior portion of the medial meniscus and runs adjacent to the medial fat pad. The medial parapatellar retinaculum and so-called *medial patellotibial ligament* (thickening of the anterior capsule inserting from the inferior aspect of the patella to the anteromedial aspect of the tibia) are retinacular tissues that have been described; however, these structures are not believed important in providing patellar stability.

The layer approach is important because the ligaments and soft tissues on the medial side of the knee are not discrete, individual structures like the SMCL, but rather, fibrous condensations within tissue planes.[57] This qualitative description of anatomy assists in understanding the spatial relationships of these structures and how they function to support the knee.[63] It is equally important to understand the quantitative anatomy from precise measurements of the attachments and origins of each individual structure. The complex medial anatomy of the knee has been illustrated in the past with oversimplification of the soft tissue attachments to bone and other structures, which makes it difficult to compare the origins, insertions, and courses of the many separate structures among studies.[6,7,15,21,37,52,57] LaPrade and coworkers[35] published detailed quantitative measurements that provide a better understanding of the medial knee anatomy (Figs. 1-2 and 1-3).

Layer 1: Deep Fascia

Layer 1 (see Fig. 1-1) consists of the deep fascia that extends proximally to invest the quadriceps, posteriorly to invest the two heads of the gastrocnemius and cover the popliteal fossa, and distally to involve the sartorius muscle and sartorial fascia. Anteriorly, layer 1 blends with the anterior part of layer 2 approximately 2 cm anterior to the SMCL.[57] Inferiorly, the deep fascia continues as the investing fascia of the sartorius and attaches to the periosteum of the tibia. Layers 1 and 2 are always distinct at the level of the SMCL unless extensive scarring has occurred.[57] The gracilis and semitendinosus tendons are discrete structures that lie between layers 1 and 2 and are easily separated from these two layers. However, according to Warren and Marshall,[57] these tendons will occasionally blend with the fibers in layer 1 anteriorly before they insert onto the tibia. As depicted in Figure 1-4, dissections and clinical experience of the authors concur in that there is a blending of layer 1 with a confluence of the semitendinosus and gracilis tendons at their common insertion onto the tibia; however, they are easily

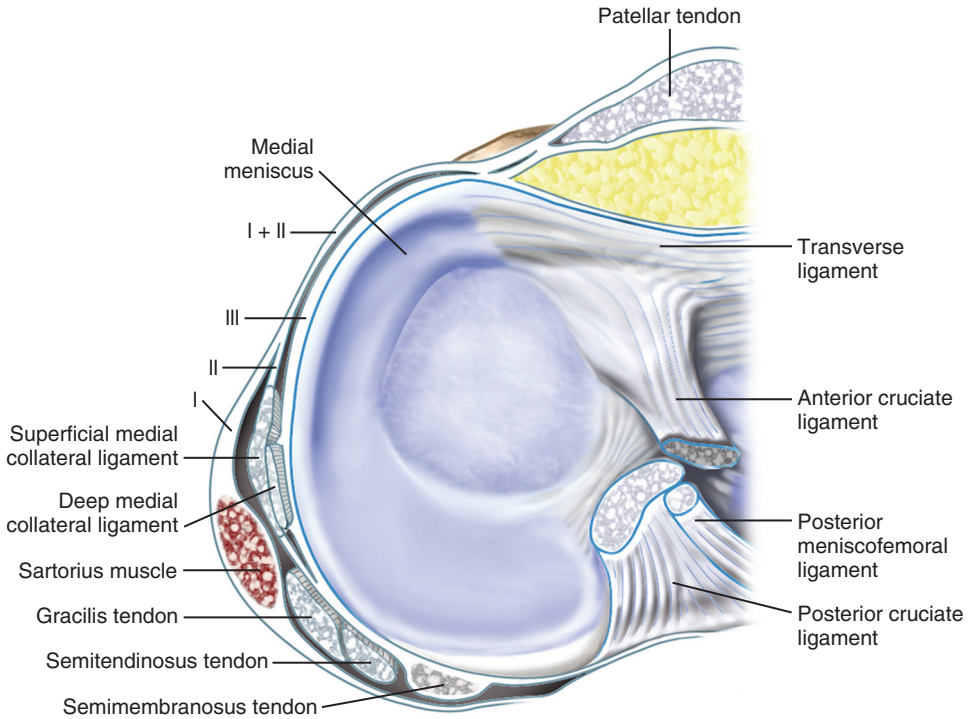


FIG 1-1 Medial layers of the knee. The gracilis and semitendinosus lie between layers 1 and 2.

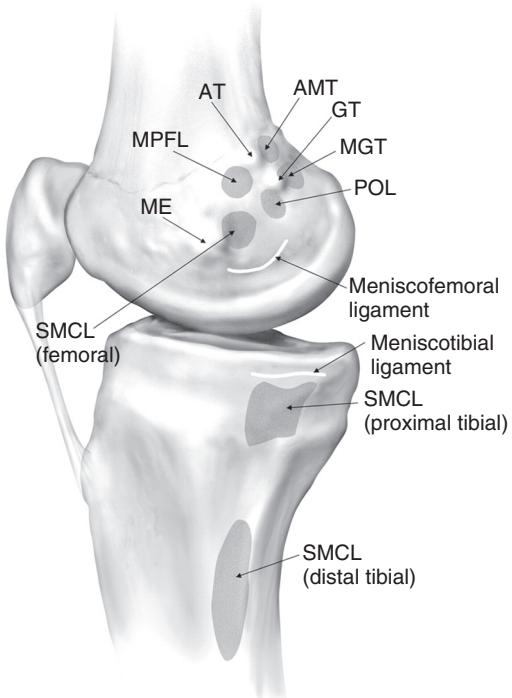


FIG 1-2 The femoral osseous landmarks and attachment sites of the main medial knee structures. *AT,* Adductor tubercle; *AMT*, adductor magnus tendon; *GT*, gastrocnemius tubercle; *ME*, medial epicondyle; *MGT*, medial gastrocnemius tendon; *MPFL*, medial patellofemoral ligament; *POL*, posterior oblique ligament; *SMCL*, superficial medial collateral ligament. (From LaPrade RF, Engebretsen AH, Ly TV, et al. The anatomy of the medial part of the knee. *J Bone Joint Surg.* 2007;89A:2000-2010.)

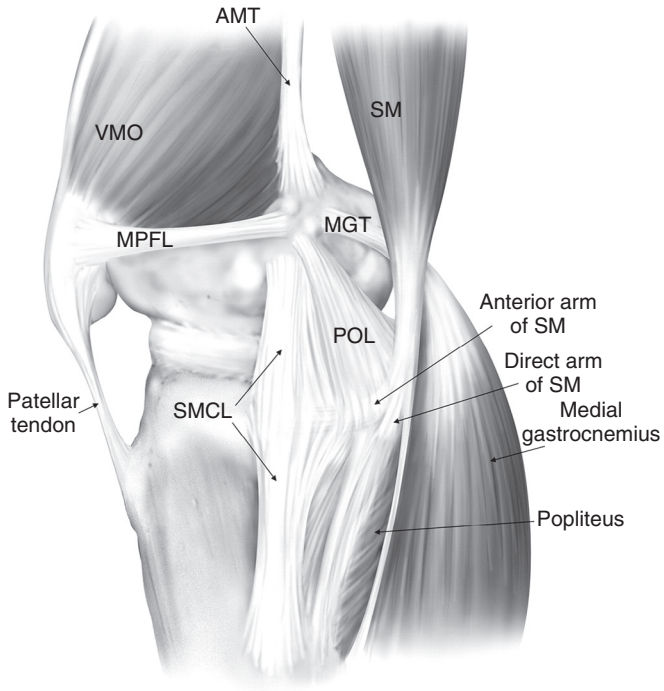


FIG 1-3 The main medial knee structures (right knee). *AMT*, Adductor magnus tendon; *MGT*, medial gastrocnemius tendon; *SM*, semimembranosus muscle; *SMCL*, superficial medial collateral ligament; *MPFL*, medial patellofemoral ligament; *POL*, posterior oblique ligament; *VMO*, vastus medialis obliquus. (From LaPrade RF, Engebretsen AH, Ly TV, et al. The anatomy of the medial part of the knee. *J Bone Joint Surg.* 2007;89A:2000-2010.)

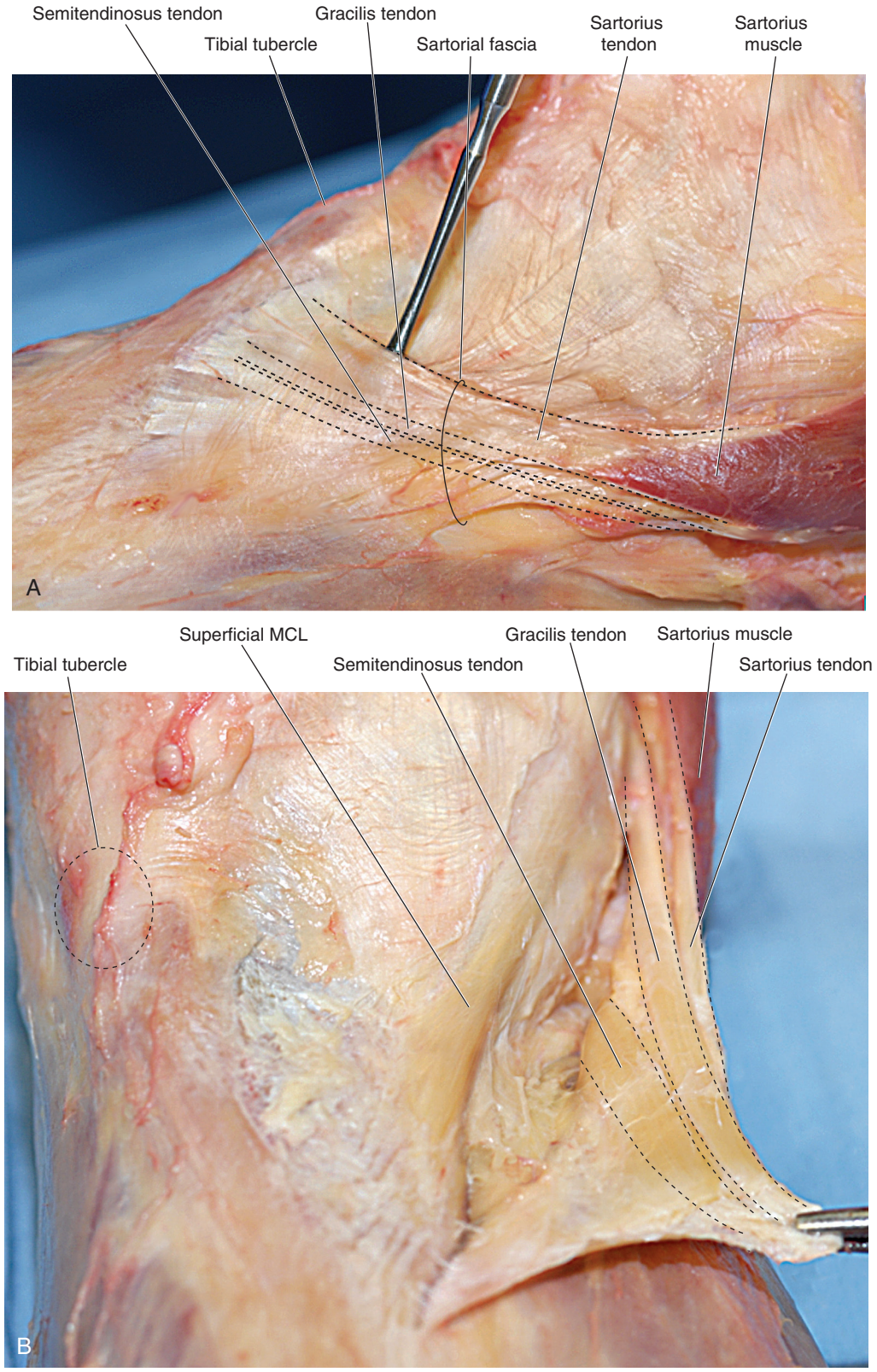


FIG 1-4 A, Sartorius fascia of layer 1 overlying the gracilis and semitendinosus tendons. **B,** Gracilis and semitendinosus tendons within pes anserine fascia. *MCL,* medial collateral ligament.

found as discrete structures more posteriorly. Thus, we recommend that when attempting to harvest the semitendinosus and gracilis tendons for an anterior cruciate ligament reconstruction, these tendons initially be identified 2 to 3 cm posterior and medial to the anterior tibial spine. This will allow for easier visualization of the tendons, which can then be traced to their insertions on the anterior tibia to allow for maximal tendon length at the time of harvest.

Layer 2: Superficial Medial Collateral Ligament and Posterior Oblique Ligament

The SMCL is a well-defined structure that spans the medial joint line from the femur to tibia. According to LaPrade and coworkers,[35] the SMCL does not attach directly to the medial epicondyle of the femur, but is centered in a depression 4.8 mm posterior and 3.2 mm proximal to the medial epicondyle center. Other studies have described the MCL attaching directly to the medial epicondyle of the femur.[6,7,29,37,40,42,47,49,55,57] The confusion lies in the confluence of fibers that reside in the area of the medial epicondyle that make it difficult to identify the precise attachment site of the SMCL. As shown in Figure 1-5 the authors agree with LaPrade and coworkers[35] that the main fibers of the SMCL attach to an area just posterior and proximal to the medial epicondyle; but the origin of the SMCL is rather broad and, therefore, there are also superficial fibrous strands attaching anterior on the medial epicondyle and posterior in a depression on the medial femoral condyle.

The posterior fibers of the SMCL overlying the medial joint line, both above and below the joint, change orientation from vertical to a more oblique pattern that forms a triangular structure with its apex posterior,[7,37] eventually blending with the fibers of the posterior oblique ligament (POL) (Fig. 1-6). LaPrade and coworkers[35] described two anatomic attachment sites of the SMCL on the tibia. The first is located proximally at the medial joint line and consists mainly of soft tissue connections over the anterior arm of the semimembranosus. The second attachment site is further distal on the tibia, attaching directly to bone an average of 61.2 mm from the medial joint line. In the authors' experience, there is a consistent attachment of the proximal portion of the SMCL to the soft tissues surrounding the anterior arm of the semimembranosus, but a discrete attachment to bone is found only distally (see Fig. 1-6).

The gracilis and semitendinosus lie between layers 1 and 2 at the knee joint. The sartorius drapes across the anterior thigh and into the medial aspect of the knee invested in the sartorial fascia in layer 1. The insertion of the sartorius, as described by Warren and Marshall,[57] consists of a network of fascial fibers connecting to bone on the medial side of the tibia, but does not appear to have a distinct tendon of insertion such as the underlying gracilis and semitendinosus. However, LaPrade and coworkers[35] located the gracilis and semitendinosus tendons on the deep surface of the superficial fascial layer, with each of the three tendons attaching in a linear orientation at the lateral edge of the pes anserine bursa.

In our experience, the sartorial fascia has a broad insertion onto the anteromedial border of the tibia and, with sharp dissection at its insertion, the underlying distinct tendons of the gracilis and semitendinosus are easily visualized (see Fig. 1-4). At the level of the joint, layers 1 and 2 are easily separated from one another over the SMCL. However, farther anteriorly, layer 1 blends with the anterior part of layer 2 along a vertical line 1 to 2 cm anterior to the SMCL.[57]

Also within layer 2 is the MPFL, which courses from the medial femoral condyle to its attachment onto the medial border of the patella.[5,44,51] This is a flat, fan-shaped structure that is larger at its

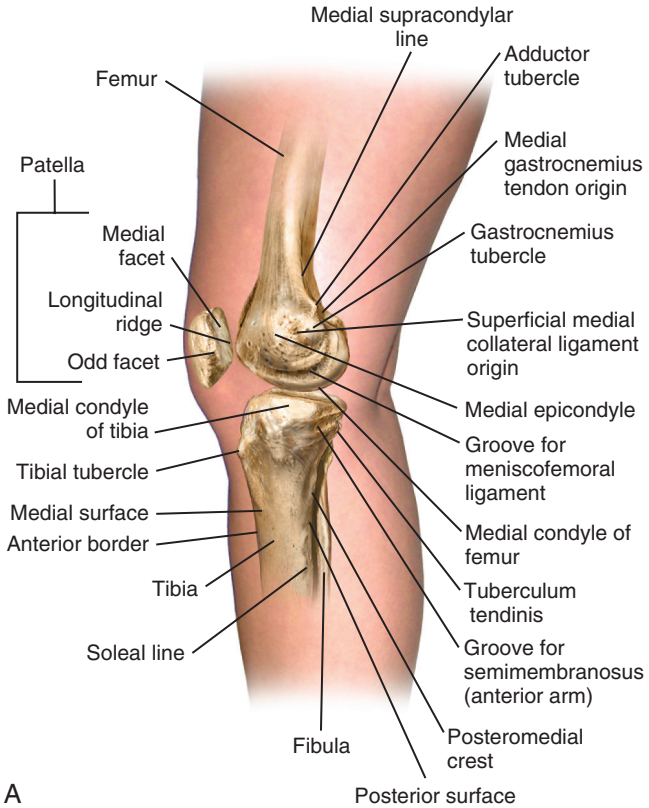
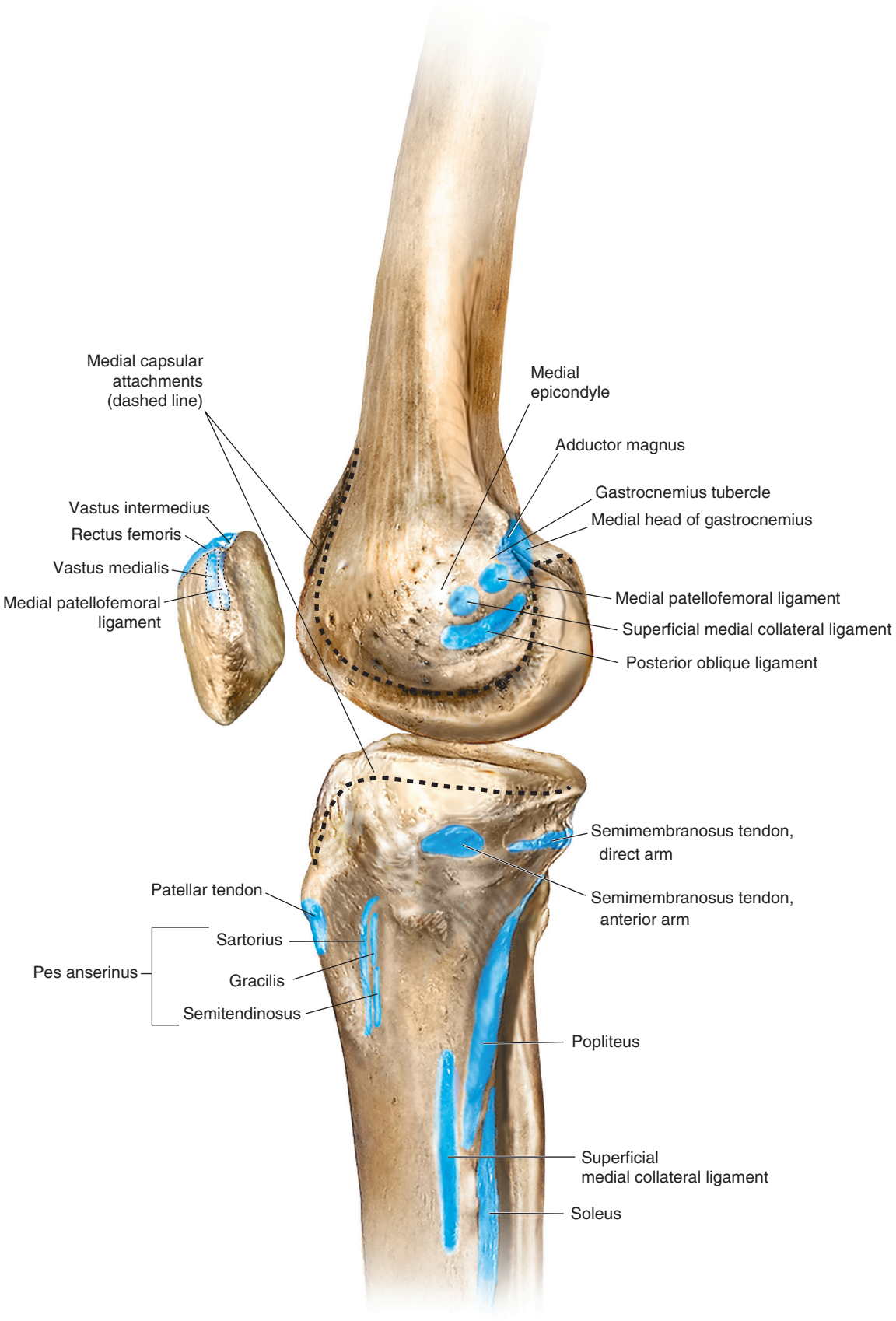


FIG 1-5 A, Osseous landmarks of knee (medial view). *Continued*



B Medial Knee Attachments

FIG 1-5, cont'd B, Soft tissue attachments to bone (medial knee).

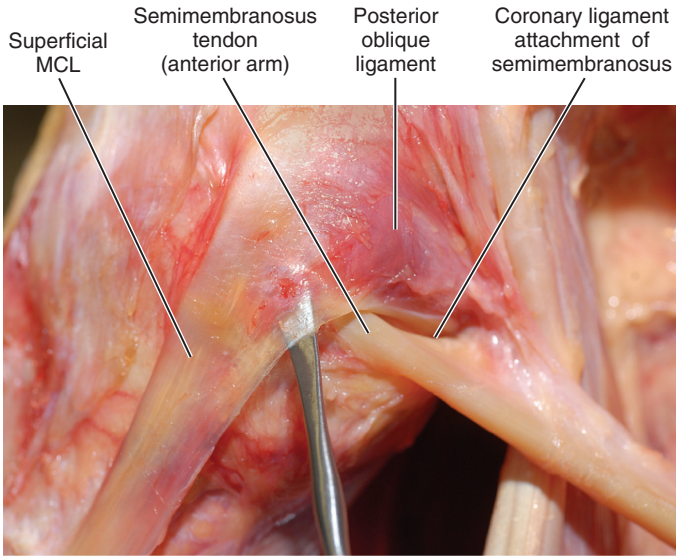


FIG 1-6 Oblique fibers of superficial medial collateral ligament (MCL) blending with the posterior oblique ligament. Note the coronary ligament attachment from the anterior arm of the semimembranosus.

patellar attachment than its femoral origin, with a length averaging 58.3 mm (47.2-70.0 mm).[48] Controversy exists regarding where the MPFL attaches at the medial femoral condyle. Mochizuki and coworkers[41] described the MPFL as a fan-shaped structure with proximal fibers extending to the medial margin of the vastus intermedius, and distal fibers interdigitating with the medial retinaculum without a distinct attachment to the vastus medialis. LaPrade and coworkers[35] noted that the MPFL attaches primarily to soft tissues between the attachments of the adductor magnus tendon and the SMCL, with an attachment to bone 10.6 mm proximal and 8.8 mm posterior to the medial epicondyle. Steensen and associates,[50] from a dissection of 11 knees, believe the MPFL attaches along the entire length of the anterior aspect of the medial epicondyle. Smirk and Morris[48] describe a variable origination of the MPFL on the femur. In dissections of 25 cadavers, the MPFL attached solely to the posterior aspect of the medial epicondyle, approximately 1 cm distal to the adductor tubercle in 44% of specimens. The adductor tubercle was included in the origin in 4%, the adductor magnus tendon in 12%, the area posterior to the adductor magnus tendon in 20%, and a combination of these in 4%. In 16% of the specimens, the MPFL attached anterior to the medial epicondyle. Fulkerson and Edgar[16] described a distinct attachment of the MPFL to the medial quadriceps tendon and named this structure the medial quadriceps tendon–femoral ligament. Kang and associates[30] described the femoral attachment point for MPFL fibers as two "relatively concentrated fiber bundles." The authors identified an "inferior straight" bundle (what is commonly referred to as the *MPFL*) that was the main static soft tissue restraint. The superior-oblique bundle was attached and associated with the vastus medialis obliquus (VMO) and was identified as a dynamic soft tissue restraint. The authors acknowledged that the two bundles were not entirely separable.

In our experience, the MPFL attaches in a depression posterior to the medial epicondyle and blends with the insertion of the SMCL (Fig. 1-7). The anterior attachment of the MPFL consists of both attachments to the undersurface of the VMO and the proximal medial border of the patella. The work of Steensen and associates[50] demonstrated that the VMO does not overlap the MPFL, with the exception in 3 of 11 knees in which only 5% of the width of the MPFL was deep to the VMO. However, LaPrade and coworkers[35] reported that the distal border of the VMO attaches along the majority of the proximal edge of the MPFL before inserting onto the superomedial border of the patella. The midpoint of the MPFL attachment is located 41% of the length from the proximal tip of the patella along the total patellar length. Our experience is that the MPFL attaches to the proximal third of the patella, with the majority of the ligament connected to the distal portion of the VMO with fibrous bands (see Fig. 1-7).

The adductor magnus and medial gastrocnemius tendons also contribute to the medial anatomy of the knee; both attach on the medial femoral condyle. Similar to the SMCL attachment, the confluence of fibers over the medial femoral condyle makes it difficult to precisely identify the exact location of each attachment (Fig. 1-8). The adductor magnus tendon is a well-defined structure attaching just superior and posterior to the medial epicondyle near the adductor tubercle. LaPrade and coworkers[35] reported the adductor magnus does not attach directly to the adductor tubercle, but rather to a depression located an average of 3.0 mm posterior and 2.7 mm proximal to the adductor tubercle. The adductor magnus also has fascial attachments to the capsular portion of the POL and medial head of the gastrocnemius.

The medial gastrocnemius tendon inserts in a confluence of fibers in an area between the adductor magnus insertion and the insertion of the SMCL (Fig. 1-9 *A*). LaPrade and coworkers[35] described a gastrocnemius tubercle on the medial femoral condyle in this region; however, these authors state that the tendon does not attach to the tubercle, but to a depression just proximal and posterior to the tubercle. In addition, fascial expansions from the lateral aspect of the medial gastrocnemius tendon form a confluence of fibers with the distal extent of the adductor magnus tendon in addition to the capsular arm of the POL (see Fig. 1-9 *A*).

Layers 2 and 3 blend together in the posteromedial corner of the knee along with additional fibers that extend from the semimembranosus tendon and sheath that form the posteromedial capsule (see Fig. 1-9). LaPrade and coworkers[35,62] used the term *posterior oblique ligament* (POL) for this same structure and described each of the three fascial attachments similar to Hughston and colleagues' original description.[27,28] The superficial arm of the POL runs parallel to both the more anterior SMCL and the more posterior distal expansion of the semimembranosus. Proximally, the superficial arm blends with the central arm; distally, it blends with the distal expansion of the semimembranosus as it attaches to the tibia.[35]

The central arm is the largest and thickest portion of the POL,[35] running posterior to both the superficial arm of the POL and SMCL. It courses from the distal portion of the semimembranosus and is a fascial reinforcement of the meniscofemoral and meniscotibial portions of the posteromedial capsule. LaPrade and coworkers[35] noted that this structure has a thick attachment to the medial meniscus. As the central arm courses along the posteromedial aspect of the joint, it merges with the posterior fibers of the SMCL and can be differentiated from the SMCL by the different directions of the individual fibers. The distal attachment of the central arm is primarily to the posteromedial portion of the medial meniscus, the meniscotibial portion of the capsule, and the posteromedial tibia.[35]

The capsular portion of the POL is thinner than the other portions of this structure and fans out in the space between the central arm and the distal portions of the semimembranosus tendon. The capsular portion blends posteriorly with the posteromedial capsule of the knee and the medial aspect of the oblique popliteal ligament (OPL).[35] It attaches proximally to the fibrous bands of the medial gastrocnemius tendon and fascial expansions of the adductor magnus tendon, with no osseous attachment identified.

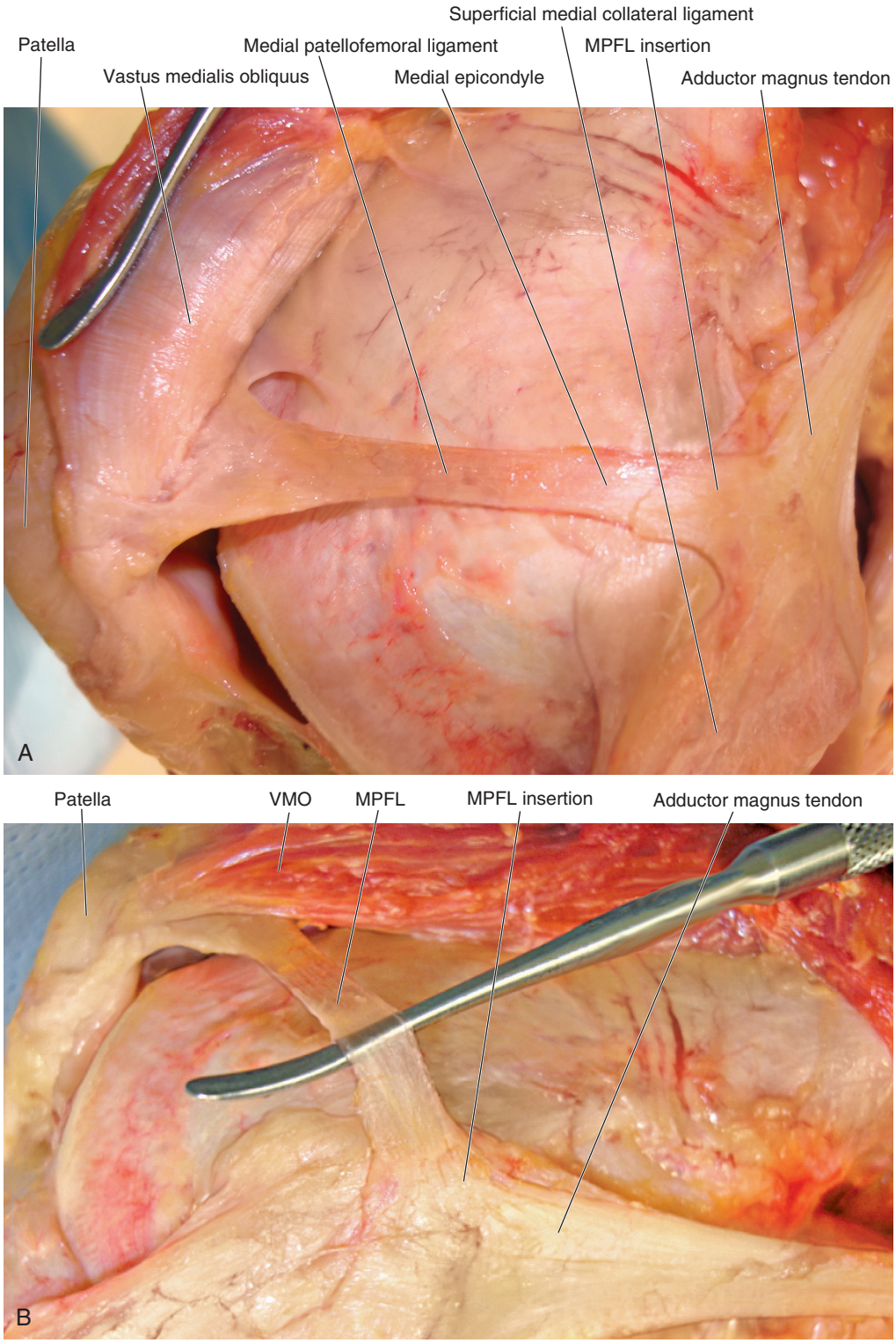


FIG 1-7 **A,** Medial patellofemoral ligament (MPFL) inserts into a depression behind the medial epicondyle and blends with fibers of the superficial medial collateral ligament. **B,** Fibrous bands from the vastus medialis obliquus (VMO) muscle connect to the MPFL before it inserts into the patella.

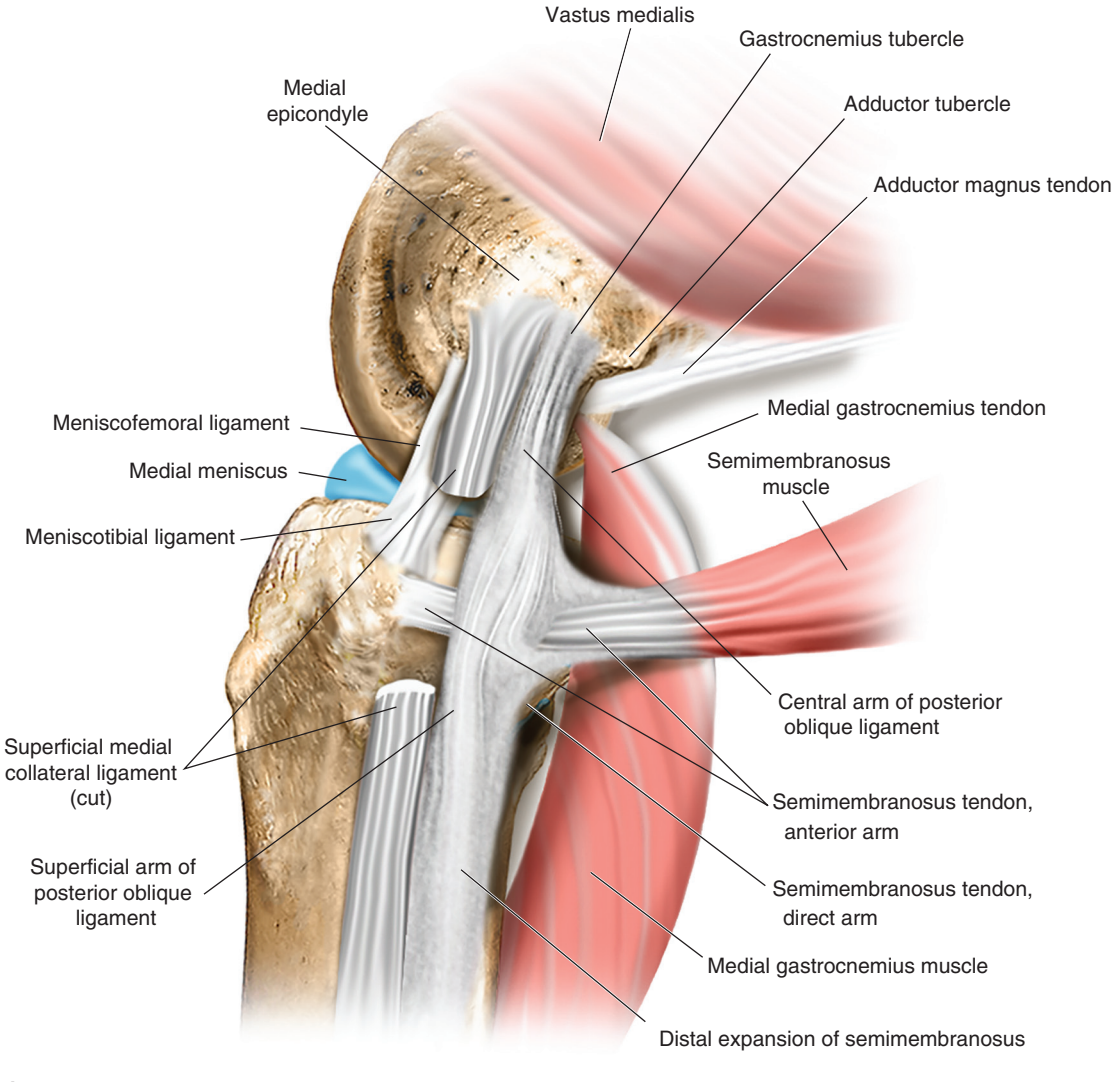


FIG 1-8 A, Insertions onto the medial femoral condyle of the adductor magnus, medial head of gastrocnemius, and the posterior oblique ligament with its three divisions: capsular, central, and superficial arms. **B,** Osseous anatomy of the medial femoral condyle with the medial epicondyle, adductor tubercle, and gastrocnemius tubercle.

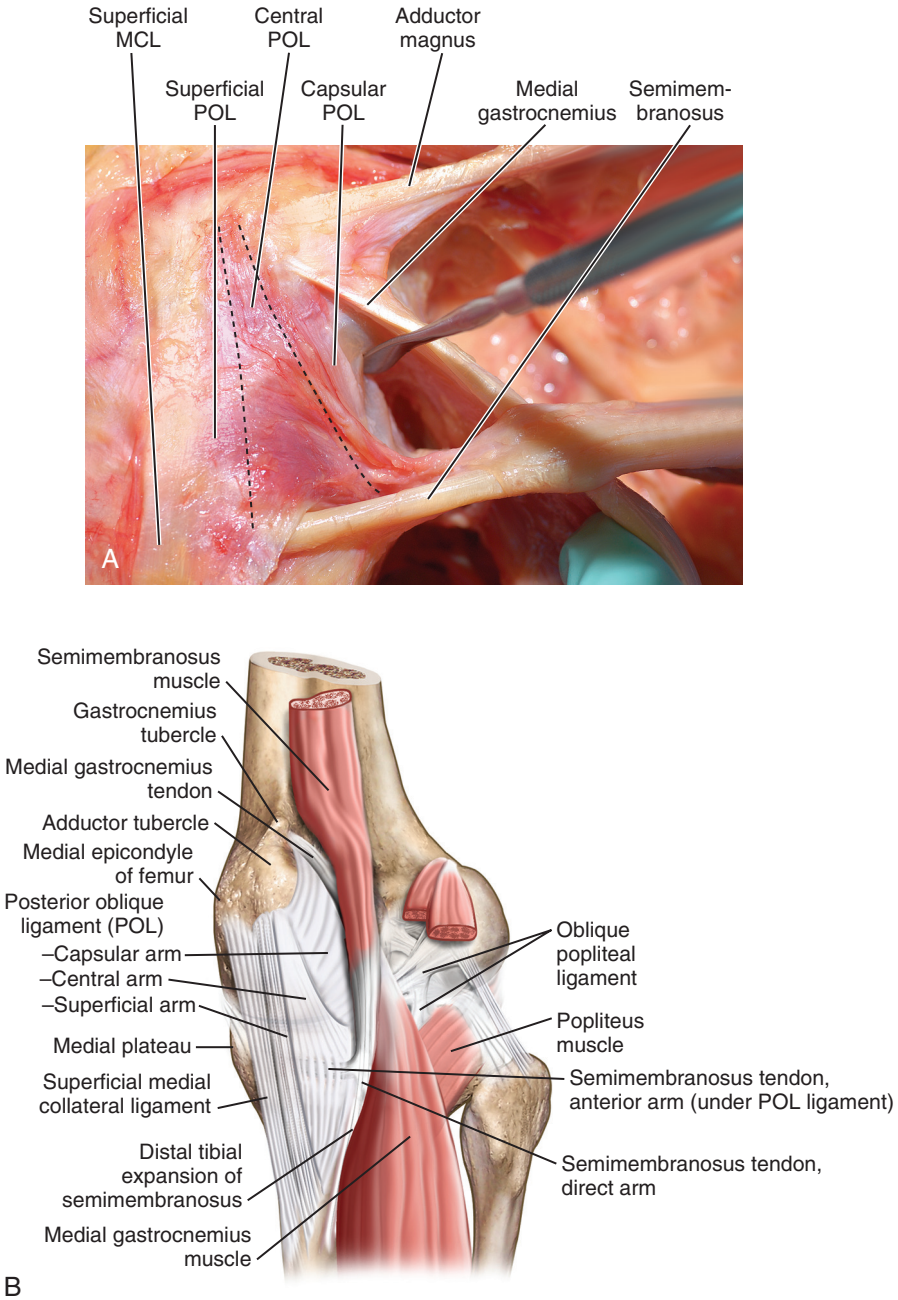


FIG 1-9 **A,** Insertions onto the medial femoral condyle of the adductor magnus, medial head of gastrocnemius, and posterior oblique ligament (POL) with its three divisions: capsular, central, and superficial arms. **B,** Anatomy of the POL with its three divisions. *MCL,* Medial collateral ligament.

The superficial portion of the POL is rather thin and appears to represent a confluence of fibers from the SMCL and the semimembranosus more distally. The capsular portion appears to represent a confluence of fibers from the semimembranosus, adductor magnus, and medial gastrocnemius (see Fig. 1-9). The central arm appears more robust, having contributions from the semimembranosus and medial gastrocnemius.

Controversy remains on whether three separate distinct anatomic structures make up the POL. Other authors[46] have not found three distinct structures and note that with tibial rotation, different portions of the posteromedial capsule appear under tension but are not anatomically separate structures.

Semimembranosus. Controversy exists with respect to the exact number of attachments of the semimembranosus tendon at the knee joint.[8,9,11,28,31,33,34,43,57] However, it appears that three major attachments have been consistently identified. The common semimembranosus tendon bifurcates into a direct and anterior arm just distal to the joint line. LaPrade and coworkers[35,36] described the direct arm attaching to an osseous prominence called the *tuberculum tendinis*, approximately 11 mm distal to the joint line on the posteromedial aspect of the tibia. These authors also note a minor attachment of the direct arm that extends to the medial coronary ligament along the posterior horn of the medial meniscus (see Fig. 1-6). A thinning of the capsule or capsular defect may be identified just distal to the femoral attachment of

the medial head of the gastrocnemius and proximal to the direct arm of the semimembranosus. This is often the site of the formation of a Baker cyst.

Warren and Marshall[57] believed the semimembranosus tendon sheath and not the tendon itself extends distally over the popliteus muscle and inserts directly into the posteromedial aspect of the tibia, with some fibers coalescing with SMCL fibers inserting in the same region. These authors contend that these fibers do not have functional significance, because no change was found in position or tension of the MCL when those fibers were transected. LaPrade and associates[36] separated the distal tibial expansion into a medial and lateral division. Both divisions originating on the coronary ligament of the posterior horn of the medial meniscus are located on either side of the direct arm of the semimembranosus. The divisions then course distally to cover the posterior aspect of the popliteus muscle and insert onto the posteromedial aspect of the tibia, forming an inverted triangle in appearance. These authors noted the medial division attaches just posterior to the SMCL, whose fibers coalesce with the superficial arm of the POL (as previously noted by Hughston and colleagues[28]) rather than the MCL.

In our experience, as shown in Figure 1-10, the semimembranosus tendon sheath and not the tendon itself comprises the distal tibial expansion, which includes a medial and lateral division with a central raphae separating the two. The anterior arm of the semimembranosus courses deep to the SMCL and attaches directly to bone just distal to the medial joint capsule on the tibia (Fig. 1-11). There are fibrous connections between the SMCL and the anterior arm of the semimembranosus, but only the anterior arm of the semimembranosus has an osseous attachment in this region. Because both the direct and anterior arms of the semimembranosus anchor directly to bone and attach distal to the tibial margin of the medial joint capsule, they are not considered part of either layer 2 or layer 3 as described by Warren and Marshall.[57]

The third major attachment of the semimembranosus is the OPL. Warren and Marshall[57] described the semimembranosus tendon sheath forming fiber tracts that make up the OPL, although they admit some collagen fibers may come from the tendon itself. LaPrade and associates[36] described a lateral expansion off the common semimembranosus tendon, just proximal to its bifurcation into the direct and anterior arms, that coalesces to form a portion of the OPL, in addition to the capsular arm of the POL. As shown in Figure 1-12, it is difficult to appreciate distinct structures comprising the origin of the OPL because of the significant confluence of fibers in the region. However, there are fibers originating from both the semimembranosus tendon and its sheath that contribute to its origin.

The OPL is described as a broad fascial band that courses laterally and proximally across the posterior capsule. LaPrade and associates[36] noted two distinct lateral attachments of the OPL (proximal and distal). The proximal attachment is broad, extending to the fabella, the posterolateral capsule, and the plantaris (see Fig. 1-12). It does not attach directly to the lateral femoral condyle. The distal attachment is on the posterolateral aspect of the tibia, just distal to the posterior root of the lateral meniscus, but not directly attaching to the lateral meniscus as described by Kim and coworkers.[34] It is theorized that this may serve a functional role limiting hyperextension, but this has not been demonstrated in any biomechanic study to date.

LaPrade and associates[36] also described a proximal capsular arm of the semimembranosus as a thin aponeurosis that traverses medially to laterally along the superior border of the OPL. As it courses laterally, it blends with the posterolateral capsule and inserts on the distal lateral femur just proximal to the capsular insertion while at the same time extending fibers to the short head of the biceps femoris tendon (see Fig. 1-12 *B* and *C*).

Layer 3: Deep Medial Collateral Ligament and Knee Capsule

The capsule of the knee joint is thin anteriorly and envelops the fat pad. In this area, the capsule is easily separated from the overlying superficial retinaculum until it reaches the margin of the patella, where it is difficult to separate the capsule from the overlying superficial

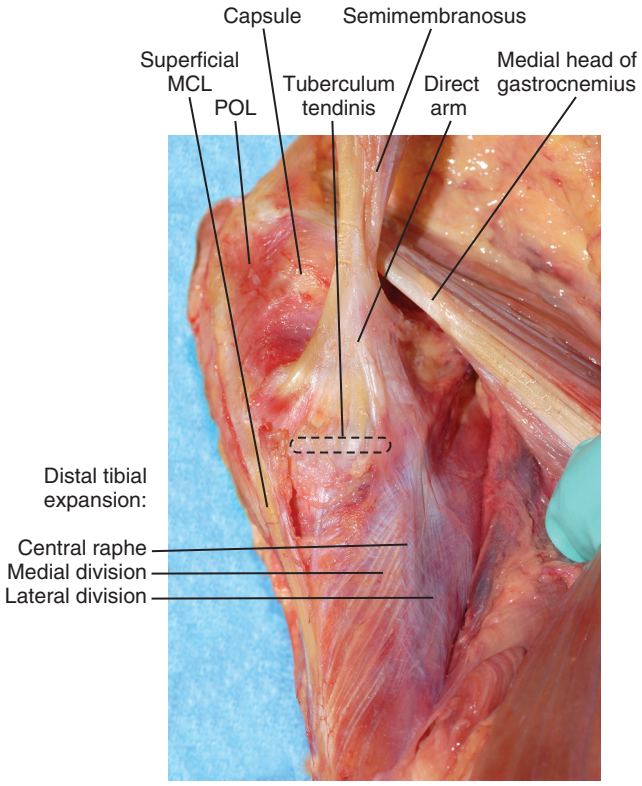


FIG 1-10 Distal tibial expansion of the semimembranosus tendon sheath with its medial and lateral divisions. *MCL,* Medial collateral ligament. *POL,* posterior oblique ligament.

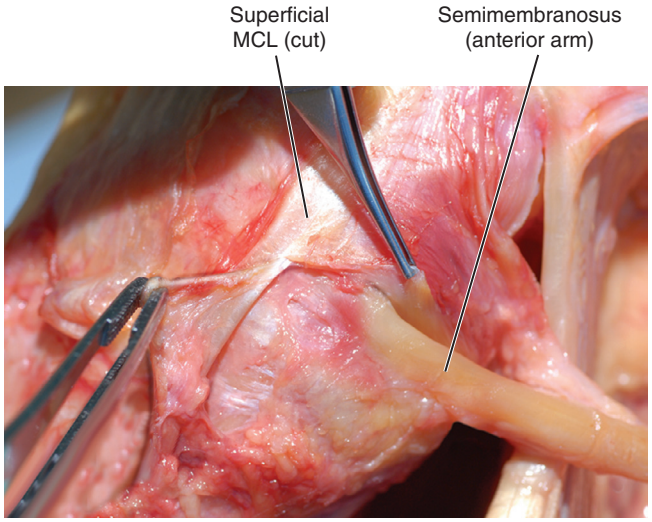


FIG 1-11 Superficial medial collateral ligament (MCL) is cut to show the anterior arm of semimembranosus attachment to bone.

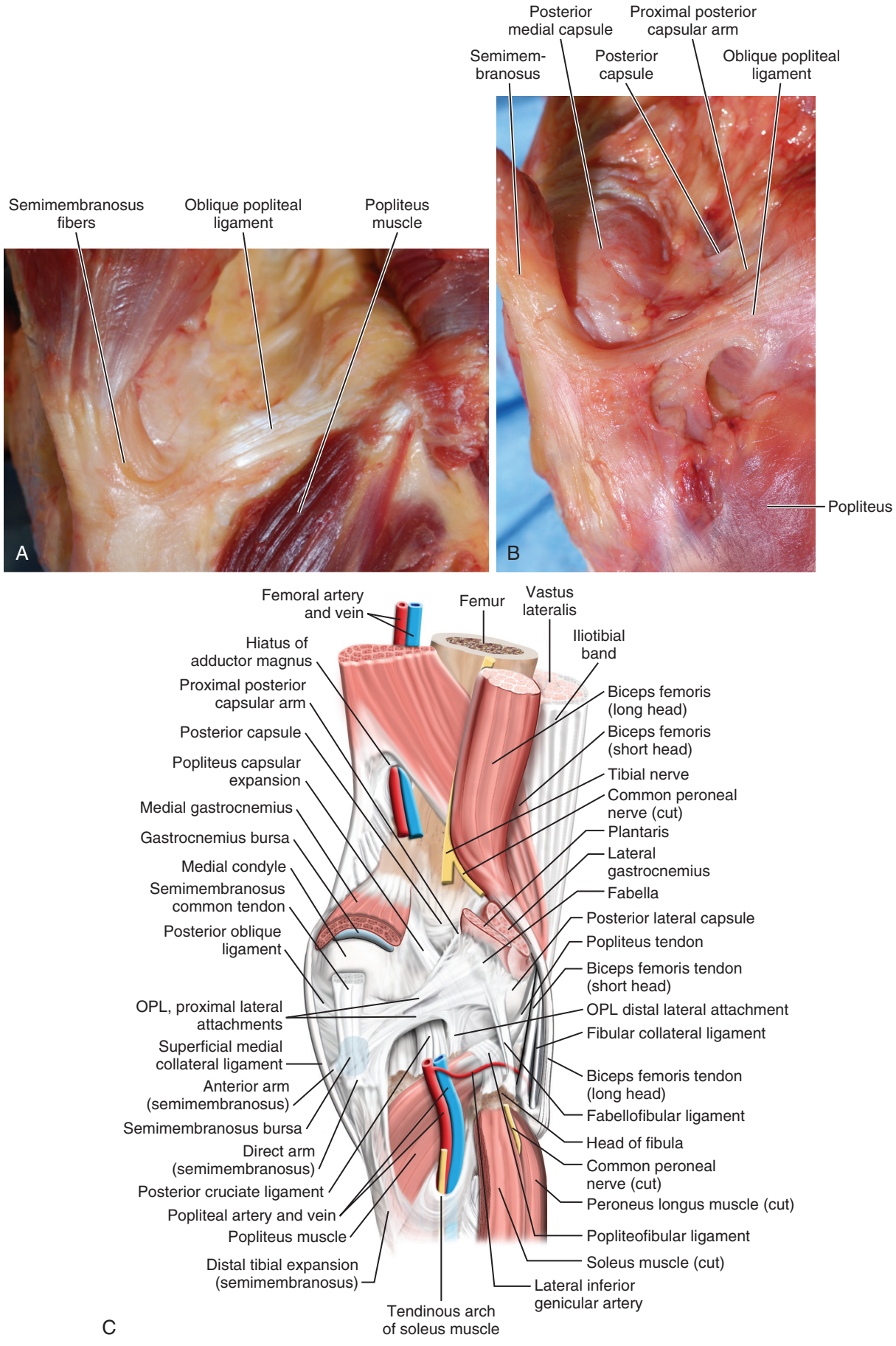


FIG 1-12 **A,** Semimembranosus fibers contributing to oblique popliteal ligament (OPL). **B,** OPL fans across the posterior knee with its multiple fibrous divisions. **C,** Posterior knee showing divisions of the POL.

structures.[57] Under the SMCL lies a vertical thickening of the knee capsule known as the *distal medial collateral ligament* (DMCL). The DMCL crosses the joint from the distal femur to the medial meniscus and inserts into the proximal tibia at sites adjacent to the articular surfaces of the femur and tibia. These separate divisions of the DMCL are named the *meniscofemoral* and *meniscotibial* ligaments. Warren and Marshall[57] noted the meniscofemoral portion of the DMCL had a discrete attachment onto the distal femur at its articular margin. Similarly, the meniscotibial portion of the DMCL, also known as the *coronary ligament*, is easily separated from the overlying SMCL in layer 2 before attaching to the tibia at its articular margin (Fig. 1-13).

The deepest structure on the medial side is the capsule of the knee, which envelops the entire joint and extends proximally up to the suprapatellar pouch and distally to the attachment site of the meniscotibial ligament on the tibia-articular cartilage border.[57]

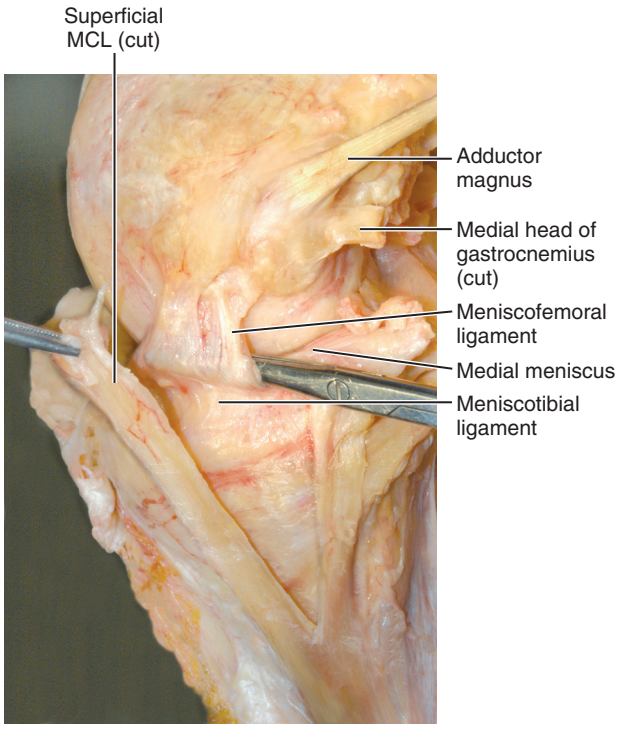


FIG 1-13 Superficial medial collateral ligament (MCL) cut to show deep medial collateral ligament with its two divisions: meniscofemoral and meniscotibial.

ANTERIOR ANATOMY OF THE KNEE

Several anatomic relationships and structures are important to recognize because they are critical to understanding the mechanics of the extensor mechanism and may be involved in several pathologic conditions.

Quadriceps Mechanism

The quadriceps consists of the rectus femoris, adjacent to the vastus medialis and lateralis on either side, and the vastus intermedius deep (Fig. 1-14). The rectus femoris is located centrally and superficially in the quadriceps mechanism and widens distally as is approaches the superior aspect of the patella. Reider and colleagues[45] found the width of the rectus femoris tendon to be 3 to 5 cm at the proximal pole of

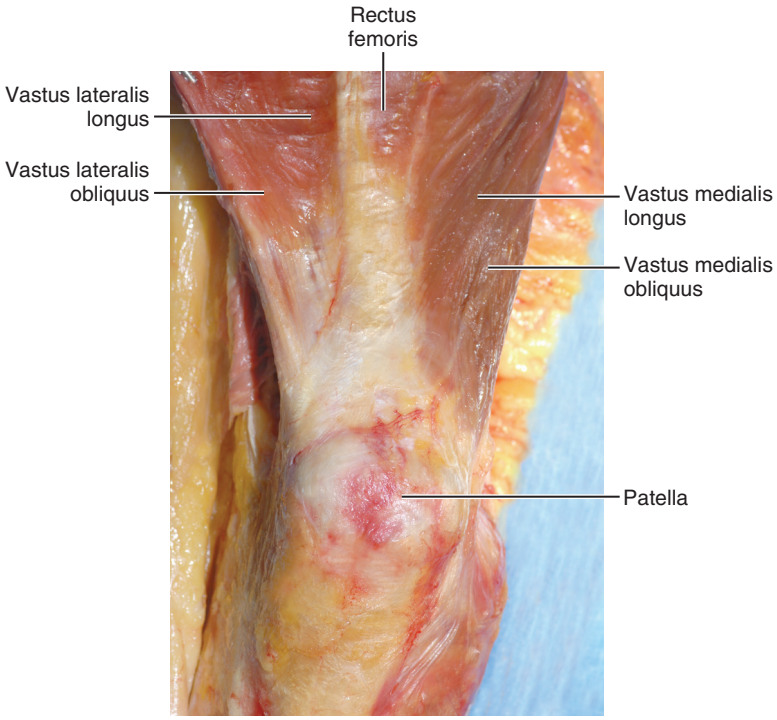


FIG 1-14 Extensor mechanism of knee showing the vastus lateralis, vastus medialis, and rectus femoris. Note the long tendon insertion of the vastus lateralis onto the proximal patella.

the patella. Some of the rectus tendon fibers insert into the superior aspect of the patella, but the majority continue over the anterior surface of the patella and are continuous with the patellar tendon distally. This is in contrast to the other components of the quadriceps mechanism that do not commonly contribute directly to the patellar tendon. The vastus medialis has fibers that run parallel to the rectus femoris fibers, called the *vastus medialis longus*, and others that run obliquely in relation to the rectus, termed the *vastus medialis obliquus* (VMO) according to Lieb and Perry.[38] Conlan and coworkers[10] described the VMO originating from the medial intermuscular septum and the adductor longus tendon proximal to the adductor tubercle. The angle of the obliquity of the VMO fibers varies considerably. Reider and colleagues[45] found a range of 55 degrees to 70 degrees in a cadaveric study. This variability in obliquity has been implicated in patellar maltracking.

The muscle of the vastus medialis extends distally and often becomes tendinous only millimeters from its patellar insertion. Reider and colleagues[45] noted some fibers insert directly into the patella, whereas others course more distally and contribute to the medial retinaculum. Conlan and coworkers[10] contended that some fibers of the VMO extend more distally and actually contribute to the patellar tendon. As shown in Figure 1-14, the vast majority of the VMO fibers either attach directly onto the patella or extend more distally to make up the medial retinaculum. The most medial fibers of the medial retinaculum converge into the medial border of the patellar tendon, but do not provide a significant contribution to the patellar tendon fibers.

The vastus lateralis muscle is divided similarly to the vastus medialis with a longus and obliquus portion. The insertions of the longus and obliquus tendons are quite variable according to Hallisey and associates.[22] These authors contended that the amount of vastus lateralis tendon that travels over the anterior cortex of the patella and contributes to the patellar tendon distally is variable. In some cases, the lateralis tendon fibers remain lateral to the patella and interdigitate with the fibers of the iliopatellar tract without contributing to the patellar tendon (Fig. 1-15). The insertion of the obliquus fibers is also variable according to Hallisey and associates.[22] These authors found that in some specimens, the obliquus tendon fibers insert into the vastus lateralis longus fibers proximal to the patella; in others, they blend into the iliopatellar tract before inserting on the patella. As shown in Figure 1-15, it is our experience that the most medial fibers of the lateralis obliquus tend to coalesce with the fibers of the longus, whereas the most lateral obliquus fibers coalesce with the iliopatellar tract. The vastus lateralis does not provide a significant contribution to the patellar tendon.

The fibers of the lateralis run more parallel to the rectus femoris fibers than the vastus medialis (see Fig. 1-14). The average obliquity of the lateralis fibers is 31 degrees according to Reider and colleagues.[45] The lateralis fibers also become tendinous more proximally than the medialis, an average of 2.8 cm proximal to the patella.[45] The angle of insertion of the obliquus fibers is rather variable, with an average of 48.5 degrees in men and 38.5 degrees in women.[30]

The vastus intermedius is deep to the rectus femoris, inserts directly into the proximal pole of the patella, and blends with the fibers of the medialis and lateralis that insert in similar fashion. Previous descriptions of the quadriceps tendon insertion depict a trilaminar arrangement of fibers, with the rectus femoris contributing the most superficial fibers, the medialis and lateralis contributing the middle layer, and finally, the intermedius contributing the deepest fibers. Reider and colleagues[45] described the inserting fibers as more of a coalescence rather than distinct layers as previously described. It is our experience that the quadriceps tendon is a coalescence of fibers at the proximal pole of the patella, but as one travels a few centimeters proximal, four distinct layers to the quadriceps tendon can be identified and separated from one another (Fig. 1-16). When harvesting a quadriceps tendon graft, it is important that all layers are identified.

Fascial Layers

Confusion arises when attempting to describe the various layers of the anterior knee structures because different nomenclature is used for

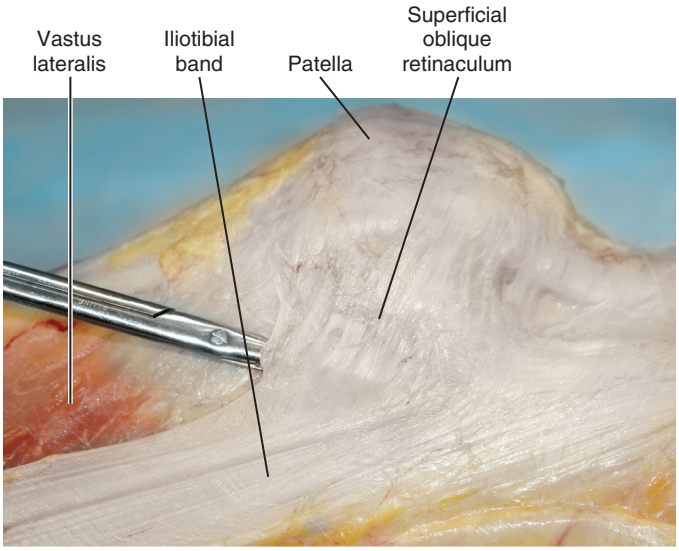


FIG 1-15 Longitudinal fibers of the vastus lateralis blend with fibers of the superficial oblique retinaculum.

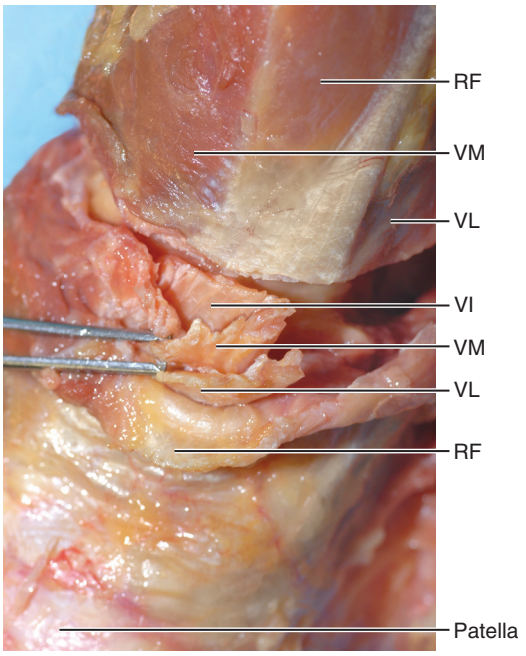


FIG 1-16 Each division of the quadriceps mechanism is dissected proximal to patella. *RF*, Rectus femoris; *VI*, vastus intermedius; *VL*, vastus lateralis; *VM*, vastus medialis.

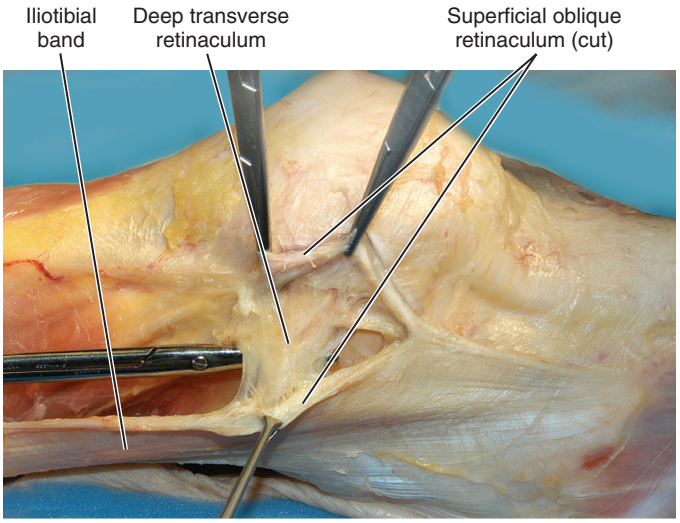


FIG 1-17 Deep transverse fibers of the iliopatellar tract.

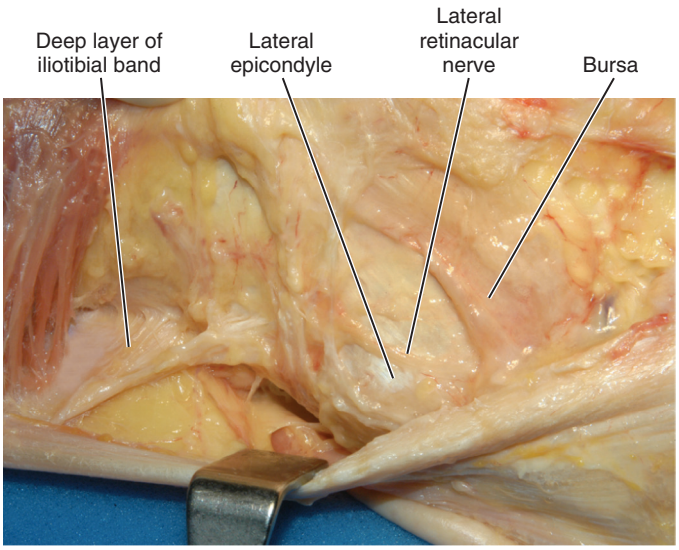


FIG 1-18 Deep lateral view of knee shows capsular-osseous layer of the iliotibial band with bursa.

both the medial and lateral parapatellar tissues. This description will break down the layers both medially and laterally and then attempt to assimilate each as they form a confluence over the anterior aspect of the patella.

Lateral

The most superficial layer laterally, termed the *aponeurotic layer* by Terry and colleagues,[54] is composed of the superficial fascia of the vastus lateralis and biceps femoris. These fibers, termed *arciform fibers*, travel transversely across the anterior aspect of the patella to blend at the midline with the superficial fascia of the sartorius, which begins medially.

The next layer is termed the *superficial layer* by Terry and colleagues.[54] It is made up of the iliopatellar tract, which connects the iliotibial band to the patella.[17,56] The iliopatellar tract has been further subdivided into a superficial and deep layer by Fulkerson and Gossling,[17] who describe two different fiber orientations. The most superficial is termed the *superficial oblique retinaculum* because its fiber orientation is oblique. This tract inserts along the lateral border of the patella (see Fig. 1-15). In addition, there are deep transverse fibers that also connect the iliotibial band with the lateral aspect of the patella (Fig. 1-17). In this deeper, more transverse tract is the patellotibial ligament, which originates just proximal to Gerdy's tubercle on the tibia and inserts on the inferior portion of the lateral aspect of the patella.[17] Just deep to this ligament is the lateral meniscopatellar ligament, which runs between the anterior horn of the lateral meniscus and the inferior aspect of the patella. It is a thickening of the anterolateral capsule. The deepest layer on the lateral side is the capsular-osseous layer, which anchors the iliotibial band to the femur through the lateral intermuscular septum and travels anteriorly to the patella. Some authors[32,54,56] contend that it includes the lateral patellofemoral ligament, but our experience is that a distinct ligament is not present.

As shown in Figure 1-18, the capsular-osseous layer of the iliotibial tract has a femoral attachment proximal to the lateral epicondyle. At the level of the lateral epicondyle is a bursa deep to the iliotibial tract. It is our experience that there commonly is an identifiable nerve, which is named the *lateral retinacular nerve*, within this bursa that may play a role in pain associated with runner's knee. During an iliotibial tract lengthening procedure for recalcitrant runner's knee, we believe that while the iliotibial bursa is excised, the lateral retinacular nerve should be identified and cut posterior to the lateral epicondyle to prevent recurrence of this painful condition.

Medial

The superficial fascia of the vastus medialis and sartorius form the most superficial layer medially. This aponeurotic layer travels laterally over the anterior aspect of the patella to merge with the same layer from the lateral side.

The next layer is considered to be the same as layer 2 as described by Warren and Marshall.[57] This is composed of the MPFL and SMCL. In this layer is the medial retinaculum, which is defined as the VMO fibers running transversely from the anterior border of the SMCL to the medial aspect of the patella. The medial patellotibial ligament is also found in this middle layer (Fig. 1-19). According to Conlan and coworkers,[10] it originates on the inferior portion of the medial aspect of the patella and travels distally and posteriorly to insert on the anteromedial aspect of the tibia. The deepest structure found on the anteromedial aspect of the knee is the medial meniscopatellar ligament, which is a thickening of the capsule that runs between the anterior horn of the medial meniscus and the inferior portion of the medial border of the patella (Fig. 1-20).[10]

Prepatellar

The fascial layer covering the quadriceps is termed the *fascia lata*. Dye and coworkers[14] note that the fascia lata extends distally as the most superficial layer overlying the patella after the skin and subcutaneous tissue. These authors describe the fascia lata as an extremely thin layer with little structural integrity but visible transverse fiber orientation. This is in contrast to the intermediate layer overlying the patella, which has an oblique fiber orientation proximally and becomes more transverse distally over the patellar tendon. Dye and coworkers[14] described the intermediate layer consisting of tendinous fibers from the vastus medialis and lateralis, in addition to the superficial fibers of the rectus femoris that extend over the anterior aspect of the patella.

The deepest layer anterior to the patella is composed of the deeper fibers of the rectus femoris that extend distal to the proximal pole of the patella and are intimately associated with the anterior cortex of the patella as they continue to contribute to the fibers of the patellar tendon (Fig. 1-21).

Dye and coworkers[14] noted these layers form three separate bursae superficial to the patella. The most superficial is termed the *prepatellar subcutaneous bursa* (between the skin and superficial fascia lata). The middle bursa is termed the *prepatellar subfascial bursa* (between the superficial fascia lata and the oblique intermediate layer). Finally, the deepest bursa is called the *prepatellar subaponeurotic bursa* (between the intermediate and deep aponeurotic layers). It should be noted that no bursa exists between the deepest aponeurotic layer and the anterior cortex of the patella, as others have suggested.[1]

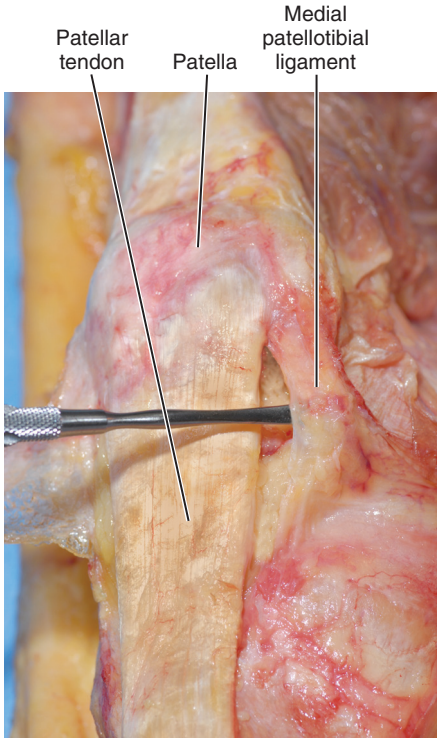


FIG 1-19 The medial patellotibial ligament is adjacent to the patellar tendon.

Patella

The patella is a sesamoid bone deeply associated with the quadriceps tendon, as previously described (Fig. 1-22). The articular surface of the patella is often divided into facets based on longitudinal ridges. The major longitudinal ridge divides the medial and lateral facets of the patella. A second longitudinal ridge near the medial border of the patella separates the medial facet from a thin strip of articular surface known as the *odd facet* (see Fig. 1-20). Wiberg[58] classified the morphology of patellae into three major types based on the position of the longitudinal ridges. Type I patellae have medial and lateral facets that are equal in size. Type II patellae have a medial facet slightly smaller than the lateral facet. Type III patellae have a very small and steeply angled medial facet, whereas the lateral facet is broad and concave. According to Dye and coworkers,[14] type II patellae are the most common (present in 57% of knees) followed by type I (24%) and type III (19%).

Patellar Tendon

The patellar tendon courses between the inferior pole of the patella and the tibial tubercle (see Fig. 1-19). This tendon consists mostly of fibers from the rectus femoris, as previously mentioned. The structure inserts on the proximal tibia, just distal to the most proximal portion of the tibial tubercle. It blends medially and laterally with the fascial expansions of the anterior surface of the tibia and the iliotibial band. Dye and coworkers[14] reported an average length of 46 mm, with a range of 35 to 55 mm.

Infrapatellar Fat Pad

The infrapatellar fat pad is an intracapsular, but extrasynovial structure; the deepest portion is covered by a synovial layer. This structure has been consistently identified to have a thick central body, with

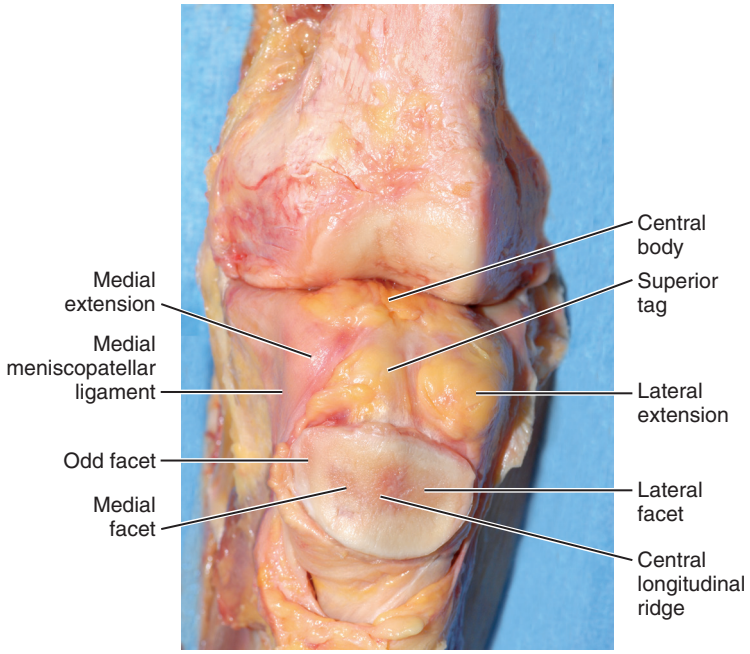


FIG 1-20 Posterior anatomy of the patella with adjacent capsular thickenings and fat pads with medial and lateral meniscopatellar ligaments.

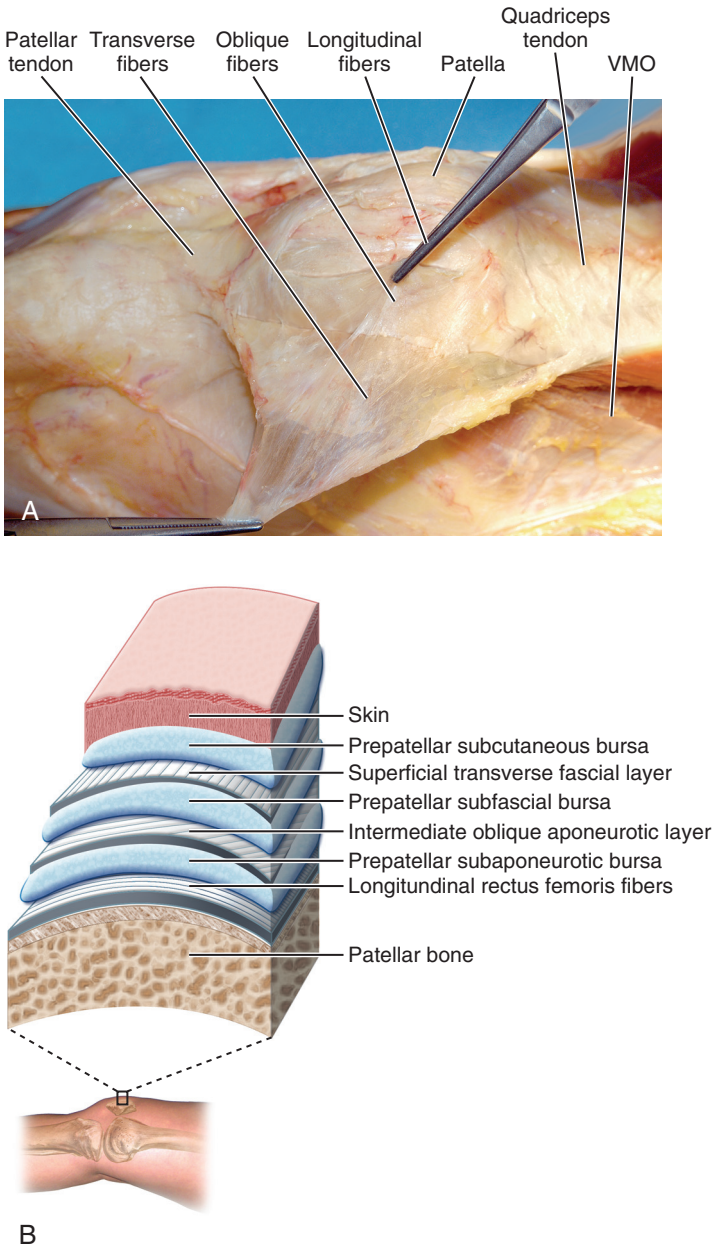


FIG 1-21 A, Fascia layers of the anterior knee. **B,** Layers of the anterior knee. VMO, Vastus medialis obliquus.

thinner medial and lateral extensions (see Fig. 1-20). It has attachments to the inferior pole of the patella proximally, the patellar tendon and anterior capsule anteriorly, the anterior horns of the medial and lateral menisci plus the proximal tibia inferiorly, and the intercondylar notch posteriorly via the ligamentum mucosum.[18] The ligamentum mucosum is an embryonic remnant separating the medial and lateral compartments of the knee. It has two alar folds that attach to the infrapatellar fat pad, allowing it to maintain its position in the joint.[23]

Gallagher and associates[18] identified two clefts in the infrapatellar fat pad: a horizontal cleft found just inferior to the ligamentum mucosum, and a vertical cleft, located anterior to the superior tag of the central body. It has been postulated that these clefts may play a role in reducing the friction between the anterior capsule and the femoral condyles, but they also may be a location for loose bodies to hide.

Inflammation in the infrapatellar fat pad has been implicated as a source of anterior knee pain. Hoffa disease is characterized by inflammation and hypertrophy, with subsequent trapping of the fat pad between the patellar tendon and femoral condyles.[18] The treatment frequently consists of resection of the fat pad, but this has been associated with a decrease in patellar blood supply.[26] The fat pad may also become inflamed after arthroscopic surgery because of portal placement. This may lead to fibrous scarring, which can limit motion and serve as a source for residual pain.[13] Fibrous scars that occur after arthroscopy have a 50% resolution rate after 1 year.[53] It is recommended that portal placement be well medial and lateral to the patellar tendon borders so that damage to the central body and superior tag are minimized to limit this potential complication.[18]

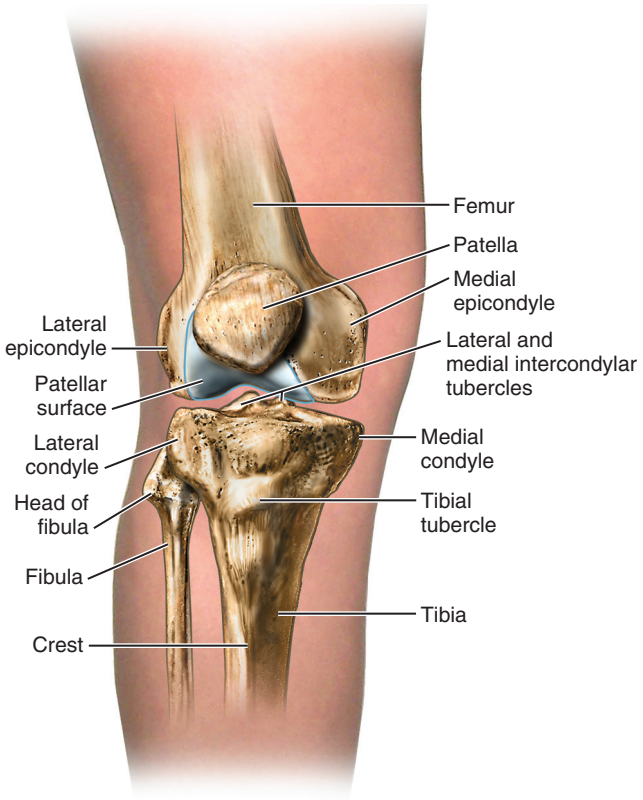


FIG 1-22 Bony landmarks of the anterior knee.

Superficial Neurovascular Structures

The medial inferior genicular artery traverses beneath the SCML after branching from the popliteal artery (Figs. 1-23 and 1-24). It can be visualized on the anterior border of the SMCL as it courses toward the patellar tendon and medial meniscus. This vascular structure may be encountered during any dissection on the medial aspect of the knee, most notably, during a posteromedial approach for meniscal repair. If identified in the approach, it must be retracted or cauterized to provide a clear approach to the medial meniscus.

Other important structures located on the medial side of the knee are the saphenous nerve with its sartorial and infrapatellar branches, the medial femoral cutaneous nerve, and the medial retinacular nerve (Fig. 1-25). These nerves may be easily injured with medial dissection of the knee. It has been reported that injury to the saphenous nerve occurs in 7% to 22% of patients during arthroscopic meniscal repair.[4] According to Dunaway and colleagues,[12] cadaver dissections in 42 knees revealed that the sartorial branch of the saphenous nerve consistently became extrafascial between the sartorius and gracilis. However, this location varied between 37 mm proximal to the joint line and 30 mm distal to the joint line, with the nerve being extrafascial at the joint only 43% of the time and deep to the sartorius fascia in 66% of specimens. Dunaway and colleagues[12] noted that only 2.8% of the specimens dissected had a sartorial branch anterior to the sartorius fascia. These authors recommend that during an inside-out medial meniscus repair, staying anterior during dissection minimizes risk of injury to the sartorial branch. Horner and Dellon[24] described the sartorial branch as the terminal branch of the saphenous nerve that passes 3 cm posterior to the central point of the medial condyle of the femur and continues to the medial aspect of the foot alongside the saphenous vein.

The infrapatellar branch of the saphenous nerve may also be easily damaged with indiscriminate dissection on the medial aspect of the knee, leading to postoperative pain and paresthesia. Postoperative numbness, paresthesia, or hypersensitivity in the distribution of the infrapatellar branch of the saphenous nerve has been reported in the literature[48]: 21% in the Mayo Clinic series, 51.5% in the Iowa series, and 40% in the Alberta series.[25] The risk of damage is increased by the varying course of the nerve. The infrapatellar branch of the saphenous nerve may have four different courses at the level of the medial joint line, which are described by the nerve's relationship to the sartorius muscle. The nerve may be posterior, penetrating, parallel, and anterior to the sartorius, with the most common type being posterior (62.2%).[3] Arthornthurasook and Gaew-Im[3] reported that the infrapatellar branch of the saphenous nerve is an average distance of 40.6 mm from the medial epicondyle when the nerve exits and travels posterior to the sartorius. Horner and Dellon[24] described the infrapatellar branch separating from the saphenous nerve in the proximal third of the thigh in 17.6% of specimens, in the middle third in 58.8%, and in the distal third of the thigh in 23.5%. This nerve innervates not only the patella but also the anterior-inferior capsule.[24]

Horner and Dellon[24] described the medial femoral cutaneous nerve traveling superficially to the sartorius muscle in 39.1% of knees. However, this nerve often travels in Hunter's canal and perforates the sartorius (30.4% of knees) or continues in Hunter's canal and exits deep to the sartorius (30.4% of knees). The termination of this nerve is the most superficial constant branch that eventually bisects the patella to form a prepatellar plexus before continuing to the lateral aspect of the knee and pairing with the infrapatellar branch of the saphenous nerve proximal the knee joint.

The medial retinacular nerve has also been described as residing on the medial aspect of the knee near the vastus medialis. The vastus medialis is innervated by branches from the femoral nerve. The terminal branch of the nerve to the vastus medialis ends at the medial retinacular nerve. According to Horner and Dellon,[24] this nerve may traverse within the vastus medialis (90% of knees) or lie superficial to its fascia (10% of knees). The nerve enters the knee capsule beneath the medial retinaculum, 1 cm proximal to the adductor tubercle, and sends a branch to the MCL.[24] This nerve was not identified in dissections by us.

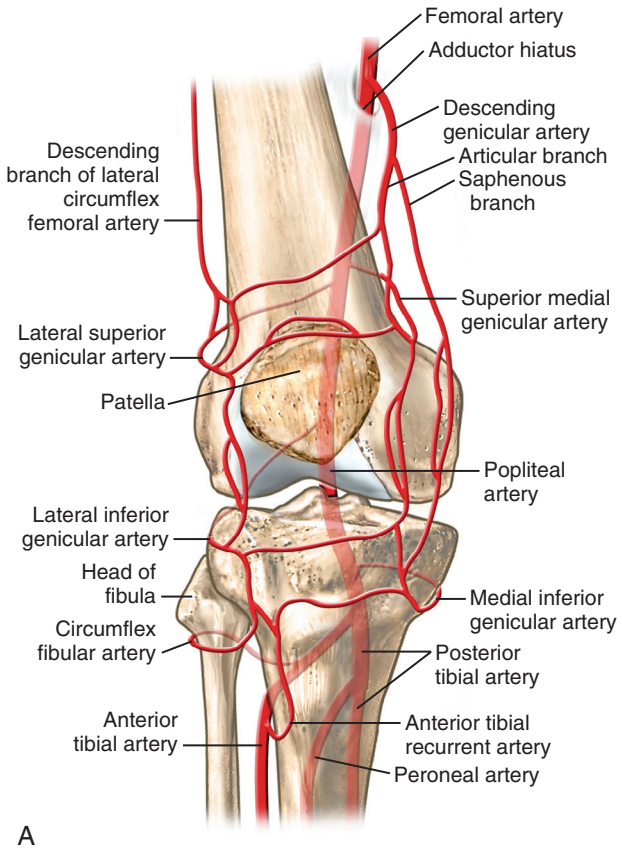
Indiscriminate dissection on the medial side of the knee could easily damage any one of these described nerves, leading to the pathology already noted. Painful neuromas and complex regional pain syndrome can turn a successful operation into a complicated pain syndrome. Horner and Dellon[24] advised that the surgeon be aware of these pitfalls and recognize the possibility that symptomatology may result from damage to one or more nerves that require diagnostic nerve blocks at multiple sites to identify the pathology. Unnecessary subsequent surgeries for postoperative pain may be prevented by identifying the true cause of pain, which may very well be the result of nerve damage. A neurectomy may be required when a nerve block provides only temporary relief of pain.[24]

CONCLUSION

The anterior and medial anatomy of the knee has frequently been oversimplified or poorly described in the literature. It is our hope that this chapter has allowed the reader a greater appreciation for the anatomic relationships present and their potential implications in various knee conditions. A key to successful operative repair and reconstruction of the medial side of the knee is detailed knowledge of the anatomy of its structures.

Video Content

Video 1-1
Video 1-2



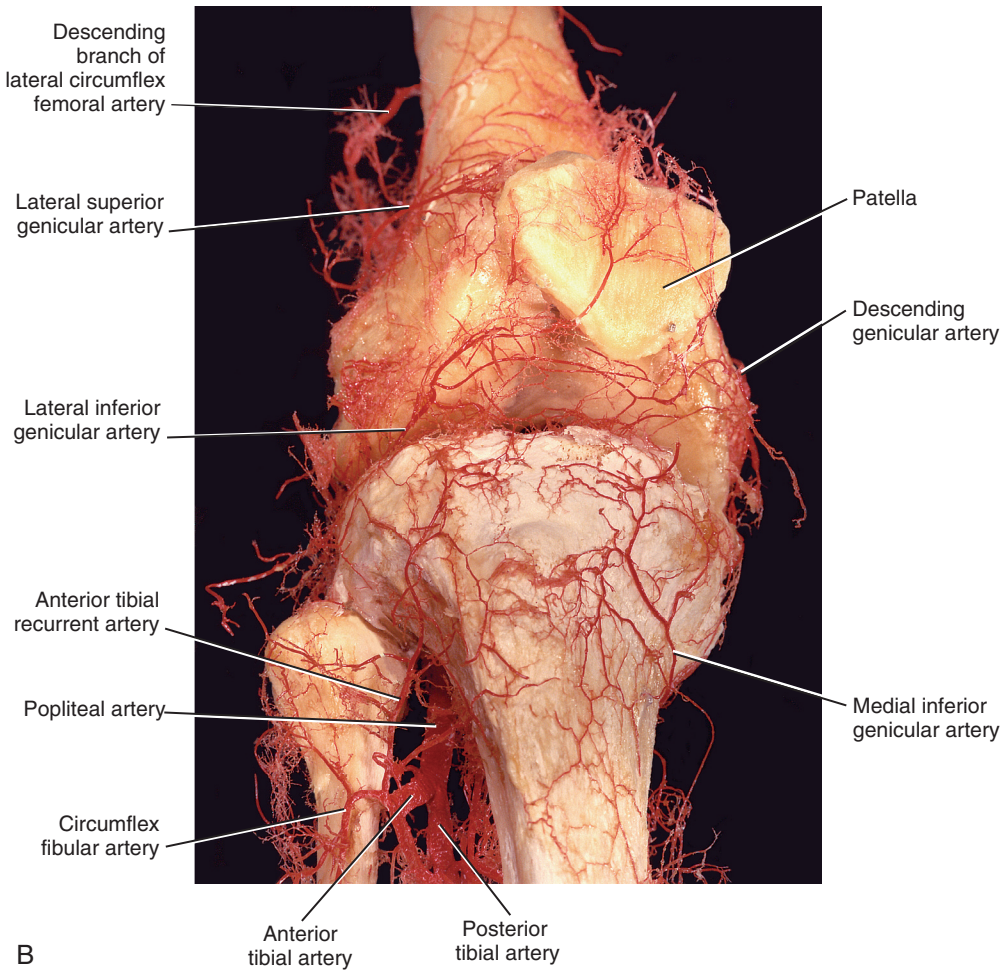


FIG 1-23 **A,** Arterial vasculature of the knee. **B,** Detailed vascularity shown after specialized injection technique. (Courtesy Dr. R.F. Kaderly.)

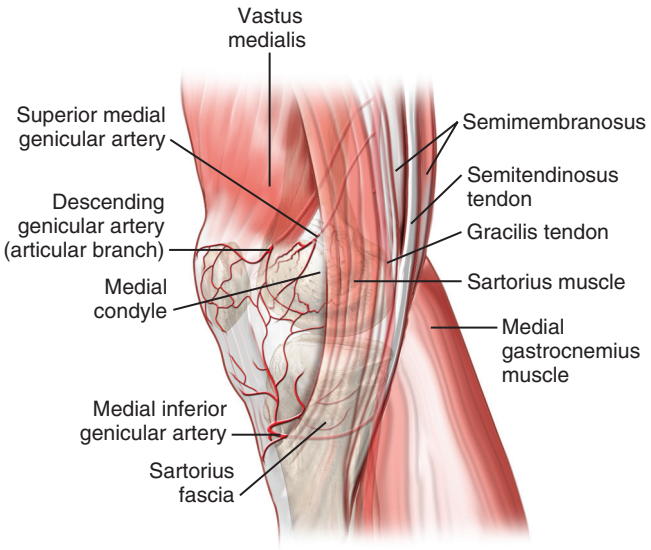


FIG 1-24 Path of the medial inferior genicular artery.

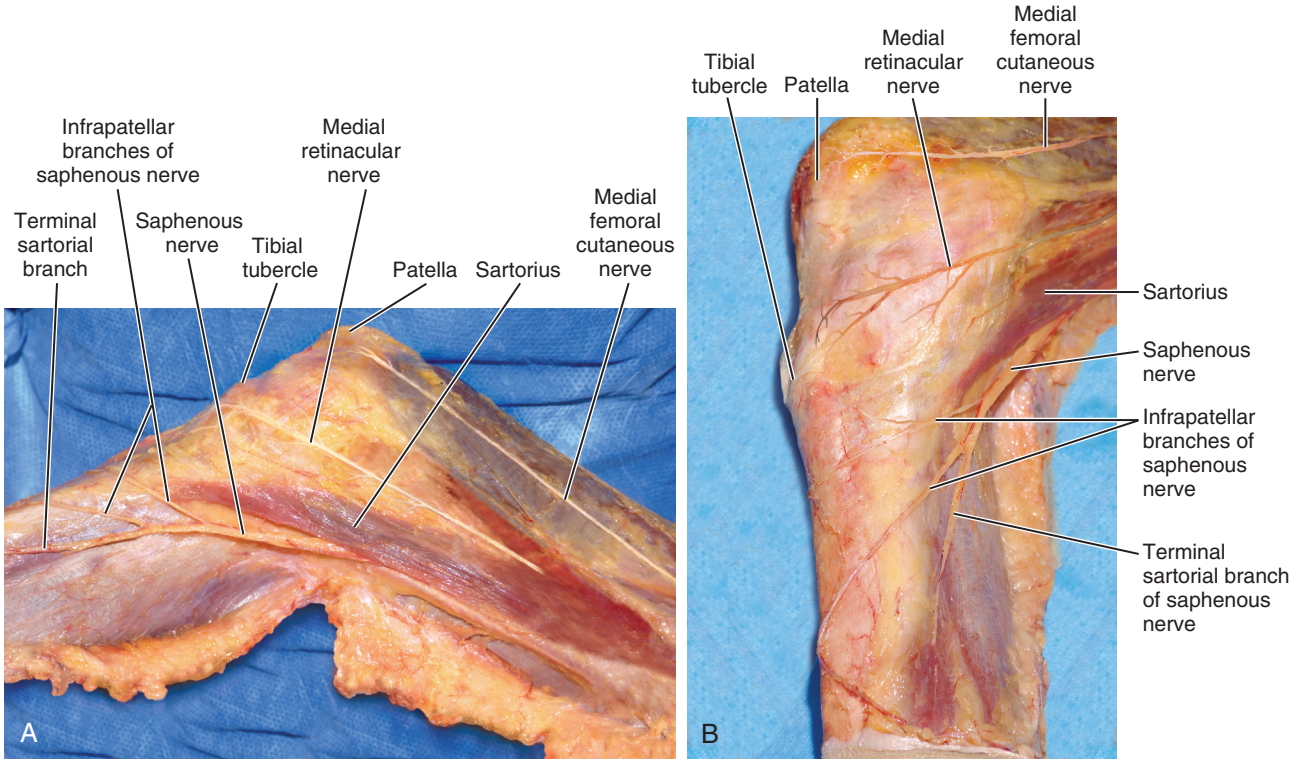


FIG 1-25 **A,** Anteromedial view of the superficial nerves. **B,** Medial view of the superficial nerves.

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2

Lateral and Posterior Knee Anatomy

Justin P. Strickland, Eric W. Fester, Frank R. Noyes

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VIDEO CONTENT

Video 2-1 The Key to the Knee: A Layer-by-Layer Demonstration of Posterior and Posterolateral Knee Anatomy

INTRODUCTION

The posterior and lateral anatomy of the knee joint presents a challenge to even the most experienced knee surgeon. Knowledge of the bony topography will result in a greater number of anatomic ligament reconstructions (Fig. 2-1). A lack of familiarity leads to hesitancy when performing approaches in these areas of the knee. The inherent anatomic complexity of this region is further complicated by variations in terminology found in the orthopedic literature. Recent work by LaPrade and coworkers[16,17,19,20] and others[14] have attempted to clarify the nomenclature used to describe these structures, allowing for better communication among surgeons. These advances also facilitate more accurate biomechanic studies.

In posterolateral reconstructive procedures, the anatomic relationships of the fibular collateral ligament (FCL), popliteus muscle-tendon-ligament complex (PMTL), popliteofibular ligament (PFL), and the posterolateral capsule are particularly important. These structures function together to resist lateral joint opening, posterior subluxation of the lateral tibial plateau with tibial rotation, knee hyperextension, and varus recurvatum (see Chapter 15).[9,32,34]

The goals of this chapter are to (1) accurately describe all relevant structures and their relationships to one another; (2) provide confidence to the knee surgeon when encountering the posterolateral aspect of the knee; and (3) apply knowledge of these structures to provide a base for safe and efficient surgical approaches to the posterolateral aspect of the knee.

ILIOTIBIAL BAND

The iliotibial band (ITB) is a large fascial expansion that originates on the anterior superior iliac spine, covering the tensor fascia lata muscle proximally and extending along the lateral aspect of the thigh. Distally, the ITB has been divided into three separate layers: superficial, deep, and the capsulo-osseous layer.[36,46] A portion of the superficial layer, called the *iliopatellar band*, extends anteriorly to the lateral aspect of the patella (Fig. 2-2).[44] This band is important for proper patellofemoral tracking because it helps resist abnormal medial patella translation (medial glide).[16] The majority of the superficial layer continues distally to insert on Gerdy's tubercle. The deep layer connects the medial portion of the superficial layer to the lateral intermuscular septum of the distal femur. The most distal fibers of the deep layer continue to attach to the posterior aspect of the lateral femoral condyle (Fig. 2-3).[46] The capsulo-osseous layer extends more medial and distal to the deep layer to merge with fibers from the short head of the biceps to form the biceps-capsulo-osseous iliotibial tract confluens.[45] The capsulo-osseous layer continues distally, creating a sling posterior to the lateral femoral condyle to attach posterior and proximal to Gerdy's tubercle.

In knee extension, the ITB is anterior to the axis of rotation and helps maintain extension. When the knee is flexed to 90 degrees, the ITB moves posterior to the axis of rotation. The anteroposterior (AP) position of the ITB with knee flexion contributes to the pivot shift phenomena with an anterior cruciate ligament (ACL) rupture.[10] The posterior portion of the ITB tibiofemoral attachment is re-created in the lateral extraarticular ACL reconstruction.[16,36] During flexion, the ITB moves posteriorly, exerting an external rotational and posteriorly directed force on the lateral tibia, contributing to the reduction in the pivot shift test. The ITB and lateral capsule are important structures that resist internal tibial rotation (see Chapter 3). In extension, the ITB acts as a secondary restraint to varus stress.[4] In severe lateral knee ligament injuries, the ITB may become abnormally lengthened, and at the time of surgery, distal advancement at Gerdy's tubercle is indicated. A bursa between the ITB and the lateral femoral epicondylar region may become inflamed and produce pain. The lateral retinacular nerve courses just posterior to the bursa and may also become symptomatic.

ANTEROLATERAL LIGAMENT

There has been recent interest in the lateral capsule and the so-called *anterolateral ligament* (ALL)[2,14] that, when avulsed from the tibia,

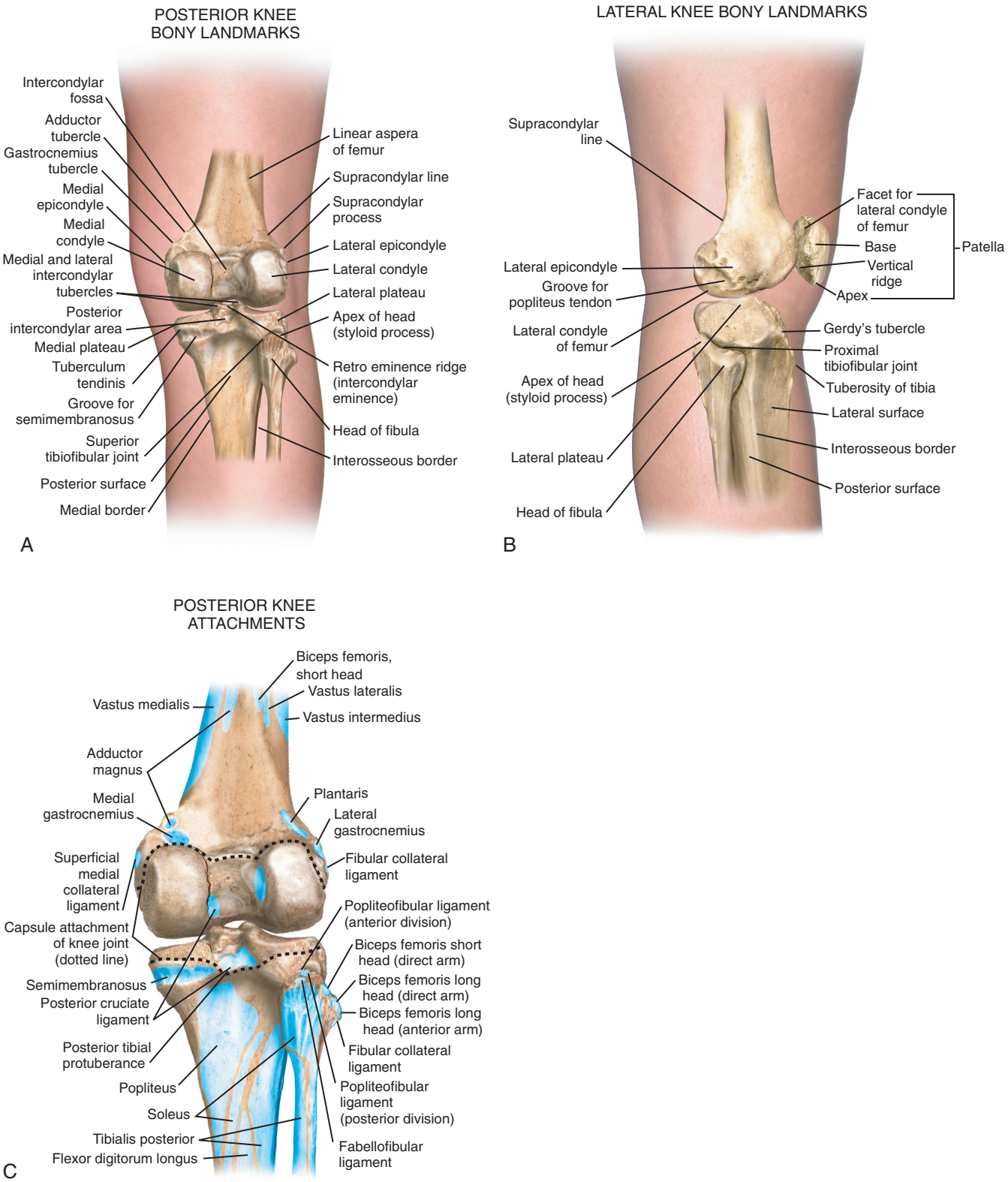


FIG 2-1 **A,** Bony anatomy of the posterior knee joint. **B,** Bony anatomy of the lateral knee joint. **C,** Key anatomic attachments of the posterior aspect of the knee with the joint capsule outlined.

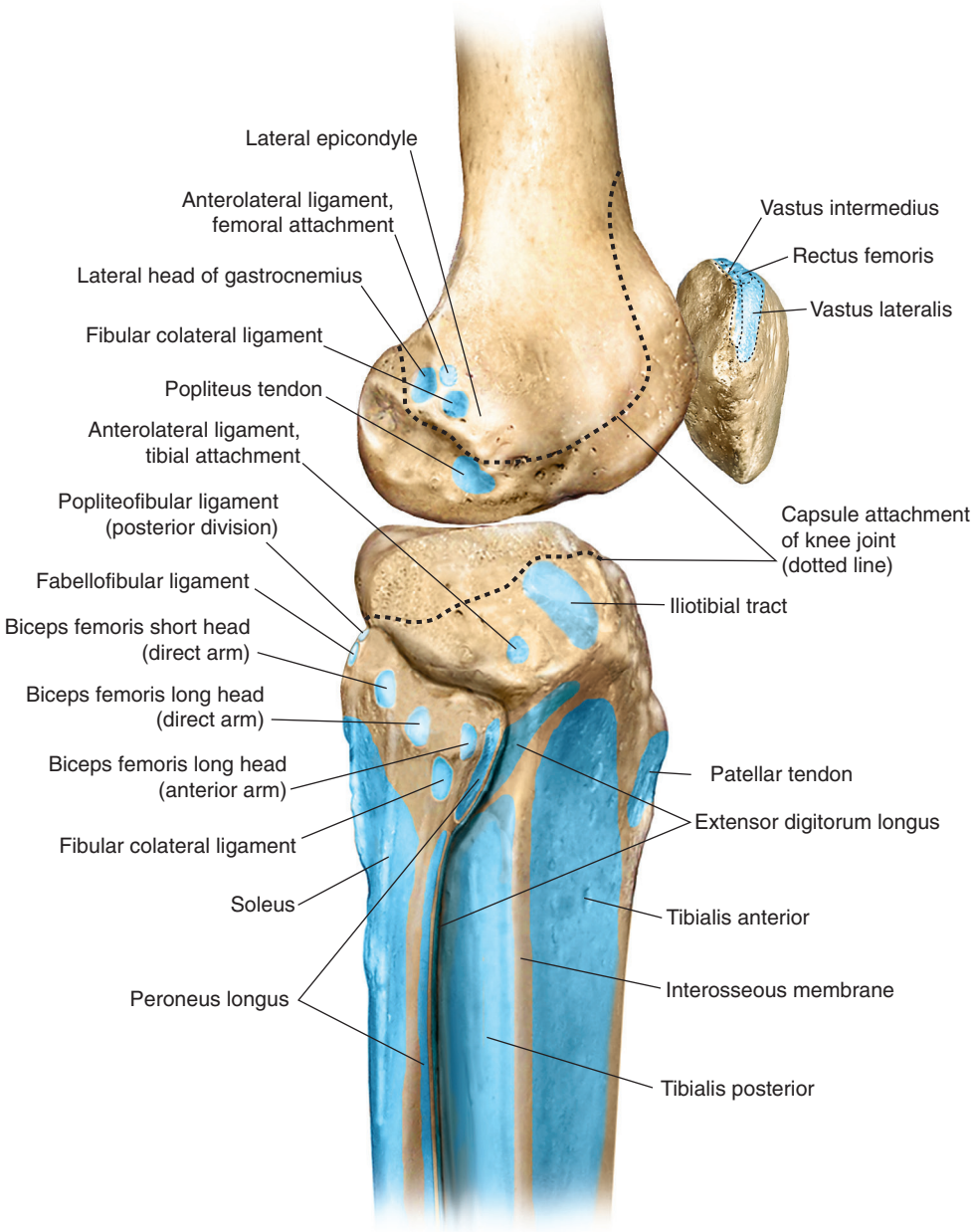


FIG 2-1, cont'd D, Key anatomic attachments of the lateral aspect of the knee with the joint capsule outlined.

produces a Segond fracture. The contribution of the ALL in limiting internal tibial rotation and anterior translation of the lateral tibiofemoral compartment has not been defined. The ALL was first described in 1879 by the French surgeon Paul Segond[38] as a fibrous band at the anterolateral aspect of the human knee attached to the Segond fracture. In 2012, Vincent and associates[47] determined the incidence of this anatomic structure in 30 consecutive patients undergoing total knee arthroplasty. These authors also evaluated the ALL's anatomy and histology in 10 cadaver knees. They found that the ALL was present in all 40 knees.

Claes and associates[2] performed an anatomic dissection on 41 unpaired cadaveric knees and reported the femoral and tibial attachments of the ALL, along with other lateral anatomic structures. These authors reported the ALL was a well-defined ligamentous structure in 40 of 41 knees. In another investigation, Claes and colleagues[1] compared anatomic details of the ALL with radiographic findings from patients with known Segond fractures. These authors found that Segond fractures consistently avulsed where the ALL inserted on the proximal tibia. They suggested that the Segond fracture was not only an indirect sign of ACL injuries, but should be considered a ligamentous avulsion of the ALL.

Dodds and associates[6] reported in an anatomic study that the ALL inserted just proximal and posterior to the lateral femoral epicondyle. The ALL has an oblique course to the anterolateral aspect of the proximal tibia, with attachments to the lateral meniscus, enveloping the inferior lateral geniculate artery and vein. It inserts onto the anterolateral tibia midway between Gerdy's tubercle and the tip of the fibular head, separate from the ITB.

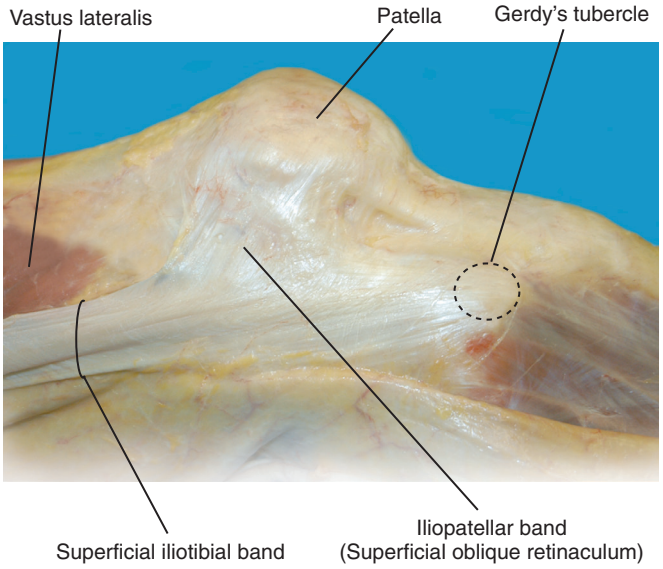


FIG 2-2 Lateral aspect of the knee demonstrates the iliotibial band with its distal insertion on Gerdy's tubercle and the iliopatellar fibers.

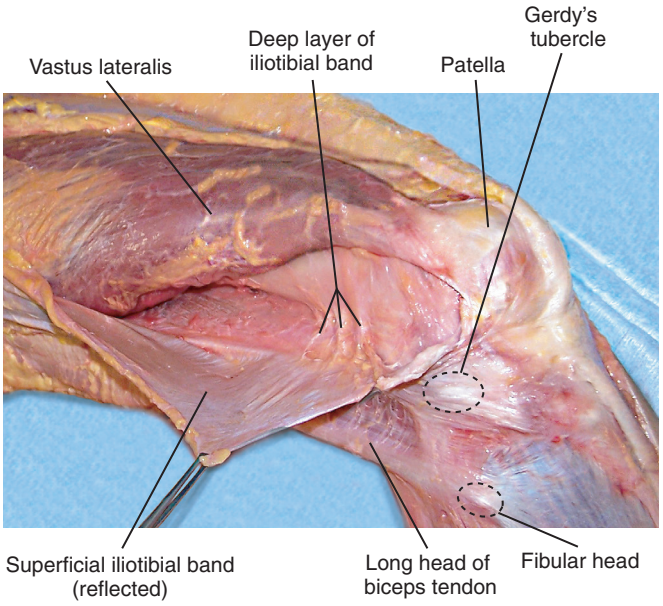


FIG 2-3 Deep fibers of the iliotibial band (ITB) are exposed as the superficial ITB is split and retracted posteriorly.

In an anatomic dissection of 15 cadaver specimens (males, mean age, 58.2 years), Kennedy and colleagues[14] reported that the ALL femoral attachment's area was 67.7 mm^2, which was located a mean of 2.7 mm proximal and 2.8 mm posterior to the FCL's femoral attachment (range, 0.9–6.7 mm proximal and 0.2–7.7 mm posterior; Fig. 2-4). The ALL had fine fascial expansions that extended anterior and distal over the FCL and lateral epicondyle. The ALL attachment was an average of 7.0 mm from the lateral epicondyle and 26.1 mm from the joint line. The tibial attachment was approximately midway between the anterior margin of the fibular head and the center of Gerdy's tubercle (Fig. 2-5). The ALL attachment was a mean of 26.1 mm anterior to the fibular head margin and 24.7 mm posterior to Gerdy's tubercle center, with a mean attachment area of 64.9 mm^2. The respective lengths from 0 to 90 degrees ranged from a mean of 36.8 to 41.6 mm. The mean maximum load to failure was 175 N (confidence interval, 139–211 mm).

It has been hypothesized by some that the ALL, along with the ITB femoral-tibial insertion, is a secondary restraint to internal tibial rotation and anterior translation of the lateral tibial plateau.[51] Wodicka and coworkers[50] found no correlation between the degree of injury to the ALL and the degree of instability after an ACL rupture. They proposed that the ALL in itself plays a minimal role in stability of the knee. Unpublished robotic research in our laboratory has confirmed no statistically significant increases in internal tibial rotation or lateral compartment translation upon sectioning the ALL. Accordingly, these two structures represent secondary restraints to lateral tibiofemoral compartment translation after ACL disruption. In our experience with anatomic dissections, it has been rare to find such a well-defined, robust structure (Fig. 2-6).

FIBULAR COLLATERAL LIGAMENT

For this chapter, the term *fibular collateral ligament* has been selected instead of lateral collateral ligament because it represents the term most commonly used in anatomy textbooks[16,40] and recent studies.[15,19,21,42,52,53] The FCL is a cordlike ligament that runs from the lateral femoral epicondyle to the fibular head (Fig. 2-7). When performing an anatomic FCL reconstruction, it is imperative that the surgeon understands the relationship of the FCL to its surrounding structures. On the femur, the FCL originates approximately 14 mm anterior[19] and slightly distal to the attachment of the lateral gastrocnemius tendon. This tendon is a key landmark during FCL reconstruction because it is frequently spared during a posterolateral corner knee injury.[46] In addition, the FCL attaches proximal and posterior to the popliteus femoral insertion. Distally, it attaches to the lateral aspect of the fibular head just medial to the anterior arm of the long head of the biceps tendon.

In 2003, LaPrade and associates[19] published a quantitative anatomic study that described the FCL and its relationship to osseous landmarks and other posterolateral structures of the knee. These authors reported that the FCL does not originate directly off of the lateral epicondyle, but attaches approximately 1.4 mm proximal and 3.1 mm posterior to the epicondyle, residing in a small bony depression. The average distance between the FCL and popliteus attachments on the femur was 18.5 mm. The ligament travels distally to insert 8.2 mm posterior to the anterior margin of the fibular head and 28.4 mm distal to the tip of the fibular styloid process (Fig. 2-8).[19] The distal 25% of the FCL is surrounded by the FCL–biceps femoris bursa, which has been implicated as a possible source of lateral knee pain.[8] The bursa is covered by the anterior arm of the long head of the biceps.[17]

The FCL is the primary restraint to varus loads at all degrees of flexion.[9] In a cadaveric sectioning study, Grood and colleagues[9] reported that the limit for varus angulation was normal as long as the FCL was intact. In addition, for large changes in external rotation to occur, the popliteus tendon, PFL, posterolateral capsule, and the FCL must all be injured.[51] Thus the FCL provides significant resistance to external rotation. The FCL is a secondary restraint to internal rotation at higher flexion angles (see Chapter 3).

FABELLOFIBULAR LIGAMENT

The fabellofibular ligament begins at the lateral aspect of the fabella (or posterior aspect of the supracondylar process of the lateral femur if a fabella is absent) and inserts distally on the posterolateral edge of

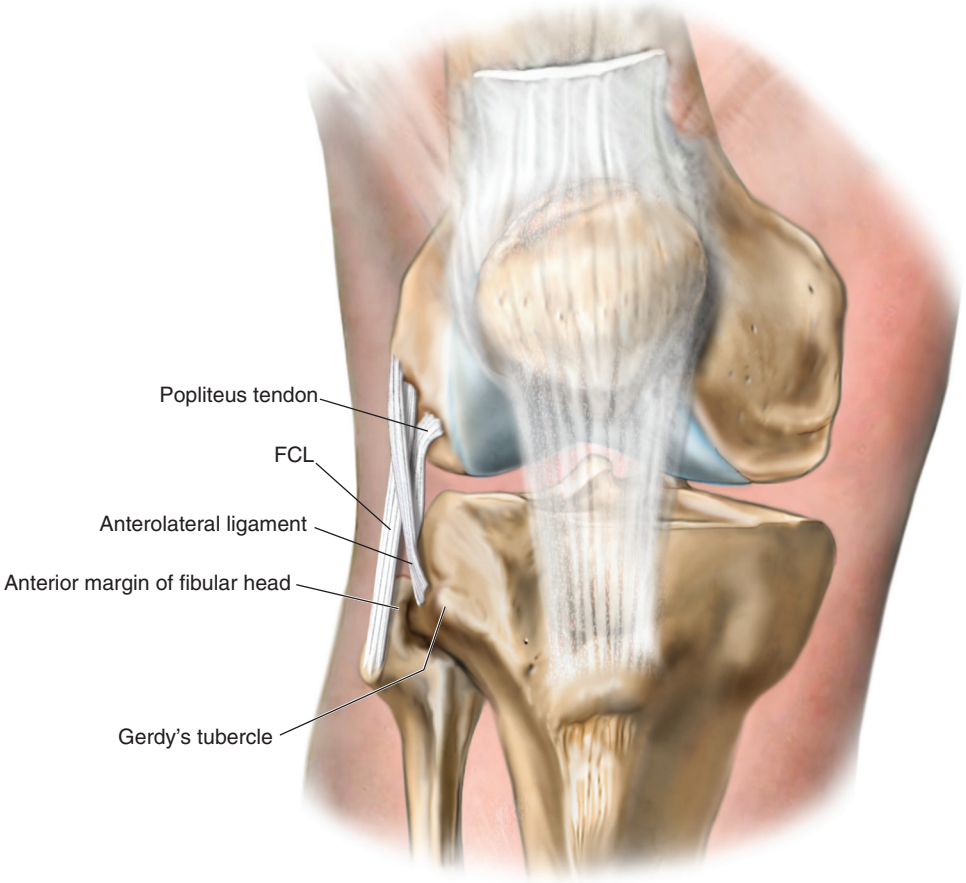


FIG 2-4 The osseous landmarks and attachment sites of the main structures of the lateral knee (iliotibial band and nonanterolateral ligament-related capsule removed, lateral view, right knee). The anterolateral ligament attached posterior and proximal to the fibular collateral ligament femoral attachment and coursed anterodistal to its anterolateral tibial attachment between the center of Gerdy's tubercle and the anterior margin of the fibular head. The short head of the biceps femoris tendon had a direct arm that attached to the fibular head and an anterior arm that attached to the anterolateral tibia. *FCL,* Fibular collateral ligament. (Modified from Kennedy MI, Claes S, Fuso FA, et al. The anterolateral ligament. An anatomic, radiographic, and biomechanical analysis. *Am J Sports Med* 2015;43[7]:1606-1615.)

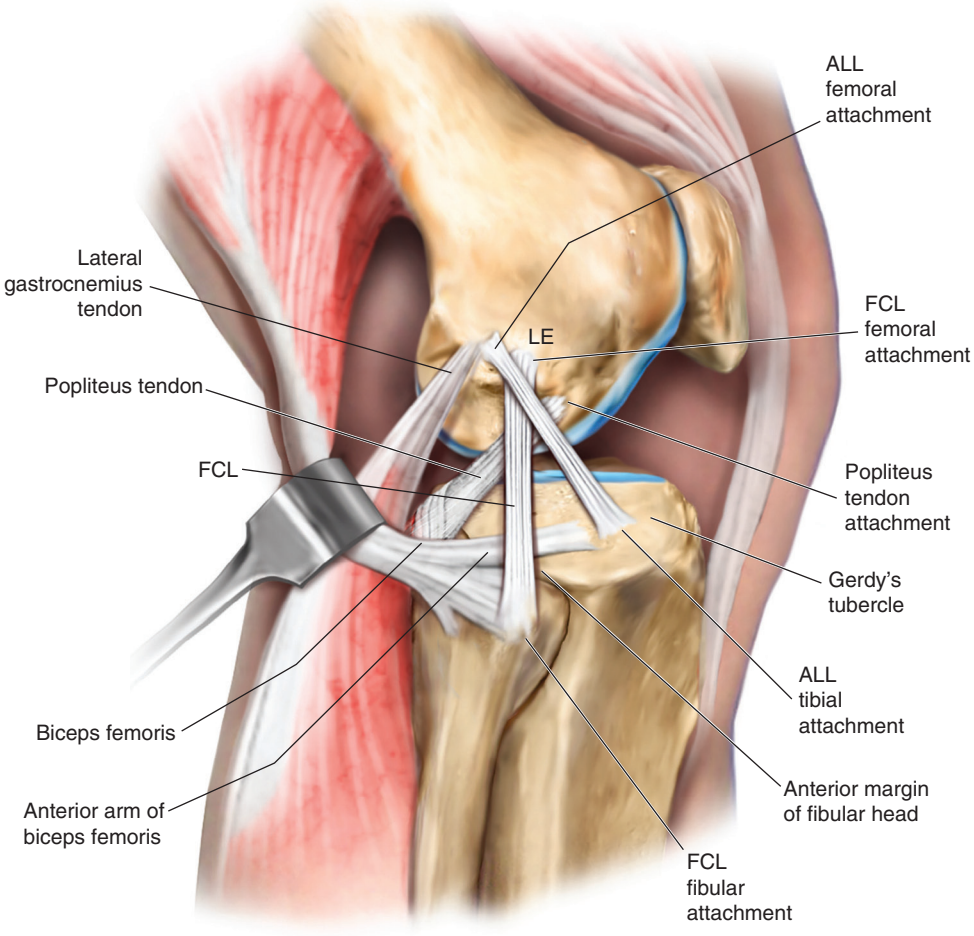


FIG 2-5 The osseous landmarks and attachment sites of the main lateral knee structures (anterior view, right knee). The tibial attachment of the anterolateral ligament (ALL) was approximately midway between the center of Gerdy's tubercle and the anterior margin of the fibular head. *FCL,* Fibular collateral ligament; *LE,* Lateral epicondyle. (Modified from Kennedy MI, Claes S, Fuso FA, et al. The anterolateral ligament. An anatomic, radiographic, and biomechanical analysis. *Am J Sports Med* 2015;43[7]:1606-1615.)

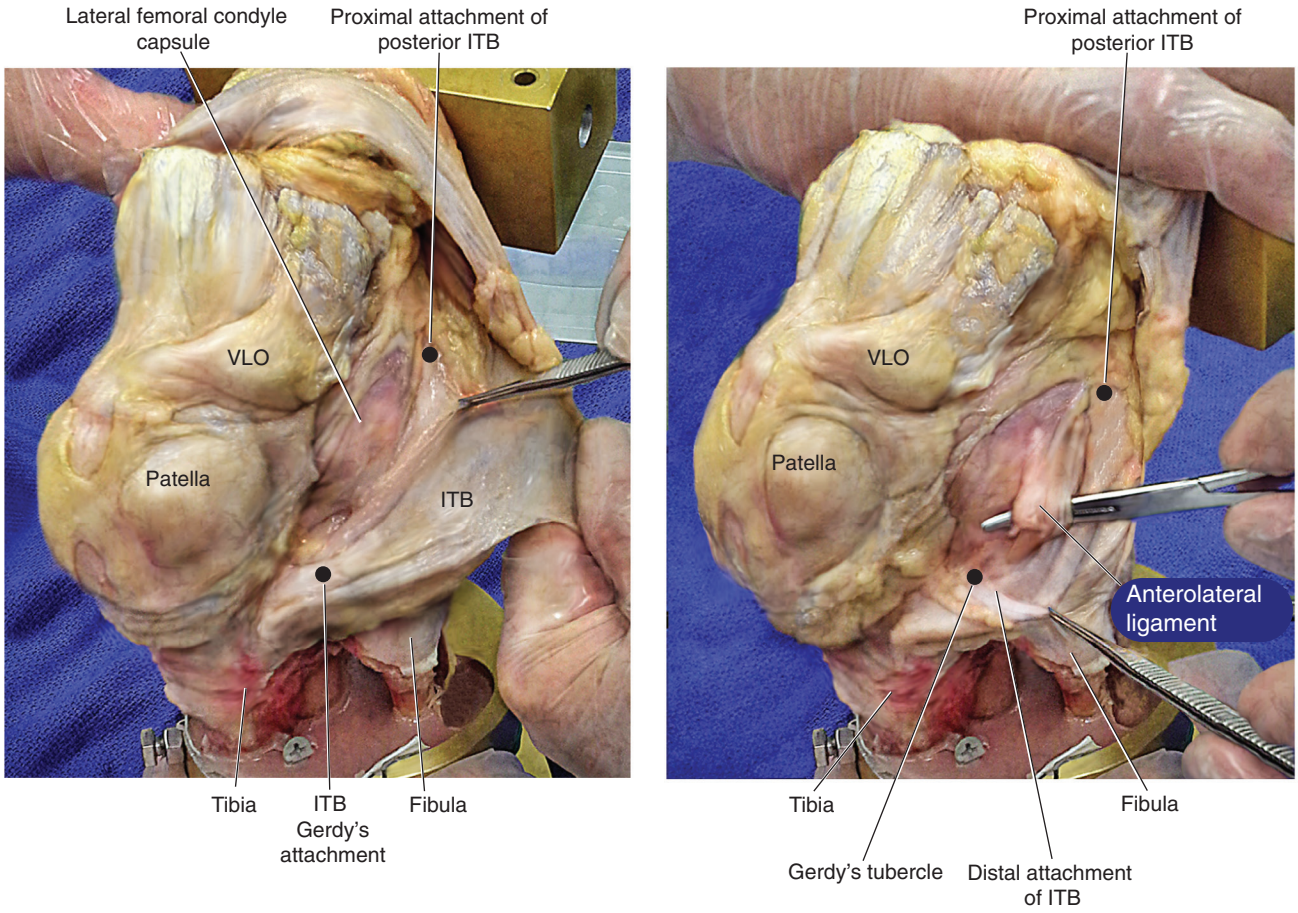


FIG 2-6 The anterolateral ligament (ALL) femoral insertion is just proximal and posterior to the lateral femoral epicondyle. The ALL tibial insertion is on the anterolateral tibia, midway between Gerdy's tubercle and the tip of the fibular head. *ITB,* Iliotibial band; *VLO,* vastus lateralis obliquus.

the fibular styloid (Fig. 2-9).[5] It attaches posterior and lateral to the insertion of the PFL. Proximally, the fabellofibular ligament is a continuation of the capsular arm of the short head of the biceps tendon.[45,46] The fabellofibular ligament is termed the *short lateral ligament* in the absence of a fabella.[13] Throughout this text, this structure is referred to as the *fabellofibular ligament*. The size of the fabellofibular ligament has been directly correlated to the presence of a bony fabella.[16,26,37] When a bony fabella is present, the ligament is more robust, with the opposite being true when the fabella is cartilaginous or absent.

The fabellofibular ligament has been identified in several studies in a variable percentage of patients.[5,19,37,43,48] Sudasna and Harnsiriwattanagit[43] reported the fabellofibular ligament was present in 68% of individuals. Minowa and coworkers[26] identified a fabellofibular ligament in 51.4% of cadaver knees. Diamantopoulos and associates[5] found the fabellofibular ligament in 40% of knees dissected using microsurgical techniques. In contrast, LaPrade[16] believes that the fabellofibular ligament is present in all knees owing to the fact that, by definition, it is the distal extension of the capsular arm of the short head of the biceps. This was confirmed in an article[20] describing these authors' anatomic findings. Functionally, the fabellofibular ligament is taut in extension.[48] Thus it can be inferred that it provides resistance to knee hyperextension. However, to date, there have been no biomechanic studies published that describe the function of the fabellofibular ligament.

FABELLA

The fabella, or little bean, is a bony or cartilaginous structure nestled in the posterolateral aspect of the knee. It is generally believed to reside in the tendon of the lateral head of the gastrocnemius; however, many structures merge at the fabella (Table 2-1). The fabella ranges in size from approximately 5 mm to over 20 mm in diameter, with the majority (70%) being oval in shape.[26,33] There are varying reports on the incidence of the fabella. Earlier radiographic studies appear to underestimate the true prevalence of the fabella compared with more recent cadaveric and histologic studies (Table 2-2). This structure is present bilaterally in approximately 80% of cases. The fabella has been implicated as a cause of posterior knee pain in multiple conditions including chondromalacia fabella, *fabella syndrome*, fracture of the fabella, impingement after total knee arthroplasty, and peroneal nerve irritation.[7,8,22-24,35,49] Thus the fabella and surrounding structures represent a rare but potential source of posterolateral knee pain.

POPLITEUS MUSCLE-TENDON-LIGAMENT COMPLEX

The PMTL is an intricate anatomic conglomerate made up of the popliteus muscle, the PFL, the femoral insertion of the popliteus tendon, the popliteomeniscal fascicles and soft tissue attachments to

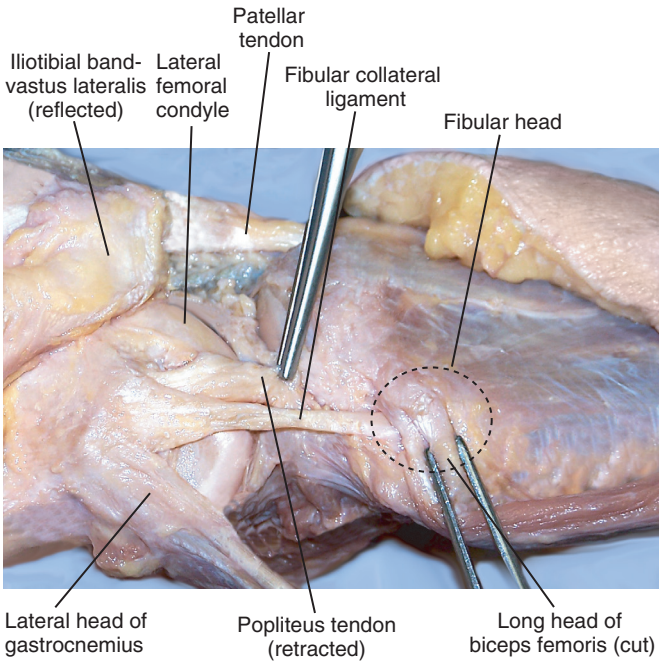


FIG 2-7 **A,** Gross picture of the fibular collateral ligament (FCL) demonstrates its relationship to the popliteus tendon and the lateral head of the gastrocnemius. **B,** The FCL and its relationship to the popliteus tendon and the lateral head of the gastrocnemius.

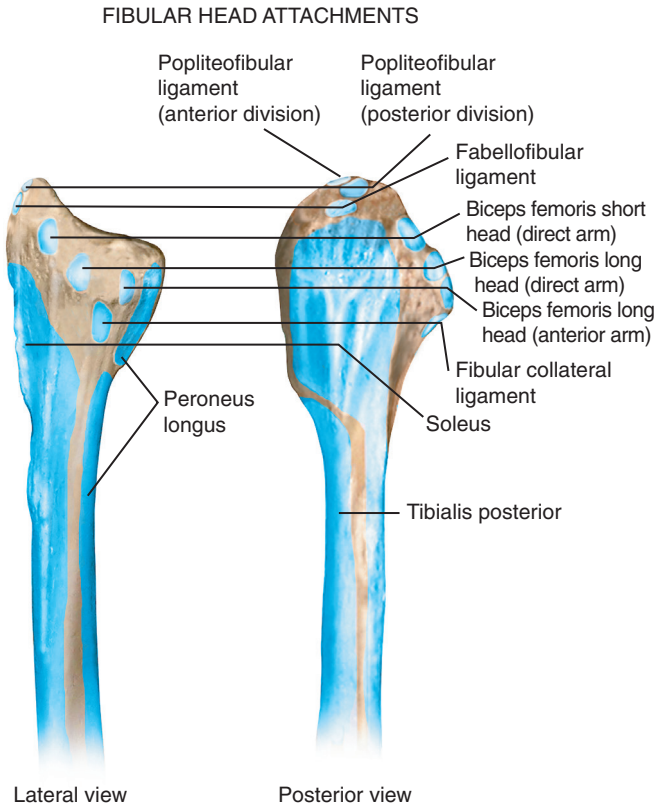


FIG 2-8 Lateral view of the knee demonstrates the fibular collateral ligament insertion onto the proximal fibula distal to the fibular styloid.

TABLE 2-1 Structures That Coalesce at the Fabella

Capsular arm of the short head of the biceps femoris
Fabellofibular ligament
Lateral gastrocnemius tendon
Proximal lateral attachment of the oblique popliteal ligament
Posterolateral capsule

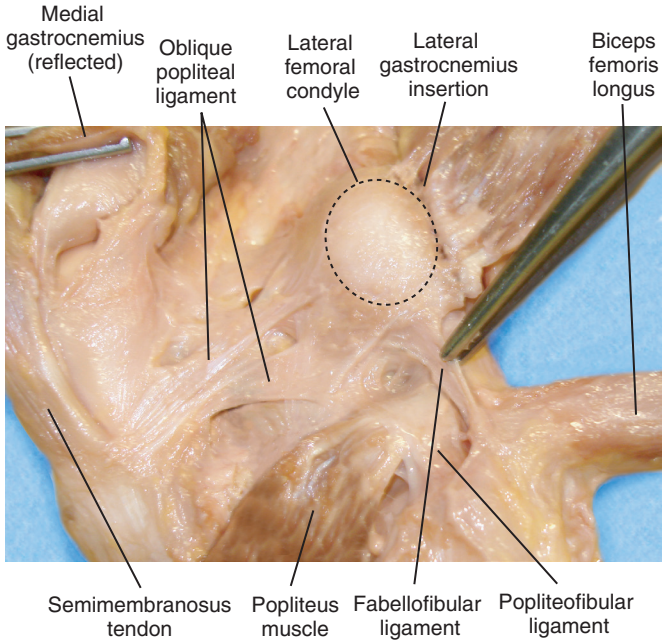
TABLE 2-2 Published Incidence of Fabella

Reference	*n*	Methodology	Prevalence
Pancoast[33]	529	Radiographs	12.3%
Falk[54]	1023	Radiographs	12.9%
Sutro[55]	700	Radiographs	11.5%
Pritchett[56]	600	Radiographs	35% in patients with OA, 15% in patients without OA
Minowa et al[26]	212	Cadavers/histology	85.8% (74% bony, 26% cartilaginous)
LaPrade et al[16]	100	Cadavers/histology	100% (38% bony, 62% cartilaginous)

OA, Osteoarthritis.

the lateral meniscus, and the proximal tibia. The crucial components for posterolateral stability include the popliteus tendon and the PFL. These structures act in concert with the FCL and posterolateral capsule to prevent excessive external rotation and varus rotation of the knee.[9,32] Restoration of only a portion of these structures may result in residual instability.[31] This is discussed in detail in Chapter 15.[27-30]

The popliteus muscle originates on the posterior tibia just proximal to the soleal line and proceeds lateral and proximal to insert on the lateral femoral condyle (see Fig. 2-8, *B*). The popliteus tendon proceeds proximally through a hiatus in the coronary ligament of the lateral meniscus, then deep to the FCL to ultimately insert anterior and distal to the insertion of the FCL (see Fig. 2-7). As referenced earlier, LaPrade and associates[19] reported that the popliteus inserted an average of 18.5 mm from the FCL on the femur. Staubli and Birrer[41] further described the anatomy of the popliteus tendon at the level of the knee



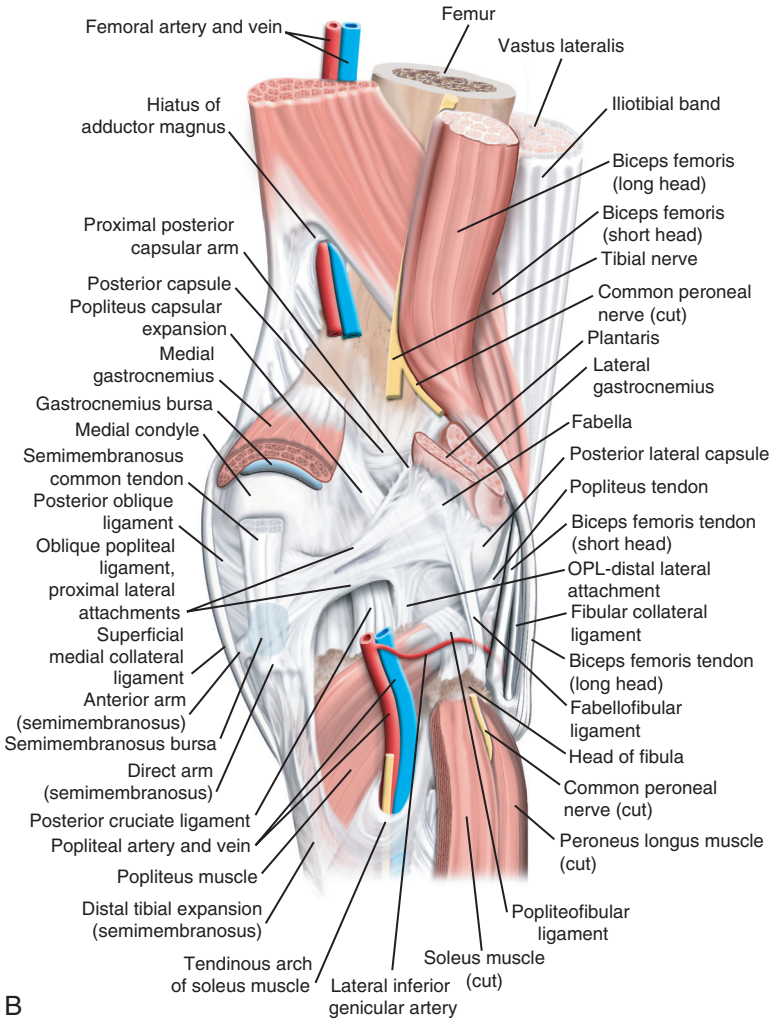


FIG 2-9 **A,** Posterior aspect of the knee with forceps holding the fabellofibular ligament. This ligament originates on the posterior aspect of the lateral femoral condyle and inserts on the fibular head. **B,** The posterior aspect of the knee. *OPL,* Oblique popliteal ligament.

joint. Three attachments of the popliteus tendon to the lateral menisci (termed the *popliteomeniscal fascicles*) were noted that include the anteroinferior, posterosuperior, and posteroinferior fascicles (Fig. 2-10). These fascicles provide stability to the lateral meniscus and, when torn, lead to abnormal translation of the lateral meniscus.[18,39] This may lead to mechanical symptoms and lateral knee pain. In Chapter 23, the repair techniques for the lateral meniscus and popliteomeniscal fascicles are described.

LaPrade and colleagues[20] described a thickening of the posterior joint capsule that extends from the medial aspect of the popliteus musculotendinous junction to the posteromedial aspect of the intercondylar notch of the femur, termed *the proximal popliteus capsular expansion* (see Fig. 2-9, *B*). The study reported this structure to be present in all dissections, and we have also found it to be a constant structure. This structure may provide an additional restraint to knee external tibial rotation and hyperextension.

The PFL originates at the musculotendinous junction of the popliteus and attaches to the medial aspect of the fibular head (Fig. 2-11), where it lies deep to the fabellofibular ligament. Of clinical significance, the inferior lateral geniculate artery courses between these two structures. The artery is frequently encountered during exposure of the posterolateral corner of the knee, especially during the approach for an inside-out lateral meniscus repair (Fig. 2-12). The artery is protected, if possible, and, if injured, requires cauterization to prevent postoperative hematoma formation. The PFL consists of two divisions, an anterior and posterior division.[19] LaPrade and associates[19] found that the average width of the anterior division's attachment at the fibular styloid was 2.6 mm, although the posterior division's width at the fibular styloid attachment was 5.8 mm. Thus the posterior division may contribute more significantly than the anterior division to stability of the posterolateral aspect of the knee.

BICEPS FEMORIS

The biceps femoris is a fusiform muscle comprising two heads: long and short. The long head originates from the ischial tuberosity and is innervated by the tibial division of the sciatic nerve. The short head originates from the lateral aspect of the linea aspera of the femur and is innervated by the peroneal division of the sciatic nerve.[36] Distally, the two heads of the biceps lie just posterior to the ITB (Fig. 2-13). Both heads of the biceps have complex attachments to the posterolateral aspect of the knee. These distinct attachments are described and shown in Tables 2-3 and 2-4. In our experience (in cadaveric dissections and at surgery), many of the attachments blend together distally and are difficult to identify as separate structures. The peroneal nerve lies just distal and posterior to the biceps, curving around the fibular neck. The biceps flexes the knee and also externally rotates the leg when the knee is flexed.[37]

There are varying descriptions of the anatomy of the biceps and the number of attachments.[11,12,25,37,45] Terry and LaPrade[45] described five attachments of the long head of the biceps, including two tendinous and three fascial components (Fig. 2-14; see also Table 2-3). The two tendinous components (direct and anterior arms) and one of the fascial components (lateral aponeurotic expansion) make up the key portion of the long head anatomy. The other fascial components are the reflected arm and the anterior aponeurotic expansion.

The most proximal component is the reflected arm. It originates just proximal to the fibular head and ascends anteriorly to insert on the posterior edge of the ITB. The direct arm inserts onto the posterolateral edge of the fibula just distal to the tip of the styloid (see Fig. 2-8).[16] The anterior arm has a more complex attachment and some important anatomic points. A portion of the anterior arm inserts onto the lateral aspect of the fibular head, and the rest continues distally just lateral to the FCL. Just proximal and at this fibular insertion, portions of the anterior arm ascend anteriorly, forming the lateral aponeurotic expansion that attaches to the posterior and lateral aspect of the FCL. Here, a small bursa separates the anterior arm from the distal fourth of the FCL. The anterior arm thus forms the lateral wall of this bursa.[45]

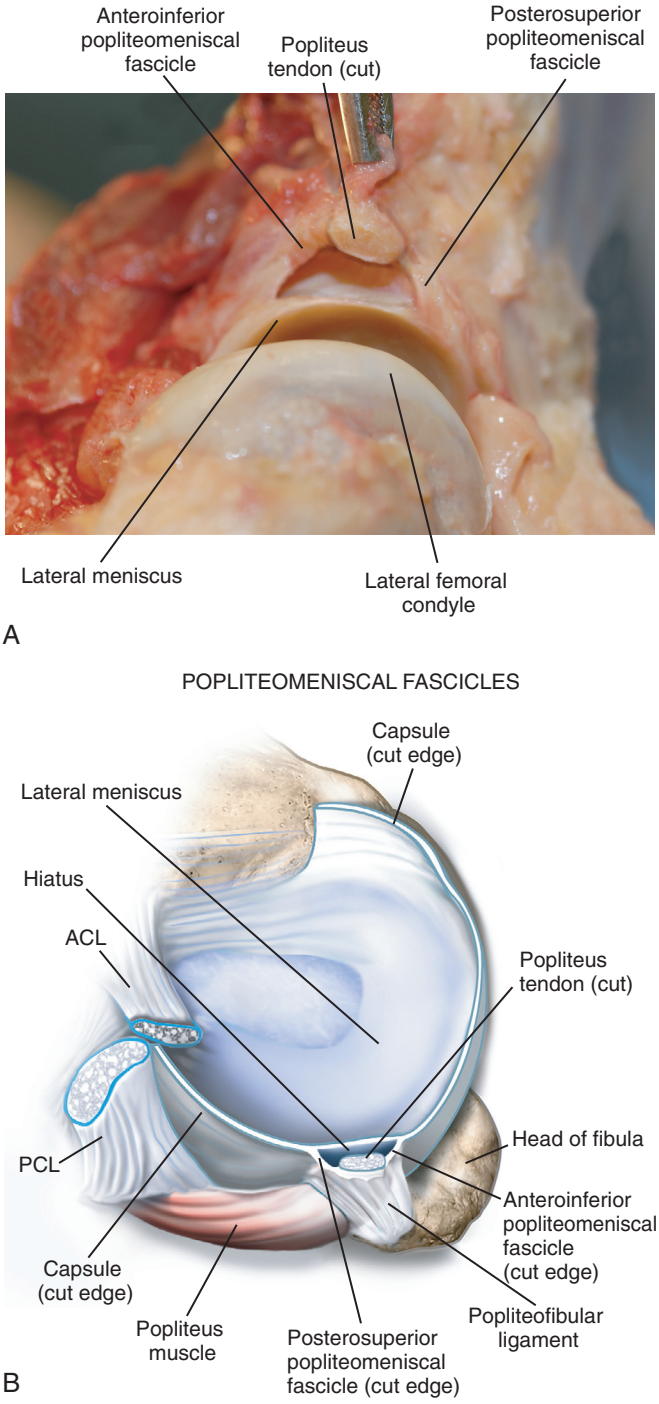


FIG 2-10 A, The popliteus tendon is cut at the level of the joint with its surrounding popliteomeniscal fascicles. The posterosuperior fascicle and anteroinferior fascicle secure the popliteus tendon to the lateral meniscus. The lateral femoral condyle is labeled for reference. **B,** The popliteus tendon and its surrounding popliteomeniscal fascicles. *ACL,* Anterior cruciate ligament; *PCL,* posterior cruciate ligament.

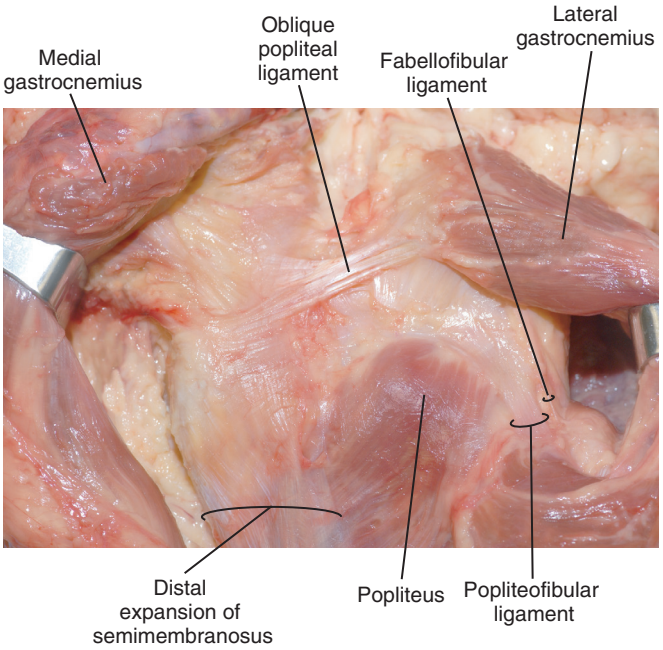


FIG 2-11 The popliteofibular ligament originates from the popliteus muscle and attaches to the medial aspect of the fibula. The lateral head of the gastrocnemius is being retracted proximally.

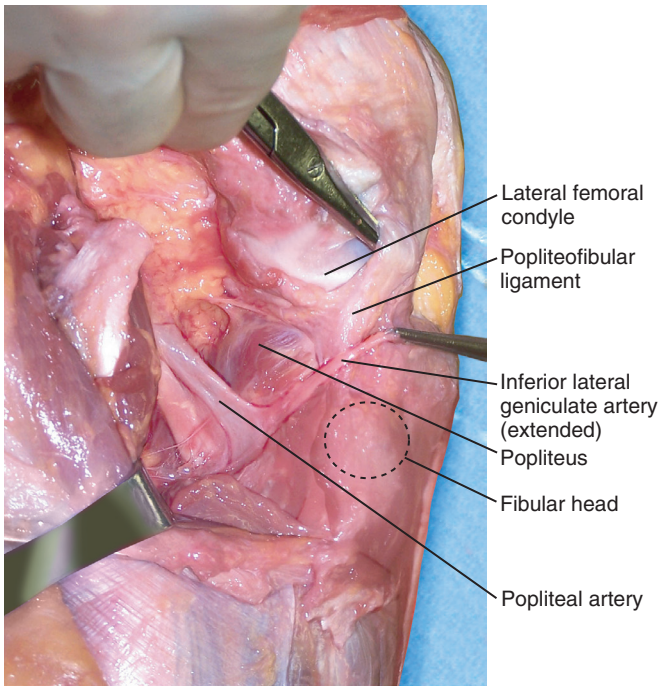


FIG 2-12 The inferior lateral geniculate artery branches off from the popliteal artery and runs superficial to the popliteofibular ligament. The fabellofibular ligament has been removed to better demonstrate the inferior lateral geniculate artery.

This is an important surgical landmark because a small horizontal incision can be made here, 1 cm proximal to the fibular head, to enter this bursa and locate the insertion of the FCL into the fibular head (Fig. 2-15).[16] The anterior arm then continues distally over the FCL, forming the anterior aponeurosis, which covers the anterior compartment of the leg.

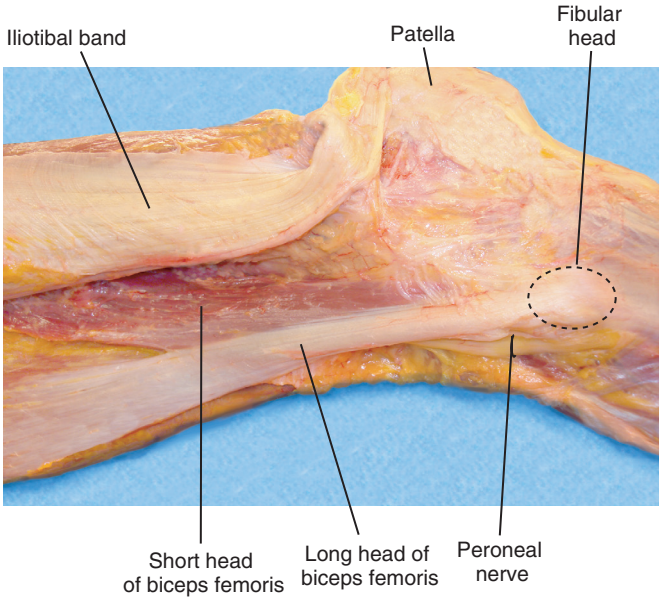


FIG 2-13 The iliotibial band is retracted superiorly demonstrating the short head of the biceps attaching to the long head tendon and inserting onto the fibular head. The peroneal nerve is seen posterior to the biceps.

TABLE 2-3 Five Components of the Long Head of the Biceps Femoris

Component	Attachment
Reflected arm	Posterior edge of ITB
Direct arm	Posterolateral edge of the fibula
Anterior arm	Lateral fibular head, FCL, anterior aponeurotic expansion
Lateral aponeurotic expansion	FCL
Anterior aponeurotic expansion	Anterior compartment of the leg

FCL, Fibular collateral ligament; *ITB*, iliotibial band.

TABLE 2-4 Six Components of the Short Head of the Biceps Femoris

Component	Attachment
Proximal muscular attachment	Anteromedial aspect of the long head
Capsular arm	Posterolateral knee capsule
Capsulo-osseus layer	Proximolateral tibia
Direct arm	Fibular head
Anterior arm	Proximolateral tibia
Lateral aponeurotic expansion	FCL

FCL, Fibular collateral ligament.

The short head of the biceps courses just deep (or medial) and anterior to the long head tendon, sending a majority of its proximal muscular fibers to the long head tendon itself.[45] It has six distal attachments (Fig. 2-16; see also Table 2-4). The most important attachments are the direct arm, the anterior arm, and the capsular arm.

The capsular arm originates just before the short head reaching the fibula. It then continues deep to the FCL to insert onto the posterolateral knee capsule and fabella. Here, the fibers of the capsular arm continue distally as the fabellofibular ligament.[45] Just distal to the

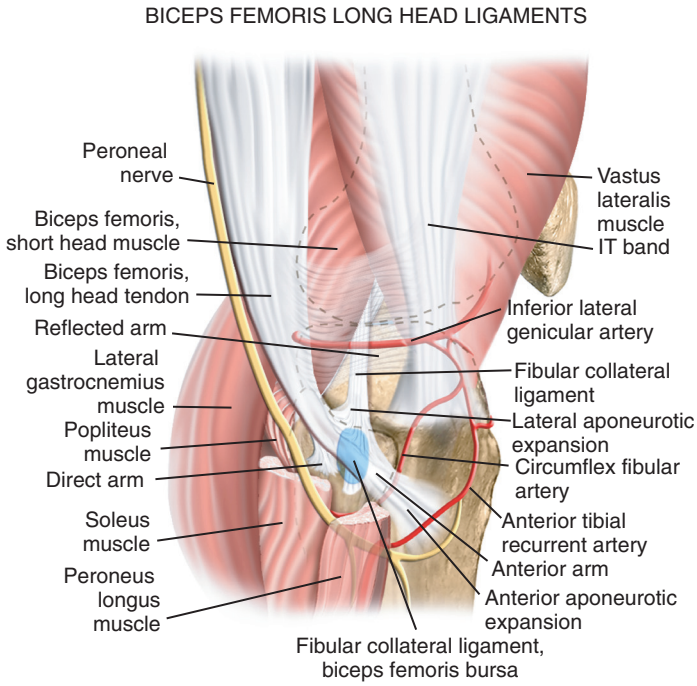


FIG 2-14 The long head of the biceps, multiple insertions.

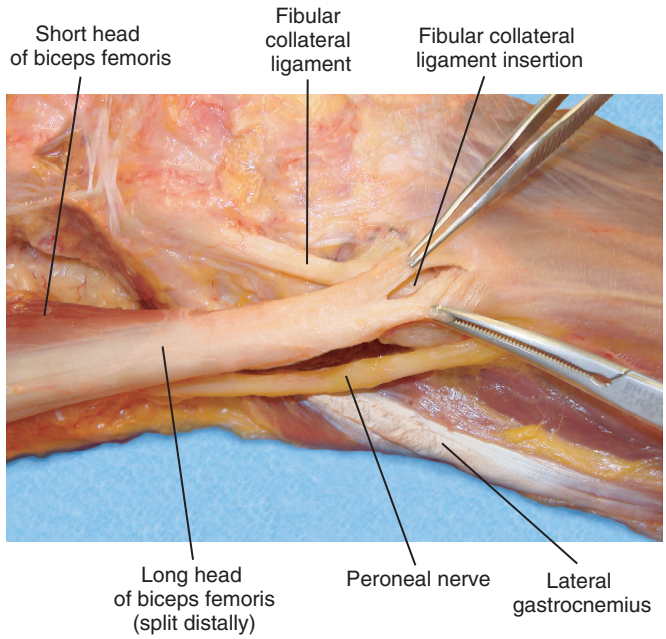


FIG 2-15 An incision in the long head of the biceps tendon reveals the insertion of the fibular collateral ligament as it lies deep to the tendon. The peroneal nerve is in close proximity as it lies superficial to the lateral gastrocnemius.

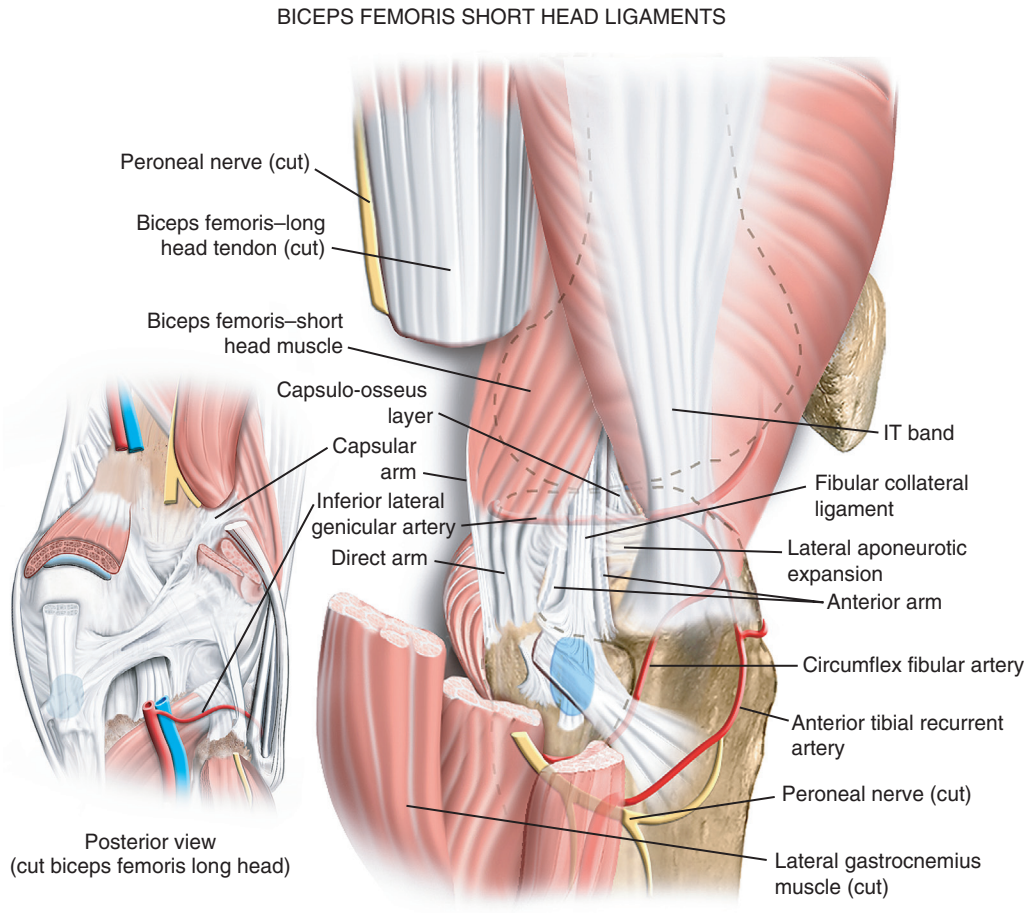


FIG 2-16 The insertion of the short head of the biceps tendon. *IT,* Iliotibial.

TABLE 2-5 Key Structures That Attach to the Fibular Head

Structure	Location on Fibular Head
LH biceps, direct arm	Posterolateral edge (lateral and distal to styloid)
LH biceps, anterior arm	Posterolateral edge (slightly distal and lateral to direct arm of the LH)
SH biceps, direct arm	Posterior edge (lateral to styloid, medial to direct arm of the LH)
Popliteofibular ligament	Medial aspect of the styloid
Fibular collateral ligament	Anterolateral edge (28 mm distal to styloid, 8 mm posterior to anterior edge of fibula)
Fabellofibular ligament	Lateral to the tip of the styloid

LH, Long head; *SH*, short head.

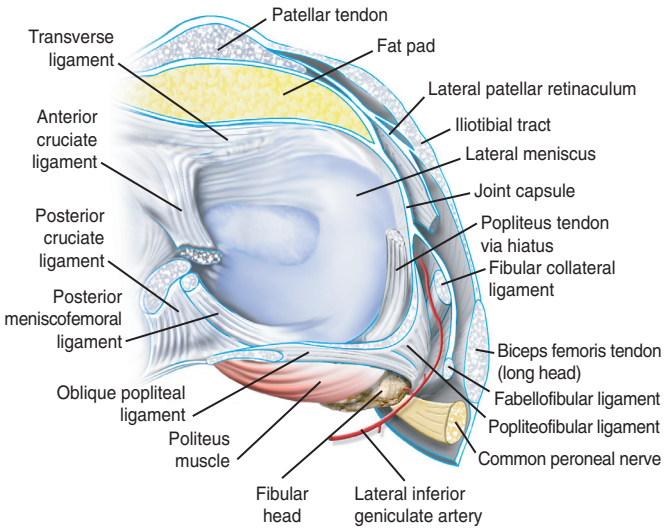


FIG 2-17 Axial view of the lateral knee joint illustrates the trilaminar relationship of the various posterolateral structures.

capsular arm, a capsulo-osseous layer forms a fascial confluence with the ITB (the biceps-capsulo-osseous-iliotibial tract confluens). The direct arm of the short head inserts onto the fibular head just posterior and proximal to the direct arm of the long head tendon. The anterior arm then continues medial or deep to the FCL, partially blends with the anterior tibiofibular ligament, and inserts onto the tibia 1 cm posterior to Gerdy's tubercle. This site is also the attachment of the mid-third lateral knee capsule.[45] It is important clinically because an avulsion fracture can be seen here in ACL injuries, known as a *Segond fracture*.[38,45] Finally, the lateral aponeurotic expansion of the short head inserts onto the medial aspect of the FCL (versus this expansion of the long head that inserts onto the posterior aspect of the FCL).[45]

FIBULAR HEAD

The fibular head is a key anatomic and structural component to the posterolateral knee. It is easily palpable in most patients and is thus an excellent anatomic reference point. In the literature, incomplete descriptions of the anatomy and insertion of structures of the proximal fibula exist. Six key structures attach to the fibular head: three tendons and three ligaments (Table 2-5; see also Fig. 2-8). The PFL attaches to the tip of the fibular styloid. Just distal and lateral, the fabellofibular ligament attaches on the slope of the styloid. The FCL, as mentioned previously, attaches proximally 28 mm distal to the styloid and 8 mm from the anterior cortex of the fibula, depending on the course on specimen size variations.[19] A portion of the anterior arm of the long head of the biceps attaches to the lateral aspect of the fibular head. The direct arms of the long and short head of the biceps attach to the posterior aspect of the fibular head, the long head being just lateral to that of the short head.

KNEE CAPSULE

The knee capsule envelops the joint, extending from the articular margin of the femur to the tibia (see Fig. 2-1, *C* and *D*). On the tibia, it inserts 4 to 14 mm below the articular surface. The most distal attachment at the tibia is located at the posteromedial and posterolateral aspect.[3] Some authors have identified a thickening of the capsule laterally, naming this the *mid-third lateral capsular ligament*.[36] This ligament is divided into two components. The meniscofemoral component and meniscotibial component extend from the femur and tibia, respectively, to attach to the lateral meniscus.[36] The lateral retinacular nerve, a branch of the sciatic nerve, courses along the surface of the lateral capsule (Fig. 2-17).

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Video Content

Video 2-1

15. LaPrade RF. Anatomic reconstruction of the posterolateral aspect of the knee. *J Knee Surg*. 2005;18(2):167-171.
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3

Scientific Basis for Examination and Classification of Knee Ligament Injuries

Frank R. Noyes, Edward S. Grood

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CLASSIFICATION SYSTEM FOR KNEE LIGAMENT INJURIES

Many different classification systems for knee ligament injuries have been proposed in the sports medicine literature.[28,29,45,47,57] A series of studies we conducted enabled the development of an algorithm for the diagnosis and classification of these injuries based on kinematic and biomechanical data.[6,19-22,50-54,56,57,72,79] The purpose of this chapter is to summarize these studies and provide the clinician with the proper examination techniques that allow precise diagnosis of abnormal knee motions, subluxations, and ligament injuries.

The purposes of a classification system are to (1) make accurate distinctions between separate pathologic conditions in laboratory and clinical studies and (2) provide a common descriptive tool for investigators who wish to present cases and describe the outcome of treatment programs. A system that allows two or more discrete types of injuries to be grouped as a single entity does not allow the association of a unique natural history or surgical result with the anatomic defect on the actual pathologic condition being treated.

The classification scheme developed from our investigations is based on seven concepts:

1. The final diagnosis of knee ligament injuries is based on the specific anatomic defect derived from the abnormal motion limits and joint subluxations.
2. Ligaments have distinct mechanical functions to provide limits to tibiofemoral motions and the types of motions that occur between opposing cartilage surfaces.
3. Although there are six degrees of freedom (DOF), the manual stress examinations are designed to test just one or two limits at a time.
4. Ultimately, the clinical examination must be analyzed by a six-DOF system to detect abnormalities.

CRITICAL POINTS Classification System for Knee Ligament Injuries

Purpose of a Classification System

- Make accurate distinctions between separate pathologic conditions in laboratory and clinical studies.
- Provide a common descriptive tool for investigators who wish to present cases and describe the outcome of treatment programs.

Our Classification System Based on Seven Concepts

1. The final diagnosis of knee ligament injuries is based on the specific anatomic defect derived from the abnormal motion limits and joint subluxations.
2. Ligaments have distinct mechanical functions to provide limits to tibiofemoral motions and the types of motions that occur between opposing cartilage surfaces.
3. Although there are six DOFs, manual stress examinations are designed to test just one or two limits at a time.
4. Ultimately, the clinical examination must be analyzed by a six-DOF system to detect abnormalities.
5. Together, the ligaments and joint geometry provide two limits (opposite directions) for each DOF.
6. Rotatory subluxations are characterized by the separate compartment translations that occur to the medial and lateral tibial plateaus during the clinical test.
7. The damage to each ligament and capsular structure is diagnosed using tests in which the primary and secondary ligament restraints have been experimentally determined.

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6. Rotatory subluxations are characterized by the separate compartment translations that occur to the medial and lateral tibial plateaus during the clinical test.
7. The damage to each ligament and capsular structure is diagnosed using tests in which the primary and secondary ligament restraints have been experimentally determined.[51]

In this chapter, the studies presented related to the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL) and posteromedial structures, the iliotibial band (ITB), and the mid-lateral capsule. Studies related to the posterolateral structures (fibular collateral ligament [FCL], popliteus muscle-tendon ligament, and posterolateral capsule) are presented in Chapters 15 and 17.

Concept 1: Final Diagnosis of Knee Ligament Injuries Is Based on the Specific Anatomic Defect Derived From the Abnormal Motion Limit and Joint Subluxation

The term *instability* has been used to describe an abnormal motion or motion limit that exists to the joint because of a ligament injury. This term has also been used to indicate symptomatic giving-way of the knee joint that occurs during activity. Instead, it is recommended to describe the giving-way event and not use the term *instability*. Giving-way may be caused by many factors, including a ligament rupture, poor muscular control of the knee joint, altered neurologic function and control mechanisms, or mechanical problems such as a torn meniscus or loose body. In many cases, giving-way occurs because of multiple factors, and the term *instability* does not precisely indicate the exact cause of the episode. Rather than a diagnosis of anterior instability, it is more appropriate to reduce the abnormality to a precise anatomic diagnosis such as ACL rupture. In addition, other ligament deficiencies, if present, should be identified.

The term *laxity* simply indicates looseness and may be applied to increases in joint motion or increases in ligament elongation. Therefore, the term *laxity* does not provide a diagnosis of a specific abnormality. The knee has a normal amount of laxity (play or motion) required for function. An abnormal amount of laxity may occur as a result of a ligament disruption. Laxity may also indicate a ligament injury in which the ligament has an increase in length or elongation during loading. The finding of abnormal laxity represents a clinical sign that does not provide a precise diagnosis. Instead, the specific anatomic defect of the ruptured ACL and associated injured ligaments or capsular structures should be recorded as the diagnosis. The goal of a comprehensive knee examination is to detect an increase in the amount of motion (translation or rotation) or an abnormal position (subluxation) to determine the specific anatomic defects that are present.

Concept 2: Ligaments Have Distinct Mechanical Functions to Provide Limits to Tibiofemoral Motions and the Types of Motions That Occur Between Opposing Cartilage Surfaces

Ligaments have distinct mechanical functions to provide limits to the amount of tibiofemoral motion that determines the types of motions occurring between opposing cartilage surfaces. The limits of motion are the main focus because loss of this function and the consequent subluxation are the underlying deficits in ligament-injured knees. In addition, the change in limits of motion is the primary basis of diagnosis.

The ability of ligaments to limit tibiofemoral motion provides the geometric parameters within which the neuromuscular system is able to control the position of the knee during activity. Although focus is placed on the mechanical function of the ligaments and capsular structures, the reader should be cognizant of the potentially important role of ligaments in providing sensory feedback to the neuromuscular system.[32,70] Ligaments have three properties that affect their ability to limit joint motion: location of their attachment on the bones, just-taut length, and stiffness.

Tibiofemoral motions are limited along the line that connects the ligament's tibial and femoral attachments in the direction that loads the ligament. Ligaments are not able to limit motions perpendicular to their orientation or motions that cause them to become slack. Just-taut length is a determinant of joint laxity because it controls the amount of motion before the ligament begins to provide a resisting force. Because the two cruciate ligaments are required to limit anteroposterior (AP) translation, total AP translation is determined by the just-taut length of both ligaments.

Ligament stiffness controls how much additional joint movement is required after the ligament has become taut to create a force large enough for the ligament to resist the applied load. Decreased ligament stiffness produces an increase in the motion limit because a greater motion is required before the ligament can develop a sufficient restraining force.

The kinematic and biomechanical concepts required to interpret clinical tests are shown in Figure 3-1. First, the appropriate clinical test must be selected to diagnose a specific ligament structural abnormality. Diagnostic information is obtained based on understanding the primary and secondary ligament restraint system. The results of the tests must be understood and communicated in terms of the six-DOF system that determines the abnormal motion limits. The medial

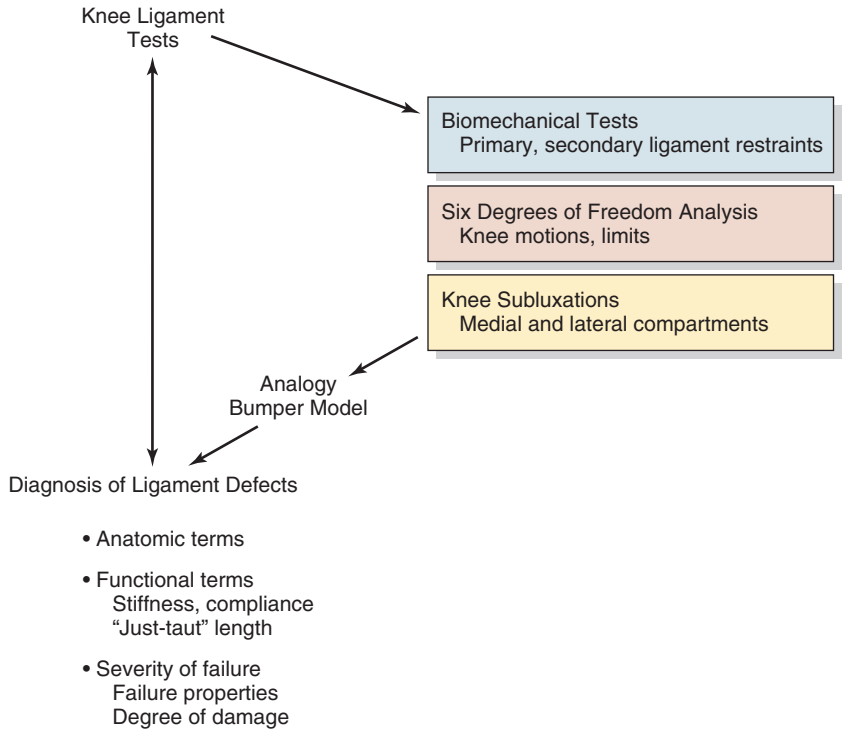


FIG 3-1 The results of clinical tests require specific biomechanical and kinematic principles for correct diagnosis of ligament defects. Ligament defects are defined by anatomic, functional, and severity categories. (From Noyes FR, Grood ES. Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. In Griffin P, editor: *AAOS Instructional Course Lectures,* Vol XXXVI. Chicago: American Academy of Orthopaedic Surgeons; 1987:185-200.)

and lateral tibiofemoral compartments are examined separately to determine the different types of subluxation. The final diagnosis of the ligament defect must be made in precise anatomic and functional terms and according to the severity of ligament failure (partial or complete).

Concept 3: Although There Are Six Degrees of Freedom, the Manual Stress Examinations Are Designed to Test Just One or Two Limits at a Time

Although there are six DOF, the knee ligament examination is specifically designed to test just one or two motion limits at a time. Combinations of these motions (coupled motions) are particularly important to the diagnosis of knee ligament injury because they occur during many of the manual stress examinations.

Translation of a rigid body (such as the tibia) is described by the motion of an arbitrarily selected point on the body. Typically, the AP translation is described by the motion of a point located midway between the medial and lateral margins of the tibia. If only translation motions occur, the amount of motion does not depend on which point is chosen—that is, whether the point is at the center of the knee or at the medial or lateral joint margin. This is because all points will move along parallel paths. However, when rotation and translation motions are combined, the amount of translation does depend on which point is used. This can be seen by considering the four cases illustrated in Figure 3-2.

Figure 3-2, *B* shows an anterior translation of 10 mm without associated tibial rotation. All points move anteriorly by the same amount. Figure 3-2, *C* shows an internal rotation of 15 degrees about an axis located midway between the spines of the intercondylar eminence. The point on the rotation axis is stationary while the lateral joint margin (edge) moves anteriorly and the medial margin posteriorly (see Fig. 3-2, *D*). The amount of anterior and posterior motion of the points at the joint margin depends on the amount of rotation and how far they are away from the rotation axis (center of rotation). This illustrates that when translation is measured in the presence of a concurrent rotation, it is important to know at which point the translation was measured.

Concept 4: Ultimately, the Clinical Examination Must Be Analyzed by a Six-DOF System to Detect Abnormalities

The clinician who understands all of the possible motions in the knee joint that are normally limited by the knee ligaments will be able to perform manual stress tests and correctly determine the specific abnormality that is present. However, a diagnosis cannot be based solely on the abnormal motions detected. The diagnosis also requires knowledge of the biomechanical data regarding which ligaments limit each of the possible motions in the knee joint.

The field of science that describes the motions between objects is known as *kinematics*. A fundamental aspect of this field is the recognition that six possible motions may occur in three dimensions. Each of the six motions is discrete and separate from the other five motions. The six motions are referred to as *degrees of freedom*. The three rotational DOF in the knee joint are shown in Figure 3-3. Each rotation occurs about one axis: flexion-extension, internal-external, and abduction-adduction.

The flexion-extension axis is located in the femur and oriented in a pure medial-lateral direction perpendicular to the femoral sagittal

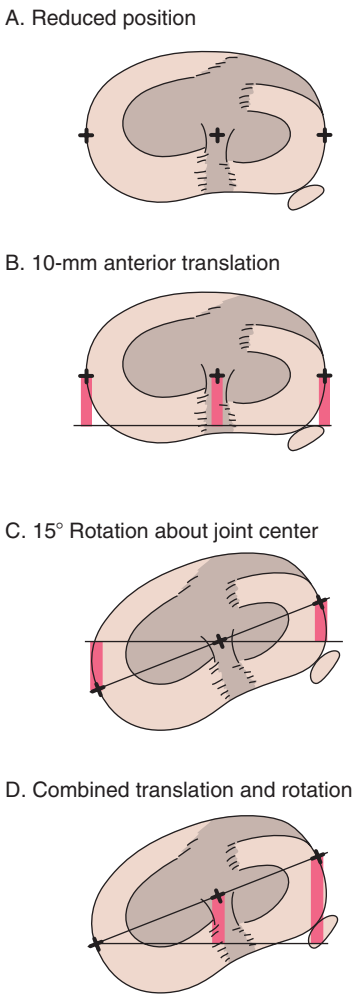


FIG 3-2 Combined anterior translation and tibial rotation. **A,** The tibial plateau is shown along with the contact area on the femur (shaded regions). The tibia is in a reduced position. **B,** Anterior tibial translation of 10 mm. The amount of translation, shown by the vertical bars, is the same at the medial and lateral joint margins as it is at the center of the joint. **C,** Fifteen degrees of internal rotation about the joint center. Tibial contact is anterior on the lateral plateau and posterior on the medial plateau. The bars show the amount and direction of its translation at the medial-lateral joint lines. The amount of translation is approximately 10 mm in an average knee 80 mm wide. There is no translation at the center of the joint where the rotation axis is located. **D,** Combined tibial translation and rotation. A 10-mm anterior translation is combined with 15 degrees of internal rotation at the medial aspect of the tibia. The center of the tibia translates 10 mm anteriorly, while the lateral joint margin translates 20 mm anteriorly. (From Grood ES, Noyes FR. Diagnosis of knee ligament injuries: biomechanical precepts. In Feagin J, editor: *The Crucial Ligaments.* New York: Churchill Livingstone; 1988:245-260.)

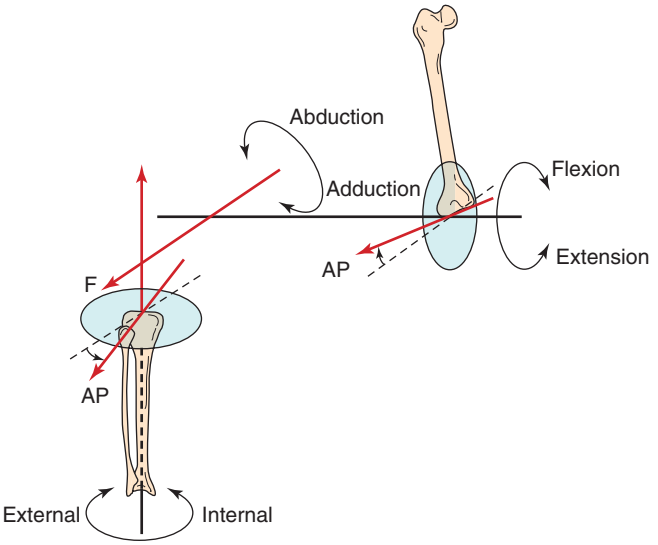


FIG 3-3 The three joint rotations in the knee joint. Flexion/extension occurs about the medially and laterally oriented axis in the femur. Internal and external tibial rotation occurs about an axis parallel to the shaft of the tibia. Abduction occurs about a third axis parallel to the femoral sagittal plane and also through the tibial transverse plane. (From Noyes FR, Grood ES. Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. In Griffin P, editor: *AAOS Instructional Course Lectures,* Vol XXXVI. Chicago: American Academy of Orthopaedic Surgeons; 1987:185-200.)

plane. Rotation of the tibia about this axis does not have associated internal-external rotation or abduction-adduction motions.[22] Because these motions occur during flexion, the flexion-extension axis shown in Figure 3-3 does not correspond to the functional flexion axis. The functional flexion axis is skewed in the knee and changes its orientation as the knee is flexed. This skewed orientation accounts for the combined motions of flexion, abduction, and tibial rotation.

The internal-external tibial rotation axis is located in the tibia, parallel to the tibial shaft and perpendicular to the tibial transverse plane. Rotations about this axis are pure internal and external tibial rotation motions without any associated abduction-adduction or flexion-extension.

The abduction-adduction rotation axis is more difficult to visualize because it is not located in either bone and its orientation can change relative to both. This axis is always parallel to the femoral sagittal plane. When the knee is flexed, the orientation of the abduction axis changes relative to the femur as it rotates in the sagittal plane. The abduction axis is perpendicular to the tibial rotation axis and parallel to the tibial transverse plane.

There are three linear DOF in the knee joint, referred to as *translations*. One simple approach to describing translations is to visualize relative sliding between the bones along each of the three rotational axes (Fig. 3-4). The sliding motion along the flexion-extension axis is the medial-lateral translation between the tibia and femur. The sliding motion along the tibial rotation axis results in joint compression and distraction translation. Sliding motions along the abduction-adduction rotation axis produce AP translations. These are also commonly known as *drawer motions*.

Therefore, there are six possible motions that can occur in the knee: three rotations and three translations. Three axes are required to explain these six motions, one fixed in each bone (see Fig. 3-4). Each axis represents two DOF, one a rotation occurring about the axis and the other a translation.

The purpose of the examination is to determine the specific increase in motion (amount and direction) of each clinically relevant DOF. In many cases, coupled motions occur in the knee joint, such as anterior translation combined with internal tibial rotation during Lachman testing, which is further increased on pivot shift testing. First, the examiner must understand the effect that ligament defects have on each of these motions, because one or both may be increased. Second, both the amount of increased motion and resulting subluxation of the tibial plateaus depend on the position of the knee joint, which is

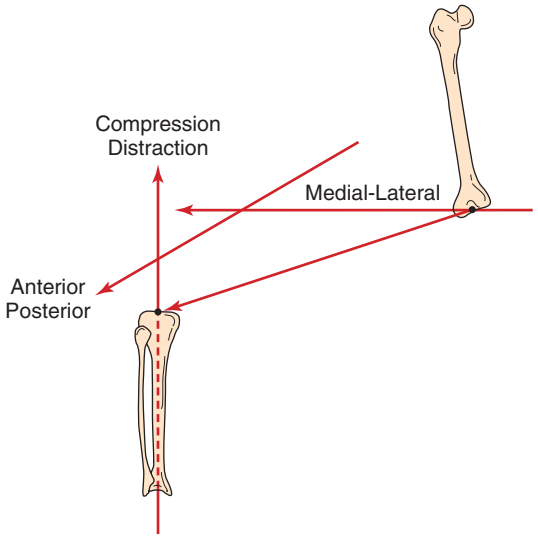


FIG 3-4 The three translations of the knee joint are motions of a point on the tibia parallel to each of the three axes. The point of the tibia used is located midway between the spines of the tibial plateau and is indicated by the arrow originating from the center point of the femur. Medial-lateral translation is motion of the point parallel to the flexion-extension axis. Anterior-posterior translation is motion of the tibial point parallel to the abduction axis, and compression-distraction translation is motion of the point along the internal and external rotation axis. (From Noyes FR, Grood ES. Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. In Griffin P, editor: *AAOS Instructional Course Lectures,* Vol XXXVI. Chicago: American Academy of Orthopaedic Surgeons; 1987:185-200.)

defined in terms of six DOF. Third, after a ligament is ruptured, an abnormal position usually is present in the axis of internal-external tibial rotation. This may be detected on examination and is helpful in diagnosing the ligament defect.

To understand the results of the clinical examination, a distinction must be made between abnormalities in joint motion and abnormalities in joint position (subluxation) that occur at the limit of the test. An abnormality in one or more motion limits can cause a subluxation of the knee joint. The subluxation depends on the direction and magnitude of the loads applied. Clinical tests are used to detect the motion limit and the final abnormal joint position. The examination usually detects a subluxation and not a complete knee dislocation, in which contact of the articulating surfaces of both tibiofemoral compartments is lost.

Concept 5: Together, the Ligaments and Joint Geometry Provide Two Limits (Opposite Directions) for Each Degree of Freedom

Together, the ligaments and joint geometry provide two limits (opposite directions) for each DOF. Altogether, there are 12 possible limits of motion of the knee (Table 3-1). Injury to the structures that limit each motion increases joint laxity. The position of the joint at the final limits of motions (reflecting the ligament attachment sites) provides the information required for diagnosis. From a diagnostic standpoint, it would be ideal if each of the 12 limits of motion were controlled by a single ligamentous structure. Differential diagnosis could then be performed by evaluating each of the 12 limits separately. Clearly, this ideal situation does not exist. The ligaments, capsular structures, and joint geometry all work together and each contributes to limiting more than one motion. Thus, the problem of diagnosing knee injuries

TABLE 3-1 Twelve Limits of Knee Joint Motion

Motion Limit	Structures Limiting the Motion
Flexion	Ligaments, leg and thigh shape, joint compression
Extension	Ligaments and joint compression
Abduction	Ligaments and lateral joint compression
Adduction	Ligaments and medial joint compression
Internal rotation	Ligaments and menisci
External rotation	Ligaments and menisci
Medial translation	Bones (spines interlocking with femoral condyles) and ligaments (to prevent distraction)
Lateral translation	Bones (spines interlocking with femoral condyles) and ligaments (to prevent distraction)
Anterior translation*	Ligaments
Posterior translation*	Ligaments
Joint distraction	Ligaments
Joint compression	Bone, menisci, and cartilage

*Menisci, joint compressive effects after injury to primary restraint.

reduces to determining how to apply individual or combination motions to lengthen primarily a single ligament or capsular structure so that structure can be evaluated independently.

The ability to isolate each structure is the key to differential diagnosis of individual ligament injuries. The isolation of a structure is accomplished by placing the knee at the proper joint position (specifically, knee flexion angle and tibial rotation position) before the clinical stress test is performed. For example, the abduction (valgus) stress test is performed both in full extension and at 20 to 30 degrees of flexion. In the flexed position, the posterior capsule becomes slack, which allows the examiner to primarily load the MCL and mid medial capsule. The evaluation of ACL function is performed at 20 degrees of knee flexion[73] as opposed to the 90-degree position[42] commonly used many years ago; the 20-degree position more often results in increased anterior subluxation because secondary restraints are more slack and less able to block this motion. Diagnosis of an injury to a specific ligament is performed at a joint position at which other structures are the most lax and least able to block the abnormal subluxation from the ligament injury. The lax secondary restraints allow an increase in joint motion before they become taut and resist further joint motion. Thus, isolating a ligament so its integrity may be individually tested requires placing the knee in a position in which other supporting structures are slack.

Another example of the importance of selecting the joint position for clinical tests is the diagnosis of PCL injury. Figure 3-5 shows the amount of increased posterior tibial translation that occurs when the PCL is removed.[10,21,22] The increase in posterior translation is two to three times greater at 90 degrees of flexion than at 20 degrees of flexion. This phenomenon is easily understood using a bumper model analogy in which the amount of joint motion after a ligament is injured depends on the role and function of the remaining ligaments that must ultimately limit the joint motion (Fig. 3-6). Thus, the increase in joint motion that occurs when a ligament is injured reflects the amount of additional joint motion required before the remaining intact ligaments become stretched and are able to limit further motion.

Figure 3-7 illustrates the limits to internal tibial rotation in the knee joint.[21] At 30 degrees of flexion (see Fig. 3-7, *A*), the limits to internal rotation are provided by posteromedial structures, lateral structures, and the ACL all working together. Sectioning either the ACL or the

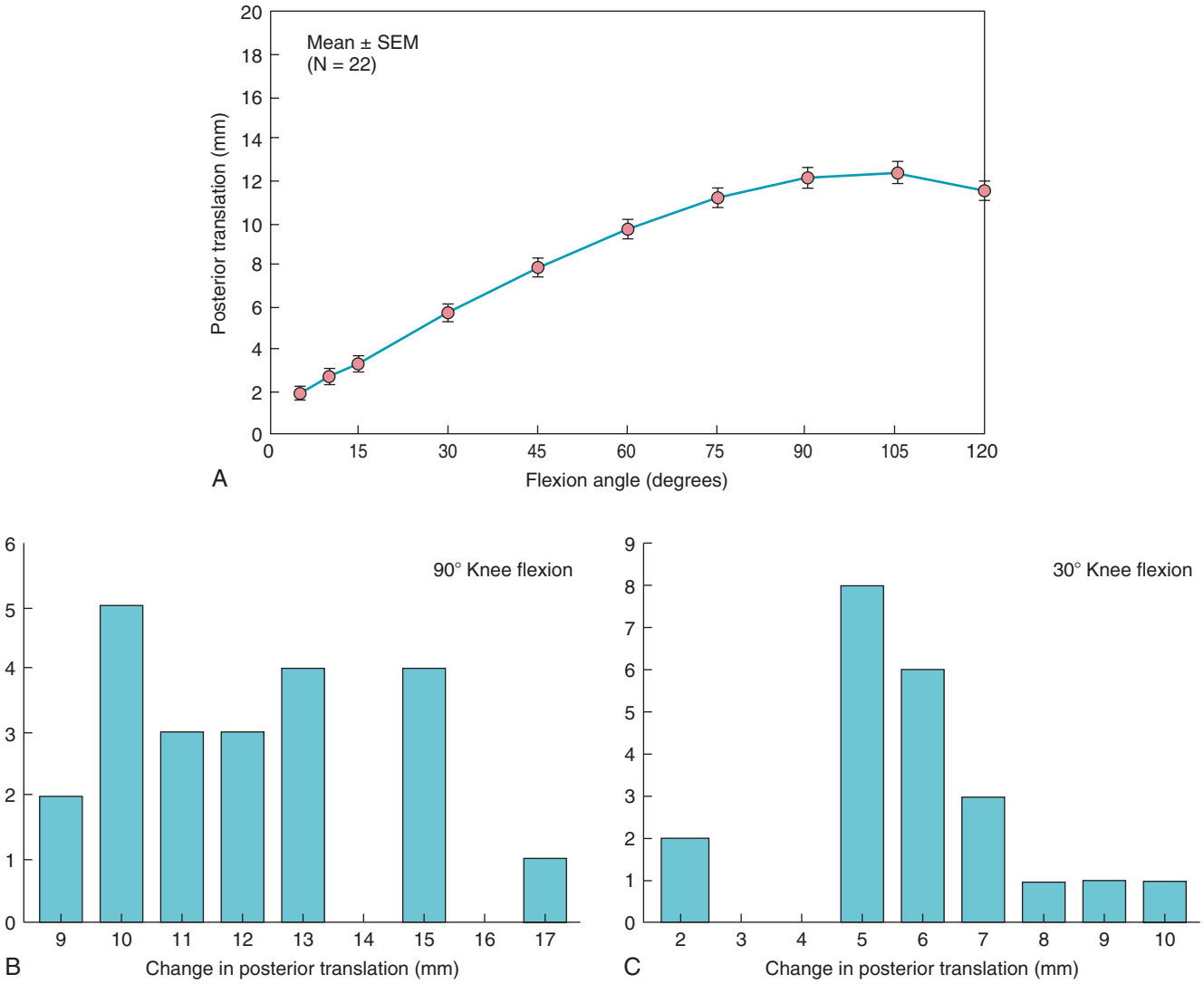


FIG 3-5 **A,** The increase in posterior translation is shown in 22 cadaveric knees under 100 N posterior force applied to the proximal tibia. The posterior force did not constrain the other degrees of freedom. The increase in posterior translation was 5.7 ± 0.4 mm at 30 degrees of flexion (**B**) and 12.1 ± 0.46 at 90 degrees of flexion (**C**). The data show that the majority of knees (15 of 22) that had the posterior cruciate ligament (PCL) sectioned alone had greater than 10 mm of increased posterior translation. This demonstrates the variability in knees in the physiologic tightness or slackness of the secondary restraints in resisting posterior tibial translation after PCL disruption.

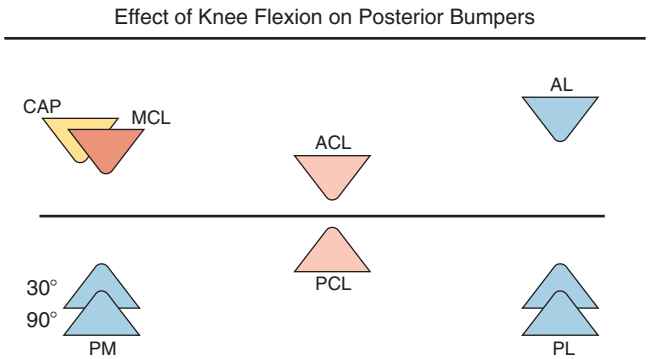


FIG 3-6 Effect of knee flexion on posterior bumpers. After loss of the posterior cruciate ligament (PCL) and as the knee is flexed, the posterior capsular structures become slack, allowing increased tibial displacement before they limit posterior translation. This is shown in the model by the more posterior position of the posteromedial (PM) structures and posterolateral (PL) structures bumpers at 90 degrees compared with 30 degrees of knee flexion. *ACL*, Anterior cruciate ligament; *AL*, anterolateral restraints; *CAP*, capsule; *MCL*, medial collateral ligament; *PM,* posteromedial structures. (From Grood ES, Noyes FR. Diagnosis of knee ligament injuries: biomechanical precepts. In Feagin J, editor: *The Crucial Ligaments.* New York: Churchill Livingstone; 1988:245-260.)

lateral structures produces a small increase in internal rotation. When both of these structures are cut together, a larger increase in internal rotation occurs. The further limit to internal rotation is the FCL, based on its anatomy.

The ACL dominates at flexion angles less than 30 degrees, whereas the lateral structures dominate at flexion angles greater than 30 degrees. This can be explained by considering the changes that occur in ligament slackness with flexion and extension. As the knee is extended past 20 degrees, the amount of AP translation decreases owing to reduction in the combined slackness of both cruciate ligaments. This brings these bumpers closer together. The posteromedial capsule (PMC) also tightens, moving its bumper anteriorly. This combination (see Fig. 3-7, *B*) results in a decreased role of the anterolateral structures because the tibia can no longer rotate to the point where it becomes taut.

With flexion beyond 30 degrees, the lateral structures become progressively tighter and the posteromedial structures become progressively slack. This combination causes internal rotation to be limited first by the extraarticular restraints, and is consistent with laboratory results showing that sectioning the ACL alone does not increase internal rotation when the knee is flexed between 40 and 80 degrees.

Figure 3-8 illustrates the limits to external rotation. At 30 degrees of flexion, external rotation is limited only by the extraarticular restraints. On the lateral side, this includes all of the posterolateral structures, which act as a unit. Large increases in rotation do not occur until all structures are cut. At 90 degrees of flexion, the posterior capsule is slack and the PCL blocks significant increases in external rotation when the posterolateral structures are sectioned. In laboratory studies, external rotation increases an average of only 5.3 ± 2.6 degrees when all of the posterolateral structures are sectioned and the PCL is intact. When the PCL is also sectioned, a large additional increase in external rotation occurs, ranging from 15 to 20 degrees.

An example of the changes in motion limits in ACL ruptures is shown in Figure 3-9. In cadaver knees, cutting the ACL causes an abnormal increase in both anterior tibial translation and internal tibial rotation.[6] The increase in anterior tibial translation is the primary abnormality, because it increases 100% while there is a small increase in internal rotation (approximately 15%). Cutting the ACL alone produced a small but significant increase in internal rotation, greatest at 0 and 15 degrees (Fig. 3-10). Subsequently, sectioning the ITB and lateral capsule produced statistically significant increases at 30 degrees and greater.

Coupled motions (anterior tibial translation, internal tibial rotation) occur in cadaver knees after sectioning the ACL and lateral extraarticular structures. Coupled motions can be caused by factors intrinsic to the knee or by the manner in which the clinical test is performed. For instance, the amount of internal tibial rotation elicited depends on the amount of rotation the clinician applies during the examination. This is why it is difficult to obtain reproducible results with the Lachman and other clinical tests. The KT-2000 (MEDmetric) provides an objective measurement of the amount of tibial translation measured at the center of the tibia. However, the millimeters produced by this device do not include the added millimeters of translation at the lateral tibiofemoral joint with added internal tibial rotation, such as that produced during the pivot shift test.

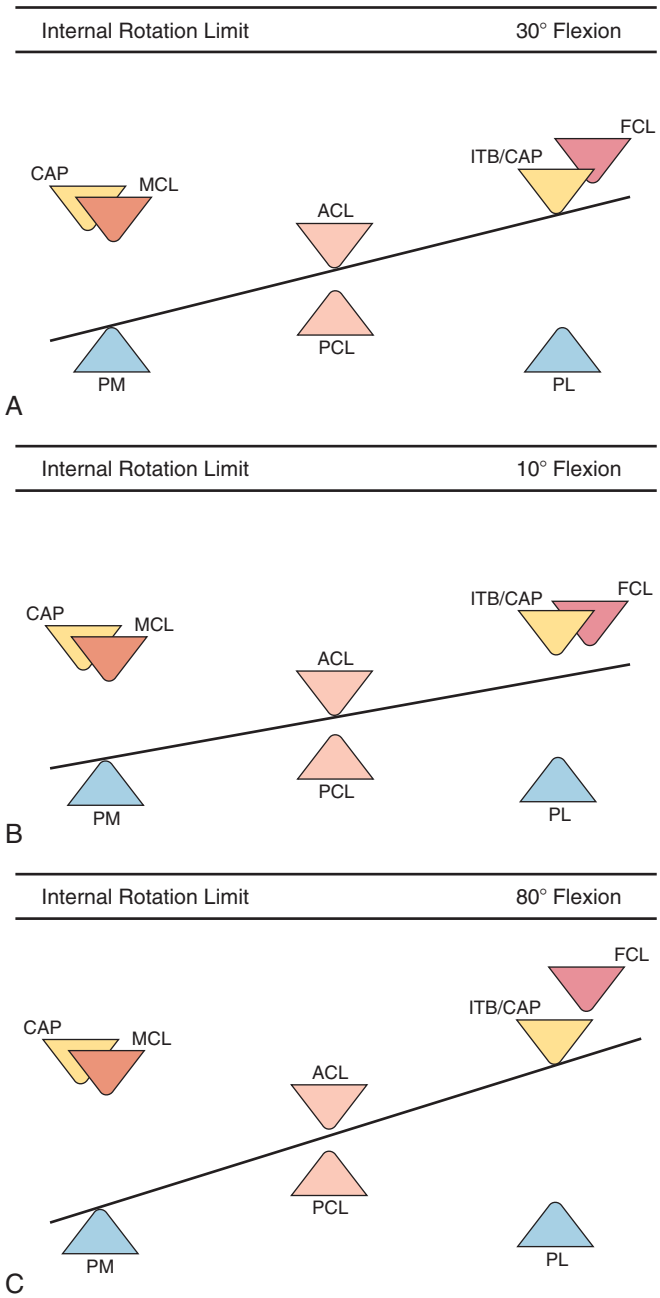


FIG 3-7 Limits to internal rotation. **A,** At 30 degrees of flexion, internal rotation is limited by the anterior cruciate ligament (ACL) centrally and the lateral restraints. These structures limit anterior translation. In addition, the posterior translation of the medial plateau is limited by the posteromedial (PM) restraints. **B,** At 10 degrees of flexion, the posterior bumpers move in closer toward the posterior cruciate ligament (PCL) owing to a reduction in the slackness present in the posterior capsule. In addition, the ACL bumper moves posteriorly as a result of tightening the ACL/PCL complex. Because of this, internal rotation of the tibia is now limited by the ACL centrally and the PM restraints alone. The tibia can no longer rotate far enough to engage the lateral restraints. **C,** At 80 degrees of flexion, the posterior bumpers move further posterior, reflecting the increased slackness in the posterior capsule. In addition, the distance between the ACL and PCL bumpers has increased slightly to reflect the increased laxity of these structures. The medial and lateral structures are now moved posteriorly as a result of tightening of the extraarticular restraints with knee flexion. Internal rotation is now limited by the lateral and PM restraints without direct involvement with the ACL. *CAP,* Capsule; *FCL,* fibular collateral ligament; *ITB,* iliotibial band; *MCL,* medial collateral ligament; *PL,* posterolateral structures. (From Grood ES, Noyes FR. Diagnosis of knee ligament injuries: biomechanical precepts. In Feagin J, editor: *The Crucial Ligaments.* New York: Churchill Livingstone; 1988:245-260.)

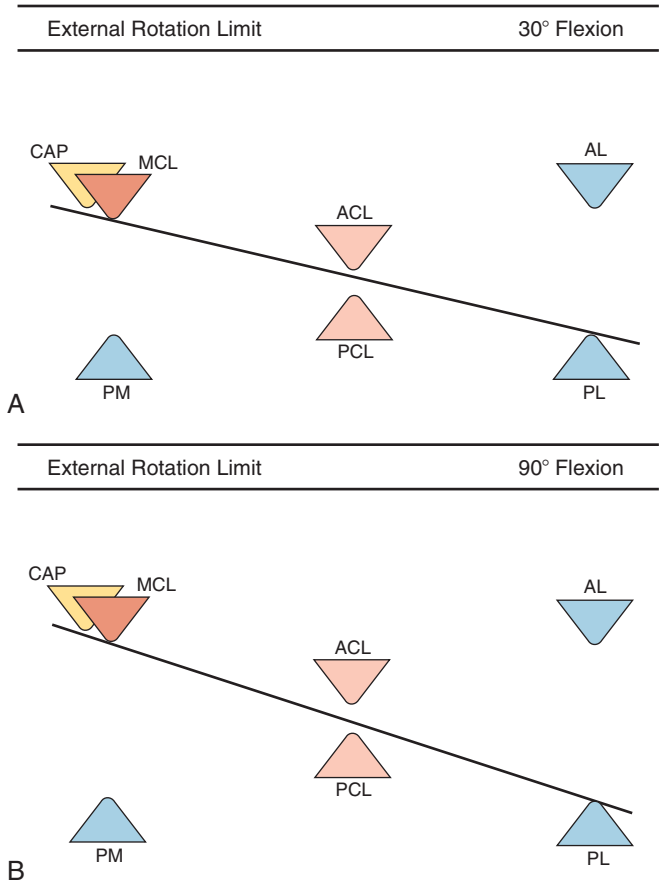


FIG 3-8 Limits to external rotation. **A,** At 30 degrees of flexion, the external rotation of the tibia is limited by the bumpers that stop anterior translation of the medial plateau and posterior translation of the lateral plateau. Owing to the position of the structures, there is no direct involvement of either the anterior cruciate ligament (ACL) or posterior cruciate ligament (PCL) in limiting external rotation. **B,** At 90 degrees of flexion, the posterior bumpers are moved posterior, reflecting the increased slack in the posterior capsule. Because of this, the PCL is nearly taut at the limit of external rotation. After removing the posterolateral (PL) restraints, only a small increase in external rotation occurs at this flexion angle. *AL,* Anterolateral; *CAP,* capsule; *MCL,* medial collateral ligament; PM, posteromedial structures. (From Grood ES, Noyes FR. Diagnosis of knee ligament injuries: biomechanical precepts. In Feagin, J. [ed.]: *The Crucial Ligaments.* New York: Churchill Livingstone; 1988:245-260.)

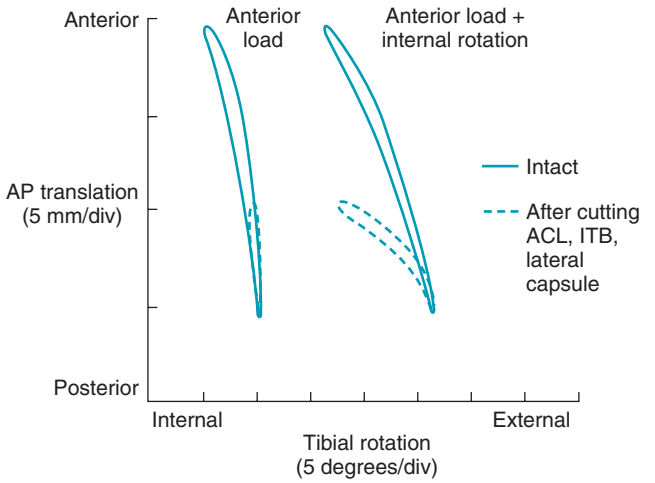


FIG 3-9 Anterior translation versus tibial rotation is shown during the Lachman-type anterior loading test at 15 degrees of knee flexion. The amount of anterior tibial translation is shown vertically and the position of tibial rotation is shown horizontally. *ACL,* Anterior cruciate ligament; *AP,* anteroposterior; div, division; *ITB,* iliotibial band. (From Noyes FR, Grood ES. Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. In Griffin P, editor: *AAOS Instructional Course Lectures,* Vol XXXVI. Chicago: American Academy of Orthopaedic Surgeons; 1987:185-200.)

The amount of anterior tibial translation induced during anterior drawer testing is dependent on the amount of internal or external tibial rotation applied at the beginning of the test (Fig. 3-11). The instrumented knee joint is shown for measuring rotations and translation motions during the clinical examination in Figure 3-12. This is because rotation tightens the extraarticular secondary restraints. The greatest amount of anterior or posterior tibial translation will be produced when the tibia is not forcibly rotated internally or externally, tightening extraarticular structures, during the clinical test. If the tibia is internally or externally rotated before the start of testing, the amount of tibial translation elicited will be smaller. Thus the clinician controls the amount of translation by both the initial rotational position of the tibia and by the amount of rotation imposed during the test. There is considerable variation in examination techniques of clinicians that makes all of the clinical tests highly subjective and qualitative, as is discussed.

The pivot shift[14] and flexion-rotation[59] drawer tests involve a complex set of tibial rotations and AP translations (Fig. 3-13). At the beginning of the flexion-rotation drawer test, the lower extremity is simply supported against gravity (Fig. 3-14, position A). After ligament sectioning, both anterior tibial translation and internal rotation increase as the femur drops back and externally rotates into a subluxated position.[57] This position is accentuated as the tibia is lifted anteriorly (Fig. 3-14, position B). At approximately 30 degrees of flexion, the tibia is pushed posteriorly, reducing the tibia into a normal relationship with the femur (Fig. 3-14, position C). This is the limit of posterior tibial translation resisted primarily by the PCL. From position C to position A, the knee is extended to produce the subluxated position again.

The rotational component of the test can be purposely accentuated by the examiner, inducing a rolling motion of the femur. One advantage of the flexion-rotation drawer test is that it is not necessary to produce joint compression or add a lateral abduction force required in the pivot shift test. The rolling motion avoids the sometimes painful "thud/clunk" phenomenon induced in the pivot shift test. A finger may also be placed along the anterior aspect of the lateral and medial plateau and the tibiofemoral step-off palpated to provide a qualitative estimate of the millimeters of anterior tibial subluxation. The examiner can easily visualize the translation and rotation motions. Translation is observed by watching the forward motion of the tibial plateaus. Rotation is observed by watching the patella rotate externally with the femur in the subluxated position and internally in the reduced position.

The pivot shift and flexion-rotation drawer tests are graded only in qualitative terms because it is not possible to determine accurately the actual amount of internal tibial rotation or anterior translation elicited. A fully positive pivot shift test (grade III) indicates a gross subluxation of the lateral tibiofemoral articulation along with an increased anterior displacement of the medial tibial plateau (Table 3-2). The amount of anterior subluxation elicited is indicative of rupture to the ACL and laxity to the secondary extraarticular restraints. The lateral

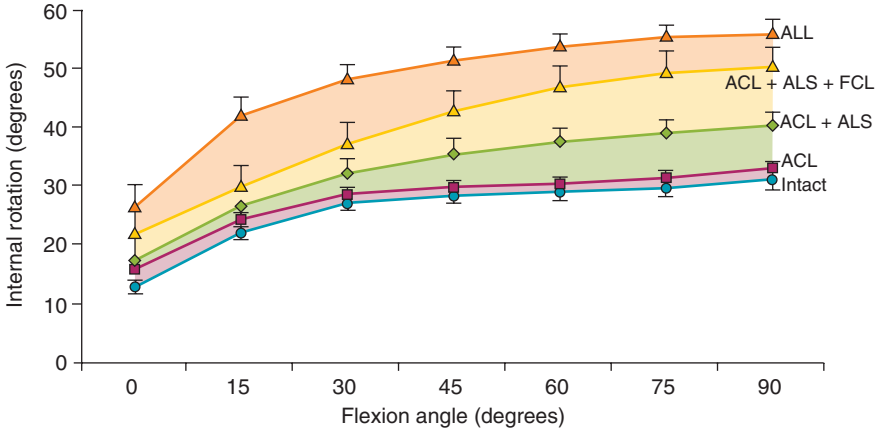


FIG 3-10 Limits of internal rotation with 5 N-m moment for intact specimens and with the anterior cruciate ligament (ACL), ACL/anterolateral structures (ALS), fibular collateral ligament (FCL), and anterolateral ligament (ALL) structures (ACL/ALS/FCL/posterolateral structures [PLS]) cut. Increases in internal rotation with the ACL cut are all statistically significant, but the magnitude of these increases is so small that they are clinically unimportant. With ACL/ALS sectioning, increases in internal rotation are statistically significant at 30 degrees of flexion and above. Statistically significant increases are found at 15 degrees of flexion and above in the ACL/ALS, FCL cut state, and at all flexion angles of the ALL cut state. The effect of the PLS on restraining internal rotation in the extended knee can be seen by comparing the ACL/ALS/FCL curve and the ALL cut curve. The difference between these curves reflects sectioning the PLS. The largest differences are found at 15 and 30 degrees of flexion. (From Wroble RR, Grood ES, Cummings JS, et al. The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee. *Am J Sports Med.* 1993;21:257-263.)

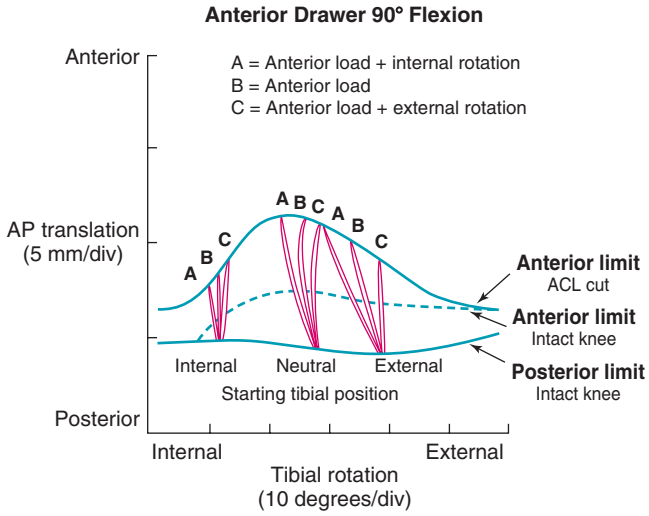


FIG 3-11 The amount of anteroposterior (AP) translation depends on the rotational position of the tibia at the beginning of the anterior drawer test. ACL, Anterior cruciate ligament; div, division. (From Noyes FR, Grood ES. Classification of ligament injuries: Why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. In Griffin P, editor: *AAOS Instructional Course Lectures,* Vol XXXVI. Chicago: American Academy of Orthopaedic Surgeons; 1987:185-200.)

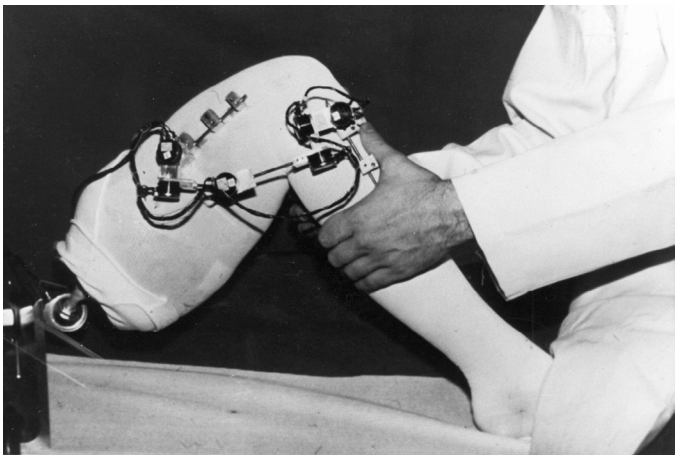


FIG 3-12 The six degrees of freedom electrogoniometer provides the clinician with immediate feedback on the motions induced during the manual drawer tests. (From Noyes FR, Grood ES. Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. In Griffin P, editor: *AAOS Instructional Course Lectures,* Vol XXXVI. Chicago: American Academy of Orthopaedic Surgeons; 1987:185-200.)

tibial plateau demonstrates the greater subluxation in a positive pivot shift test, indicating that the lateral restraints (ITB, lateral capsule) are not functionally tight. This does not mean that these restraints are injured because a physiologic slackness of the ITB tibiofemoral attachments is normal at the knee flexion position used in this test. These attachments are tightest at knee flexion angles 45 degrees and higher. Therefore the majority of knees with an isolated ACL tear will have a positive pivot shift phenomenon.

In knees with a grade III pivot shift, the amount of anterior tibial subluxation is so great that the posterior margin of the lateral tibial plateau impinges against the lateral femoral condyle and blocks further knee flexion during the test. The examiner must add both a maximal anterior force and internal tibial rotation force to determine whether the maximum subluxation position can be reached. In revision ACL reconstructions, a combined intraarticular graft and extraarticular ITB surgical approach is often considered.[48]

In a small percentage of knees with ACL ruptures, the classic "thud" or "clunk" will not be elicited during the pivot shift test. An

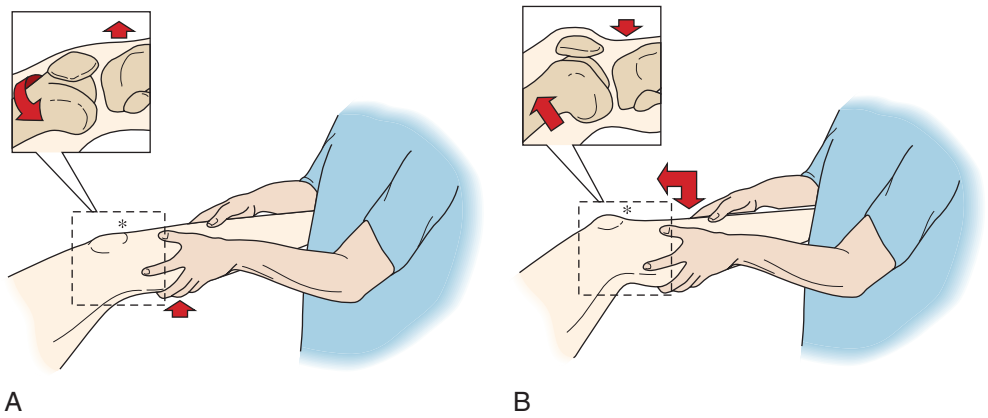


FIG 3-13 A, Flexion-rotation drawer test, subluxated position. With the leg held in neutral rotation, the weight of the thigh causes the femur to drop back posteriorly and rotate externally, producing anterior subluxation of the lateral tibial plateau. **B,** Flexion-rotation drawer test, reduced position. Gentle flexion and a downward push on the leg reduces the subluxation. This test allows the coupled motion of anterior translation-internal rotation to produce anterior subluxation of the lateral tibial condyle. (From Noyes FR, Bassett RW, Grood ES, et al. Arthroscopy in acute traumatic hemarthrosis of the knee. *J Bone Joint Surg Am.* 1980;62:687-695.)

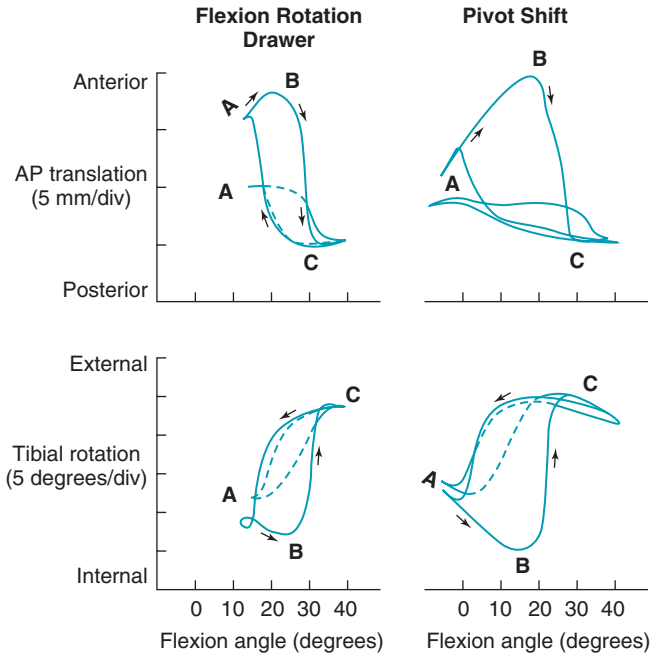


FIG 3-14 The knee motions during the flexion-rotation drawer and pivot shift tests are shown for tibial translation and rotation during knee flexion. The clinical test is shown for the normal knee (*solid-line waveform*) and after ligament sectioning (*dotted-line waveform*). The ligaments sectioned were the anterior cruciate ligament, iliotibial band, and lateral capsule. Position A is the starting position of the test, B is the maximum subluxated position, and C indicates the reduced position. The pivot shift test involves the examiner applying a larger anterior translation load, which increases the motion limits during the test. div, Division. (From Noyes FR, Grood ES, Suntay WJ. Three-dimensional motion analysis of clinical stress tests for anterior knee subluxations. *Acta Orthop Scand.* 1989;60:308-318.)

experienced examiner will detect an increased slipping sensation in the knee (grade I), which indicates that the extraarticular secondary restraints are physiologically tight, limiting the amount of anterior tibial subluxation, or that a partial ACL tear exists.

Concept 6: Rotatory Subluxations Are Characterized by the Separate Compartment Translations That Occur to the Medial and Lateral Tibial Plateaus During the Clinical Test

A simple concept may assist in explaining the abnormal motions that occur after ACL rupture: rotatory subluxations can be classified according to the amount of anterior and posterior translation of each tibiofemoral compartment. Figure 3-15, *A* shows a Lachman test performed on a knee in which the combined motions of anterior tibial translation and internal tibial rotation occur about a medially located rotation axis. In this example, only planar motion occurs; the ACL rupture doubles the amount of anterior tibial translation and slightly increases internal tibial rotation. The rotation axis shifts medially. The ratio of tibial translation to degrees of internal tibial rotation determines how far medially the axis of rotation shifts.

The abnormalities in tibial rotation and translation are easily expressed in terms of the different amounts of anterior translation that occur to the medial and lateral compartments (see Fig. 3-15, *B*) in biomechanical tests. During the clinical tests, the clinician may qualitatively palpate and observe the anterior or posterior translation of each tibial plateau. The AP translation of each plateau is characterized instead of defining the individual components of translation, rotation, and rotation axis location that all lead to the anterior subluxation. The combined effect of the rotation and translation determines the translation of the medial and lateral tibiofemoral compartments.

The type of rotatory subluxations that occur depends on both the ligament injury and the knee flexion position. The subluxations of the medial and lateral compartment are usually recorded at two knee flexion positions, such as 20 and 90 degrees. Described later is the dial test for posterolateral injuries, in which the examiner determines whether increases in external tibial rotation reflect anteromedial or posterolateral tibial subluxations. It should be noted that rotatory

TABLE 3-2 Classification of Pivot Shift Test Grades

	STRUCTURES INVOLVED				
Test Grade	Anterior Cruciate Ligament	Iliotibial Band, Lateral Capsule	Medial Ligaments, Capsule	Positive Tests	Comments
Normal	Intact	Intact	Intact		
I	Intact to slight increase in laxity	Intact	Intact	Lachman, flexion-rotation drawer, pivot shift "slip" but not "jerk"	Either physiologic laxity or partial ACL laxity allow subtle subluxation-reduction phenomena. Secondary ligament restraints limit the amount of joint subluxation. Subluxation is detected as a "slip," indicating increased lateral compartment translation.
II	Ruptured	Intact to slight increase in laxity	Intact	All tests	Hallmark is an obvious "jump," "thud," or "jerk" with the gross subluxation-reduction during the test. There is either a normal physiologic laxity (lateral capsule, iliotibial band) or injured secondary restraints.
III	Ruptured	Significant increase in laxity	May have increase in laxity	All tests	Hallmark is a gross subluxation with impingement of the posterior aspect of the lateral tibial plateau against the femoral condyle. The examiner must decrease internal rotational torque on the leg to allow lateral tibiofemoral reduction and further knee flexion.

ACL, Anterior cruciate ligament.

subluxations are historically based on increases in tibial internal or external rotation, and only in a few studies have the actual medial and lateral tibial subluxations in an AP direction been determined.[21,60] There are complex rotatory subluxations involving increases in translation, but in opposite directions of both the medial and lateral compartments with combined medial and lateral ligament injuries.

Robotic Studies

There have been numerous in vitro and in vivo studies published over the past decade on ACL function in regard to providing rotational knee stability.[12,25,35,38,41,75,81] Based on the results of these studies, recommendations for ACL single- and double-bundle graft reconstructions, graft placement, and tensioning have been published.[12,13,25,34,35,38,41,43,75,80,81] These investigations involved a simulated Lachman test and, more importantly, the pivot shift test, which correlates with patient-subjective giving-way symptoms. In our opinion, there are problematic errors in many studies of which the surgeon should be aware in terms of application of the results to surgical treatment of ACL ruptures. For example, nearly all published studies describe rotational knee stability according to the changes in degrees of internal tibial rotation without measuring the center of tibial rotation or the position or subluxation of the tibiofemoral compartments. We believe that providing only the changes in degrees of tibial rotation, without specification of the medial and lateral tibiofemoral compartment position or subluxation, is an inadequate descriptor of rotational knee stability. In fact, after ACL rupture, there is a change of only a few degrees of internal tibial rotation as long as the lateral extraarticular structures remain intact.[7,54,62,63]

A second problem we have identified in a majority of in vivo and in vitro pivot shift studies is the loading profile used to induce anterior tibial subluxation. Studies commonly report, in the pivot shift simulation, an abnormal anterior tibial translation after ACL sectioning that is only half that obtained in the Lachman test. However, under clinical conditions, a positive pivot shift test produces greater anterior tibial subluxation than the Lachman test. Accordingly, these prior studies were conducted under low knee displacement conditions in which the loading profile involved an internal rotation-valgus condition during knee extension to produce anterior tibial subluxation. There was an absence of a simultaneous combined anterior tibial loading, which is important in the clinical pivot shift test to induce anterior tibial subluxation of both the lateral and medial tibiofemoral compartments.

Bedi and colleagues[3] reported (from in vitro and in vivo pivot shift studies) that the magnitude of lateral compartment translation showed a correlation with the clinical grade of the pivot shift and that a threshold of 6 to 7 mm was necessary to produce a positive pivot shift. This study measured both lateral and medial compartment translations. The mechanized pivot shift involved only small increases in medial tibiofemoral compartment translations, reflecting an internal rotation torque in the absence of anterior tibial loading. ACL sectioning failed to produce a positive pivot shift (grade II) in nearly all specimens, which limits interpretation of these data.

For reasons not apparent, pivot shift loading with a predominant internal rotation-valgus torque, without a coupled anterior tibial loading, has been the typical loading profile in nearly all cadaveric studies on ACL function and surgical reconstructions even though this limits anterior tibial subluxation of the medial compartment. In Figure 3-16, the results of a typical cadaveric knee specimen are shown under two pivot shift loading conditions. Two points are important. In the two simulated pivot shift tests, there is a greater anterior tibial subluxation of the lateral and medial compartment, with the pivot shift subluxation produced by a coupled anterior translation–internal rotation during the valgus loading (pivot shift [PS] 4), compared with an absence of the anterior tibial loading component (PS 3). Second, an analysis of rotational knee stability requires knowledge of the resulting subluxations (translations) of the medial and lateral tibiofemoral compartments. We recommend that future in vitro and in vivo pivot shift studies use loading profiles of coupled anterior tibial translation and

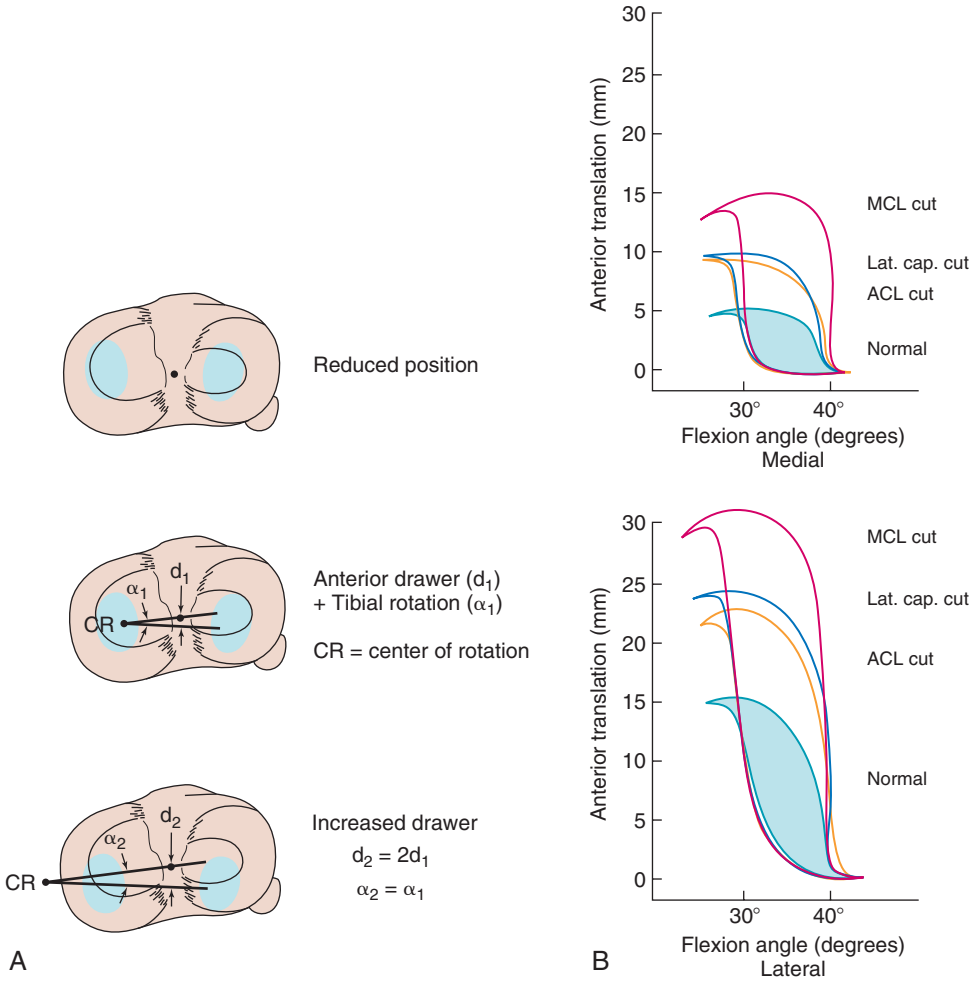


FIG 3-15 **A,** A simplification of the abnormal knee motions after anterior cruciate ligament (ACL) sectioning. An understanding of rotatory subluxations requires specifying changes in (1) position of the vertical axis of rotation and (2) displacement of the medial and lateral tibiofemoral compartments. The normal or subluxated position of the joint is determined by the degrees of rotation and the amount of translation. In the figure, an anterior pull is applied to the knee, which has an intact ACL. There is a normal anterior translation (d_1) and internal tibial rotation (α_1) about the center of rotation (CR). After ACL sectioning, there is a 100% increase in tibial translation (d_2) along with only a slight (15%) increase in internal tibial rotation (α_2). This shifts the axis of rotation medially and produces the subluxation of the lateral compartment and medial compartment as demonstrated. Loss of the medial extraarticular restraints would result in a further medial shift in the axis of rotation. This would increase the anterior subluxation of the medial tibial plateau and lateral tibial plateau. **B,** The amount of anterior tibial translation is shown for the medial and lateral tibiofemoral compartments during the flexion-rotation drawer test in a cadaveric knee preparation using the instrumented spatial linkage and digitization of the tibial and femoral joint geometry. *ACL,* Anterior cruciate ligament; *Lat. cap.,* lateral capsule; *MCL,* medial collateral ligament. (***A,*** From Noyes FR, Grood ES. Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. In Griffin P, editor: *AAOS Instructional Course Lectures,* Vol XXXVI. Chicago: American Academy of Orthopaedic Surgeons; 1987:185-200; ***B,*** From Noyes FR, Grood ES, Suntay WJ. Three-dimensional motion analysis of clinical stress tests for anterior knee subluxations. *Acta Orthop Scand.* 1989;60:308-318.)

internal tibial rotation, along with valgus loading, to induce a maximum anterior tibial subluxation of both tibiofemoral compartments. Furthermore, rotational torques should remain low in order not to constrain the maximum subluxation of the medial compartment.

We conducted a series of robotic cadaveric in vitro studies on the kinematic function of the ACL.[15,24,55] The studies involved a six-DOF robotic testing protocol on intact knees, ACL-sectioned knees, and ACL-reconstructed knees. The robotic testing protocol involved, for the first time, the simulation of the pivot shift event using four DOF—namely, anterior tibial translation with internal tibial rotation with valgus loading of the limb during knee flexion-extension to induce maximum anterior tibial subluxation (PS 4). The study also involved, for the first time, digitization of the tibial plateau to determine medial and lateral tibiofemoral compartment translations and centers of tibial rotation in the simulated pivot shift test.

The studies that found a single ACL graft placed into the anatomic center of the femoral and tibial attachment sites restored normal tibiofemoral compartment translations and rotations under simulated Lachman and pivot shift testing conditions. The reconstruction restored rotational stability as defined by normal motion limits and

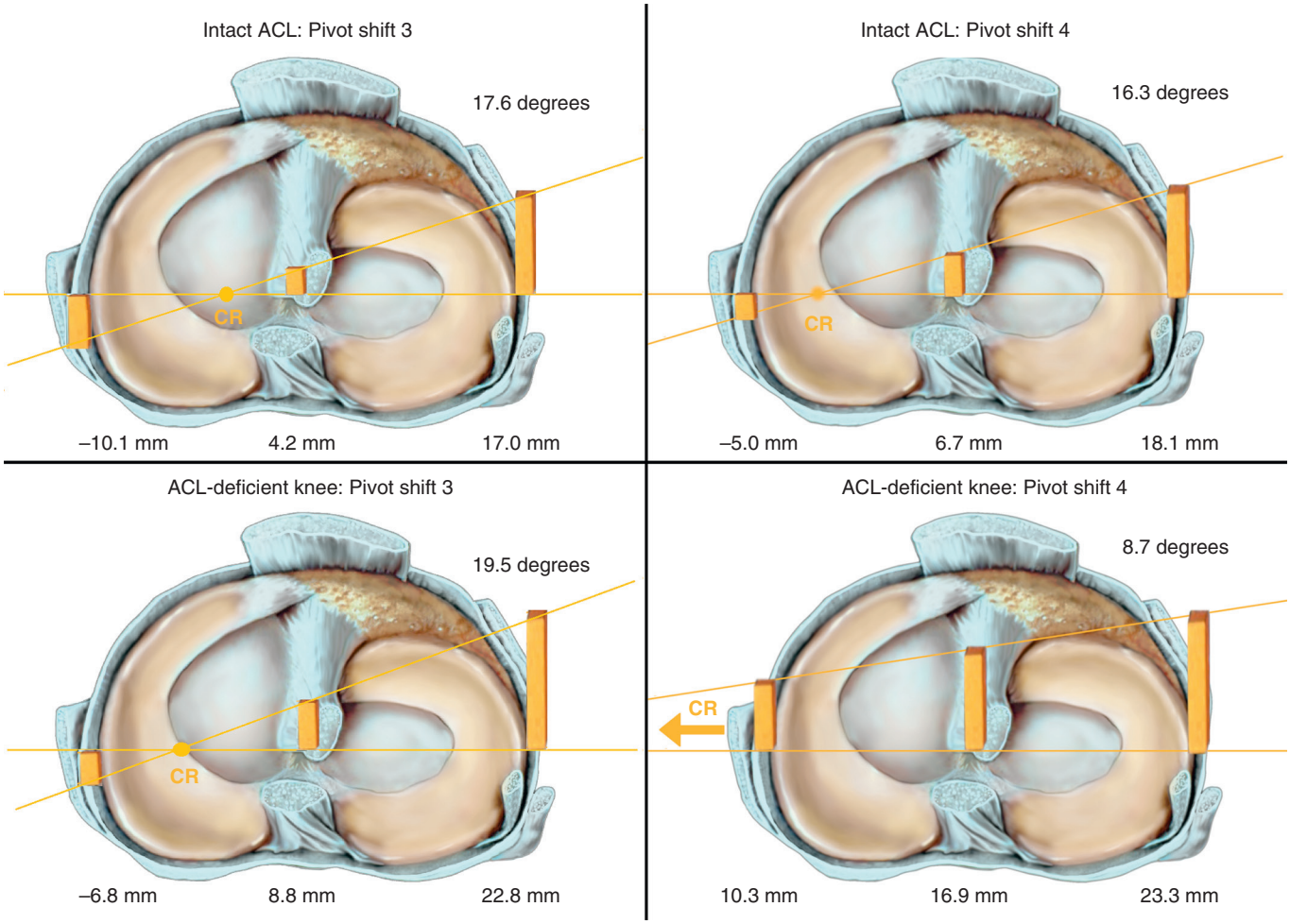


FIG 3-16 A representative right knee specimen showing compartment translations and tibial rotation under two loading conditions: pivot shift 3 and pivot shift 4. In the pivot shift 3 loading, there is no subluxation of the medial tibiofemoral compartment because the anterior tibial loading was of a small magnitude. In contrast, in the pivot shift 4 loading, a major anterior tibial loading is added along with internal rotation-valgus loading. In addition, the internal tibial torque is reduced from 5 to 1 N-m. There is a medial shift in the center of tibial rotation, with subluxation of the medial, center, and lateral tibiofemoral compartments. Loading conditions for pivot shift 3 were 35 N anterior, 5 N-m internal rotation, and 7 N-m valgus. Loading conditions for pivot shift 4 were 100 N anterior, 1 N-m internal rotation, and 7 N-m valgus. *ACL,* Anterior cruciate ligament; *CR,* center of tibial rotation.

normal medial and lateral compartment translations under simulated pivot shift loading conditions (Fig. 3-17). The results support the recommendation for the use of a single ACL graft instead of a double-bundle ACL graft construct (see Chapter 7).

Concept 7: Damage to Each Ligament and Capsular Structure Is Diagnosed Using Tests in Which the Primary and Secondary Ligament Restraints Have Been Experimentally Determined

Tears to the ACL and injury to the extraarticular ligamentous and capsular structures may be diagnosed using the Lachman, pivot shift, and flexion-rotation drawer tests. These tests provide the basic signs that allow the clinician to determine which structures are injured based on abnormal motion limits and resultant joint subluxations. The tests are performed in knee flexion positions in which the secondary restraints are unable to resist abnormal motions so that maximum displacement (subluxation) of the joint is produced. Table 3-3 provides a general summary of the primary and secondary restraints for the major tests used in the clinical examination. Later in this chapter, the specific restraining function of the ligaments is discussed in detail.

The qualitative grading of the pivot shift phenomenon is illustrated in Figure 3-18 to explain how ligament structures resist combined tibiofemoral motions. The cruciate ligaments are represented by a set of central bumpers that limit the amount of AP translation. There are also medial and lateral sets of bumpers that resist medial and lateral tibiofemoral compartment translations. For the medial and lateral bumpers, different ligament structures commonly work together as systems to provide the resistance. The bumpers represent not the anatomic position of the ligament structures, but rather a visual schematic to show the final restraints to tibial motion, summarizing the effect of the ligaments, menisci, and capsular structures. The tension-restraining effect of the ligaments is replaced by an opposite mechanism, a compressive bumper.

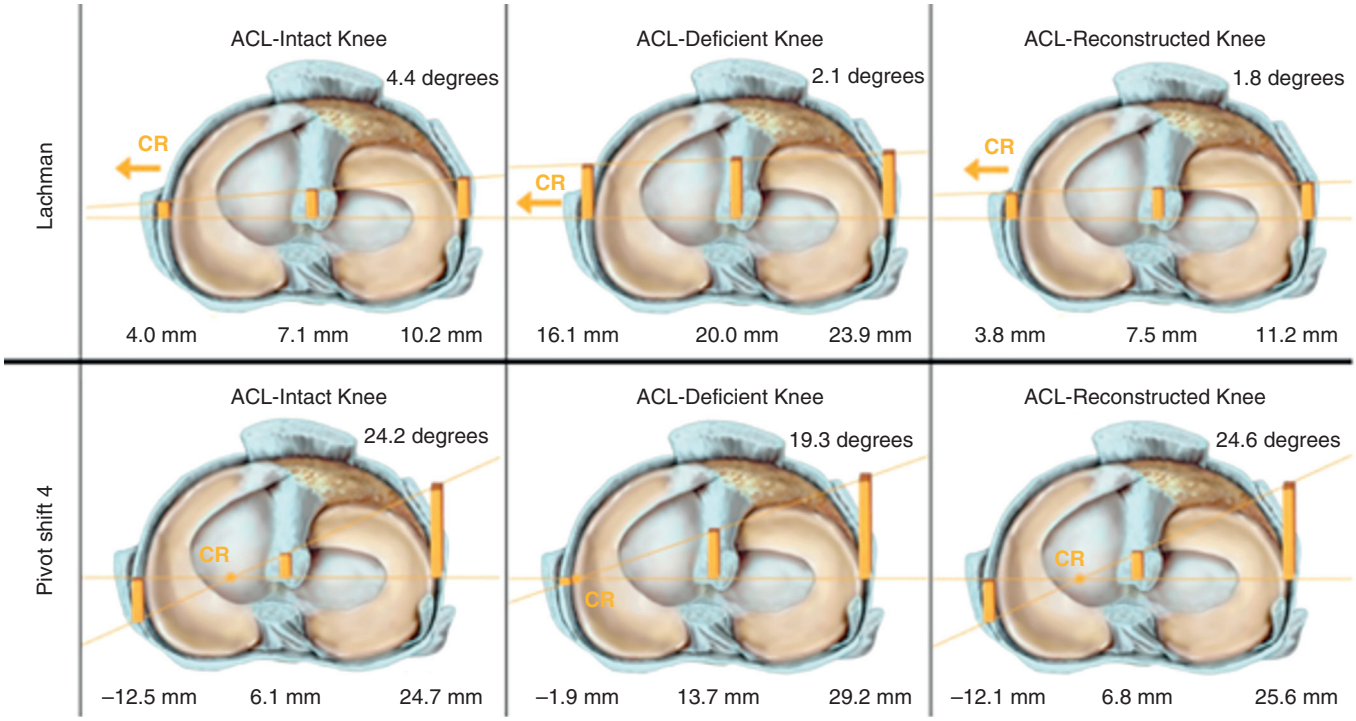


FIG 3-17 Compartment maps of a representative right knee specimen under the Lachman and simulated pivot shift test for intact, anterior cruciate ligament (ACL) deficient, and central anatomic bone-patellar tendon-bone reconstructed conditions. The data from this study showed a restoration of normal tibiofemoral compartment translation after ACL reconstruction. Loading conditions: Lachman anterior translation, 100 N; pivot shift anterior translation, 100 N; internal rotation, 1 N-m; valgus, 7 N-m. *CR*, Center of tibial rotation.

TABLE 3-3 Ligamentous Restraints of the Knee Joint

	PRIMARY RESTRAINT				SECONDARY RESTRAINT		
Clinical Test	**Medial**	**Central**	**Lateral**	**Degrees**	**Medial**	**Central**	**Lateral**
Anterior drawer	—	ACL	—	20/90	MCL	—	ALS
Anterior drawer + internal rotation	—	ACL	ALS	20/90	—	—	ALS + FCL
Anterior drawer + external rotation	MCL	ACL	—	20/90	PMC, MM	—	—
Flexion-rotation drawer, pivot-shift	—	ACL	—	15	MCL, PMC	—	ALS + FCL
Posterior drawer	—	PCL	—	20/90	MCL + PMC	—	FCL + PMTL
Posterior drawer + external rotation	—	PCL	FCL + PMTL	30	MCL	—	LM
Posterior drawer + external rotation	PMC	PCL	FCL + PMTL	90	MCL	—	LM
Posterior drawer + internal rotation	—	—	—	20	PMC + MCL	—	ALS
Posterior drawer + internal rotation	PMC	PCL	—	90	MCL + PMC	—	ALS
Valgus	MCL + PMC	—	Lat TF joint	5	—	PCL + ACL	—
Valgus	MCL	—	Lat TF joint	20	PMC	PCL + ACL	—
Varus	Medial TF joint	—	FCL + PLC + PMTL	5	—	ACL + PCL	—
Varus	Medial TF joint	—	FCL + PMTL	20	—	ACL + PCL	PLC
External rotation	MCL + PMC	—	FCL + PMTL	30	MM	PCL	PLC
External rotation	MCL + PMC	PCL	PMTL + FCL	90	MM	—	PLC
Internal rotation	PMC + MCL	ACL	ALS	20	—	PCL	FCL
Internal rotation	MCL + PMC	ACL	ALS	90	—	PCL	FCL

ACL, Anterior cruciate ligament; *ALS*, iliotibial band + anterior + mid lateral capsule; *FCL*, fibular collateral ligament; *Lat*, lateral; LM, lateral meniscus; *MCL*, superficial medial collateral ligament plus middle one-third deep capsule; *MM*, medial meniscus; *PCL*, posterior cruciate ligament; *PLC*, posterolateral capsule (includes fabellofibular ligament); *PMC*, posteromedial capsule (includes posterior oblique ligament); *PMTL*, popliteus muscle-tendon-ligament; *TF*, tibiofemoral.

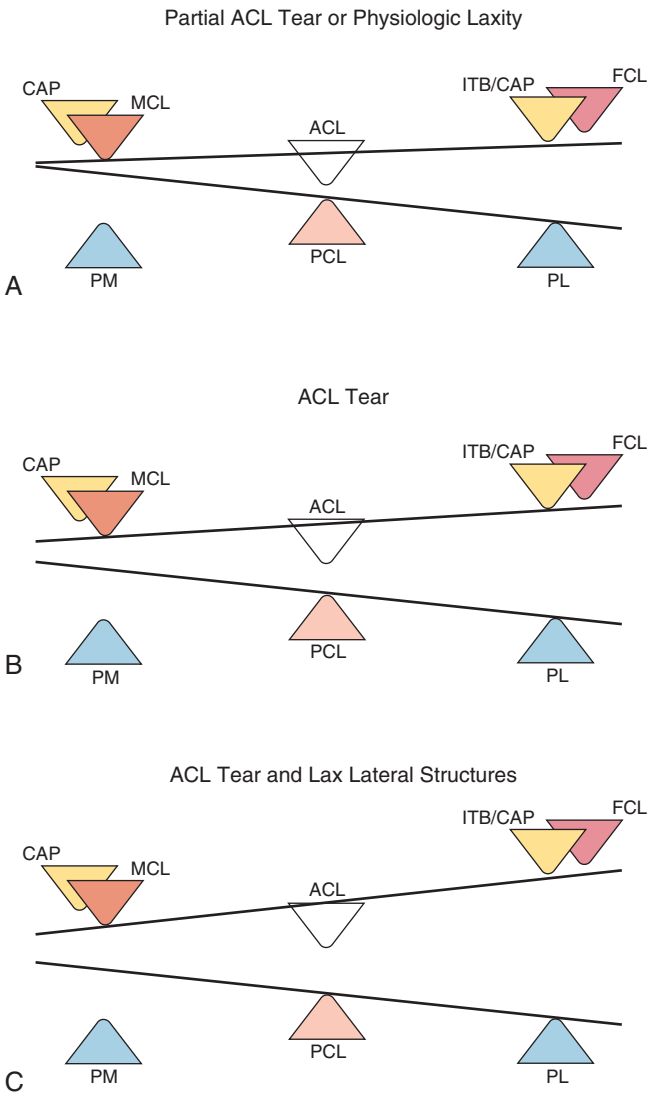


FIG 3-18 **A,** Grade I pivot shift. There is anterior translation of the lateral compartment that is resisted by the anterior cruciate ligament (ACL). There will be a slight increase in anterior translation with a partial ACL tear. Many knees with physiologic ACL laxity have a normal grade I pivot shift. Rarely, a knee will have excessively tight lateral structures that also limit anterior translation, and even with an ACL tear, there is only a grade I pivot shift phenomena. The *lower line* represents the posterior limit of tibial displacement. The *upper line* represents the anterior limit of tibial excursion resisted by the appropriate ligament bumpers. The distance of increased translation to the lateral-central-medial compartments is shown, reflecting the coupled motions of anterior translation and internal rotation. **B,** Grade II pivot shift. This is the usual finding after ACL disruption. The lateral extraarticular structures are physiologically lax between 0 and 45 degrees of knee flexion, allowing for increased anterior translation of the lateral tibiofemoral compartment. The lesion may also involve injury to the lateral structures (iliotibial band [ITB], lateral capsule [CAP]). **C,** Grade III pivot shift. There is associated laxity of the lateral extraarticular restraints. There may also be associated laxity of the medial ligament structures. This allows for a gross subluxation of both the medial and lateral tibial plateaus easily palpable during the pivot shift test, as well as the flexion-rotation drawer and Lachman tests. *ACL,* Anterior cruciate ligament; *CAP,* capsule; *FCL,* fibular collateral ligament; *MCL,* medial collateral ligament; *PCL,* posterior collateral ligament; *PL,* posterolateral structures; *PM,* posteromedial structures. (From Noyes FR, Grood ES. Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. In Griffin P, editor: *AAOS Instructional Course Lectures,* Vol XXXVI. Chicago: American Academy of Orthopaedic Surgeons; 1987:185-200.)

In diagnosing abnormal knee motion limits, the Lachman test involves primarily tibial translation without significant tibial rotation, testing the central bumper represented by the ACL. A bumper model representation of a partial ACL tear or an ACL-deficient knee with tight medial and lateral extraarticular restraints that limit the amount of anterior tibial translation is shown in Figure 3-18, *A*. The amount of central and lateral tibial translation is only slightly increased. The bumper model illustrates how the anterior restraints limit motion during the flexion-rotation drawer test, which allows the maximal anterior excursion of the medial and lateral tibiofemoral compartments. In this knee, the pivot shift is qualitatively listed as a grade I.

The most common type of anterior subluxation that occurs after an ACL rupture is shown in Figure 3-18, *B*. The center of rotation shifts medially outside the knee joint, with a resultant increase in translation to both the medial and lateral compartments, with the anterior subluxation of the lateral compartment being the greatest. The anatomic structures include the ACL and the lateral extraarticular restraints. In this knee, the pivot shift is qualitatively listed as a grade II.

A knee with gross anterior subluxation is represented in Figure 3-18, *C*. There is increased translation and subluxation to both the medial and lateral compartments and the rotation axis shifts even further medially outside the knee joint. The pivot shift test is listed as grade III, indicative of gross subluxation with impingement of the posterior aspect of the tibia against the femoral condyle. Partial damage to the medial ligamentous structures may be present.

LIGAMENTOUS RESTRAINTS TO AP TRANSLATION

In a series of biomechanical cadaveric experiments,[6] the ranked order of the importance of each knee ligament and capsular structure in resisting the clinical anterior and posterior drawer tests was determined, providing the primary and secondary restraints to specific knee motions. The ranked order was based on the force provided by each ligament in resisting AP translation.

Before these experiments, investigators performed studies in which selective sectioning of ligaments was conducted and the

CRITICAL POINTS Ligamentous Restraints to Anteroposterior Translation

- This investigation was the first to introduce the concepts of primary and secondary ligament restraints to joint motion.
- A testing method was developed that allowed the restraining force of each individual ligament to be determined.
- A precise displacement was applied and the resultant restraining force measured.
- The reduction in restraining force that occurred after sectioning a ligament defined its contribution.
- The ACL is the primary restraint to anterior translation, providing 86% of the total restraining force.
- Secondary restraints to anterior tibial translation include the iliotibial tract and band, mid medial capsule, mid lateral capsule, MCL, and FCL. No statistical difference exists among these structures in their contribution.
- The PCL provides 94% of the total restraining force of posterior tibial translation at 90 degrees of knee flexion, with similar findings at 30 degrees of flexion.
- The posterolateral capsule, popliteus tendon, and MCL provide the greatest secondary restraint to posterior tibial translation. The posterior medial capsule, FCL, and mid medial capsule provide only modest secondary restraining contribution.

increases in anterior or posterior tibial displacement were measured.[2,4,11,16,27,40,42,64,67] For example, the displacement test was done by applying a force on an intact knee, cutting a ligament, repeating the test, and measuring the increase in displacement. One problem with this experimental design is that the increase in displacement is dependent on the order in which the ligaments are sectioned. If this order is altered, the measured increase in displacement will change. Therefore, it is not possible to define the function of a single ligament in a precise manner. In addition, the amount of residual joint displacement after ligament sectioning is dependent on the just-taut length of the remaining ligaments, which varies between physiologic "tight" and "loose" knee joints.

To solve these problems, a testing method was developed that allowed the restraining force of each individual ligament to be determined. A precise displacement was applied and the resultant restraining force measured. The reduction in restraining force that occurred after sectioning a ligament defined its contribution. Because the joint displacement was controlled, the contributions of the other ligaments and capsular structures of the knee to the resultant tibial displacement were not affected. Controlling and reproducing the joint displacement from test to test eliminated the effect of the cutting order of the structures. This is because the joint displacement controls the amount of ligament stretch and, thereby, its force. Reproducing the displacement reproduces the force in each ligament. This indicates that even after a single ligament is cut, the remaining structures are unaffected. The reader should distinguish the difference between these two testing methods in ligament sectioning studies because the data provide different conclusions on ligament function.

Fourteen cadaver knees were tested from donors aged 18 to 65 years (mean, 42 years). The knee specimens were mounted in an Instron Model 1321 biaxial servo controlled electrohydraulic testing system (Fig. 3-19). A pair of grips was used for the femur and tibia that allowed for their precise position to be adjusted. First, the femur was secured with its shaft aligned along the axis of the load cell. The tibia was placed horizontally, with its weight supported by the lower grip. The output of the load cell was adjusted to zero to compensate for the weight of the upper grip and femur. The tibia was placed in a rotated position halfway between its limits of internal and external rotation. The output of the load cell was monitored while the tibia was secured to avoid preloading the ligaments. Single-plane anterior and posterior drawer tests were conducted by causing the actuator to move up and down without rotation. This is a constrained test in which coupled tibial rotation is purposely blocked. Specific details regarding the tests and data acquisition and statistical analyses are described in detail elsewhere.[6]

An AP drawer test is shown in Figure 3-20. Two curves are present, one for each direction of motion, as a result of the viscoelastic behavior of the knee ligaments. The peak restraining force of this specimen is approximately 500 N (112 lb) at 5 mm of drawer. The general shape of the force-displacement curve for the intact knee is nonlinear. The stiffness of the knee, or slope of the curve, is smallest near the neutral position and increases as the joint is displaced. The average restraining force in the intact knee is approximately 440 N (95 lb) at 90 degrees of flexion and approximately 333 N (75 lb) at 30 degrees of flexion. This is comparable with forces expected during moderate to strenuous activity and is well above the manual force applied during clinical drawer testing.[39,40]

The effect of sectioning the ACL is shown by the decrease in slope of the anterior curve and increase in displacement in Figure 3-18. Note that the anterior curve does not drop to zero owing to the presence of secondary ligament restraints. The ACL is the primary restraint to anterior translation (Fig. 3-21). Its contribution at displacements from

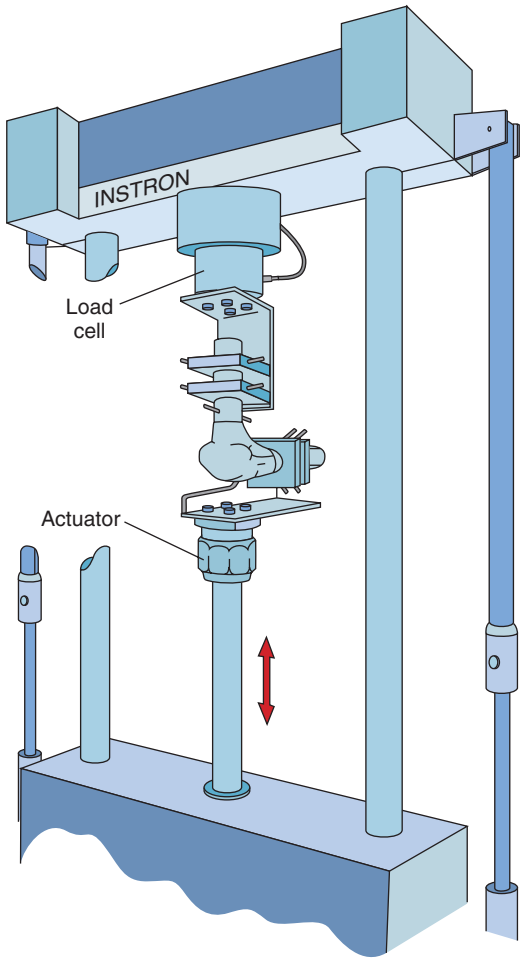


FIG 3-19 Cadaver knee mounted in 90 degrees of flexion. The femur and tibia are potted in aluminum tubes. The femur is secured to the load cell above and the tibia to the moving actuator below. Single-plane anterior and posterior drawer is produced by vertical motion of the actuator. (From Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am.* 1980;62A:259-270.)

1 to 5 mm is shown in Figure 3-22. The percentages given above the bars are for 90 degrees of knee flexion. Nearly identical results are shown at 30 degrees of flexion, which represents the position of the knee during the Lachman test. No significant differences were found between 1 and 5 mm of drawer regardless of the trend toward increasing percentages at larger joint displacements.

The secondary restraints to anterior translation when the ACL is sectioned are shown in Table 3-4. The range in values for each structure demonstrates the large variation in results among specimens. No statistical difference was found among the percentages calculated. The contributions of the PCL, the anterior and posterior capsules, and the popliteal tendon were not included because they provided minimum restraining force.

It is important to characterize the effect of the ACL and secondary restraints on the coupled motions of anterior translation and internal-external tibial rotations. Figure 3-23 shows the effect of the lateral secondary restraints on both anterior translation and internal tibial rotation.

The PCL provides 94.3% ± 2.2% of the total restraining force at 90 degrees of knee flexion, with similar findings at 30 degrees of flexion

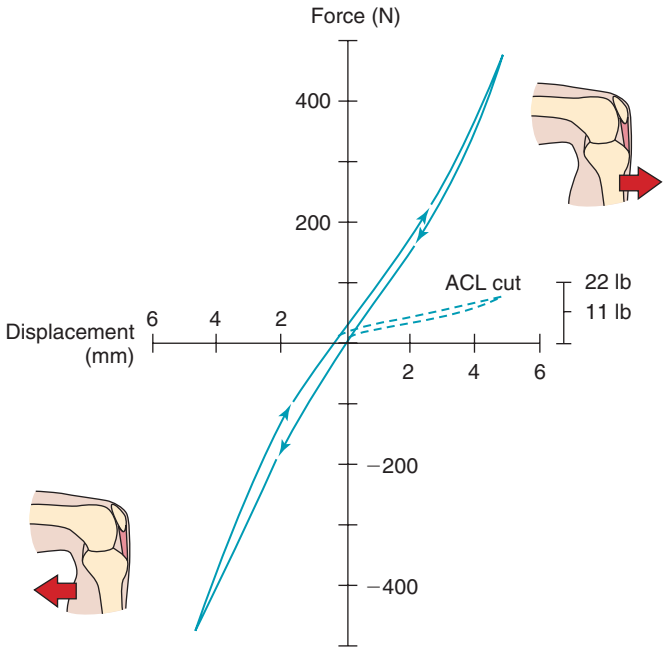


FIG 3-20 A typical force-displacement curve for anterior-posterior drawer in an intact joint (*solid line*) and after cutting the anterior cruciate ligament (ACL) (*dashed line*). The arrows indicate the direction of motion. (From Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am.* 1980;62A:259-270.)

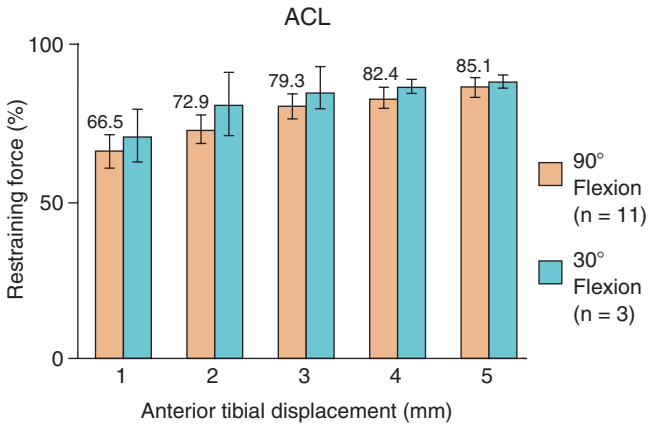


FIG 3-22 Anterior drawer in neutral tibial rotation. The restraining force of the anterior cruciate ligament (ACL) is shown for increasing tibial displacements at 90 and 30 degrees of knee flexion. The mean value ±1 standard error of the mean (SEM) is shown. Percentage values are given for 90 degrees of flexion. No statistical difference was found between 90 and 30 degrees or between 1 and 5 mm of displacement using the Welch modification of the Student t test ($P > .05$). (From Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am.* 1980;62A:259-270.)

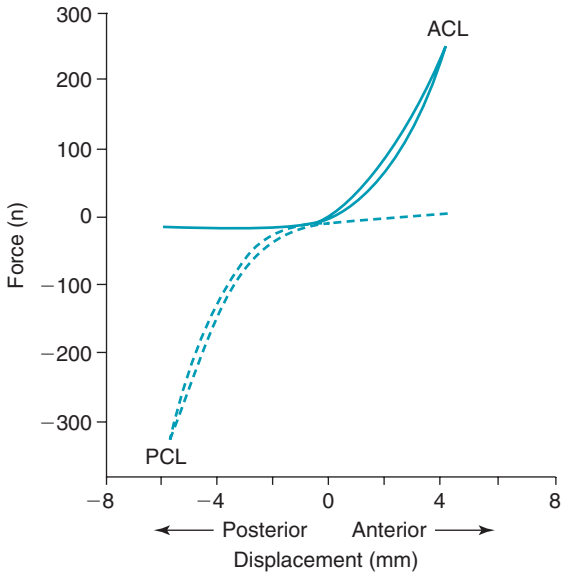


FIG 3-21 Restraining forces of the anterior cruciate ligament (ACL) (*solid line*) and posterior cruciate ligament (PCL) (*dashed line*) during a 5-mm anterior-posterior drawer test on a typical knee specimen. The curves are constructed by taking differences between the curves of the joint before and after cutting the ligament. The ACL resisted nearly all of the force anteriorly with no contribution posteriorly. The PCL restrained posterior joint displacement but had minimum effort anteriorly. Note the hysteresis that is present. (From Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am.* 1980;62A:259-270.)

(Fig. 3-24). No other structure contributes greater than 3% of the total restraint. The secondary restraints to the posterior drawer after the PCL is sectioned (including the lateral meniscofemoral ligament when present) are shown in Table 3-5. The posterolateral capsule and popliteus tendon (combined contribution, 58.2%) and the MCL (15.7%) provided the greatest restraint. The posterior medial capsule, FCL, and mid medial capsule contributed only modest restraints. The combined restraint provided by the posterolateral capsule and popliteus tendon was significantly different from those provided by the other structures.

This investigation was the first to introduce the concepts of primary and secondary ligament restraints to joint motion. The cruciate ligaments are the primary restraints to the AP drawer and provide approximately 90% of the total restraining force at 5 mm of joint displacement. The remaining structures provide only a small contribution. This study also made a distinction between clinical forces, which are small loads applied to the knee during a clinical examination, and functional forces, which are large in vivo loads experienced during moderate or strenuous activities (Fig. 3-25). The increase in joint displacement after the loss of either the ACL or PCL depends on the forces applied to the knee. Although the light forces applied during a clinical test may produce only a slight increase in joint displacement, these increases are expected to be much larger under moderate or strenuous functional forces. Therefore, all clinical ligament examination tests do not predict the magnitude of joint displacement that may occur during functional activities.

LIGAMENTOUS AND CAPSULAR RESTRAINTS RESISTING MEDIAL AND LATERAL JOINT OPENING

We have previously determined the ligaments and capsular structures that resist medial and lateral joint opening in cadaver knees. The ligaments were ranked in order of importance based on the percent of the total restraining force that each provides. The results are independent

of the order in which ligaments are sectioned, allowing all ligaments to be studied in each cadaver knee. Most prior studies of knee ligament function were based on knee motion limits after cutting selected ligaments[4,27,40,76] or on the injury patterns associated with observed clinical pathologies.[2,9,28,29,33,46,61,64,71]

An Instron model 1321 biaxial testing system was used in which the femur was secured to the load cell with two grips that allowed its position to be adjusted.[20] The tibia was attached to the actuator through a plantar hinge mechanism that prevented axial rotation and flexion of the tibia during testing. Each knee was placed to the full-extended (hyperextended) position by applying a 5 N-m extension moment. The tests were performed with the knee flexed 5 and 25 degrees from this position. Single-plane varus and valgus displacements were produced by causing the actuator to move up and down, but not to rotate. The tests were done in a fixed manner that first produced medial and then lateral joint opening. A constant rate was used so that peak opening occurred in 1 second. A series of 25 conditioning tests that produced 6 mm of medial and 6 mm of lateral joint opening were done at the two knee flexion angles. Typically, the peak force changed less than 0.25% per cycle during the last five conditioning tests. Then, baseline

TABLE 3-4 Comparison of Secondary Structures at Increased Anterior Displacement

	Iliotibial Tract and Band	Mid Medial Capsule	Mid Lateral Capsule	Medial Collateral Ligament	Fibular Collateral Ligament
Mean ± SEM (%)	24.8 ± 4.7	22.3 ± 6.9	20.8 ± 5.4	16.3 ± 2.9	12.4 ± 3.3
Minimum (%)	9.8	3.4	1.6	8.1	7
Maximum (%)	44.4	43.6	36.9	29.4	25.2

By Duncan's multiple range test, no statistical difference was found among the percentages for any of the structures shown ($P > .05$). Values are $n = 6$, anterior drawer of 12.2-16.3 mm at 90 degrees of knee flexion.
SEM, Standard error of the mean.

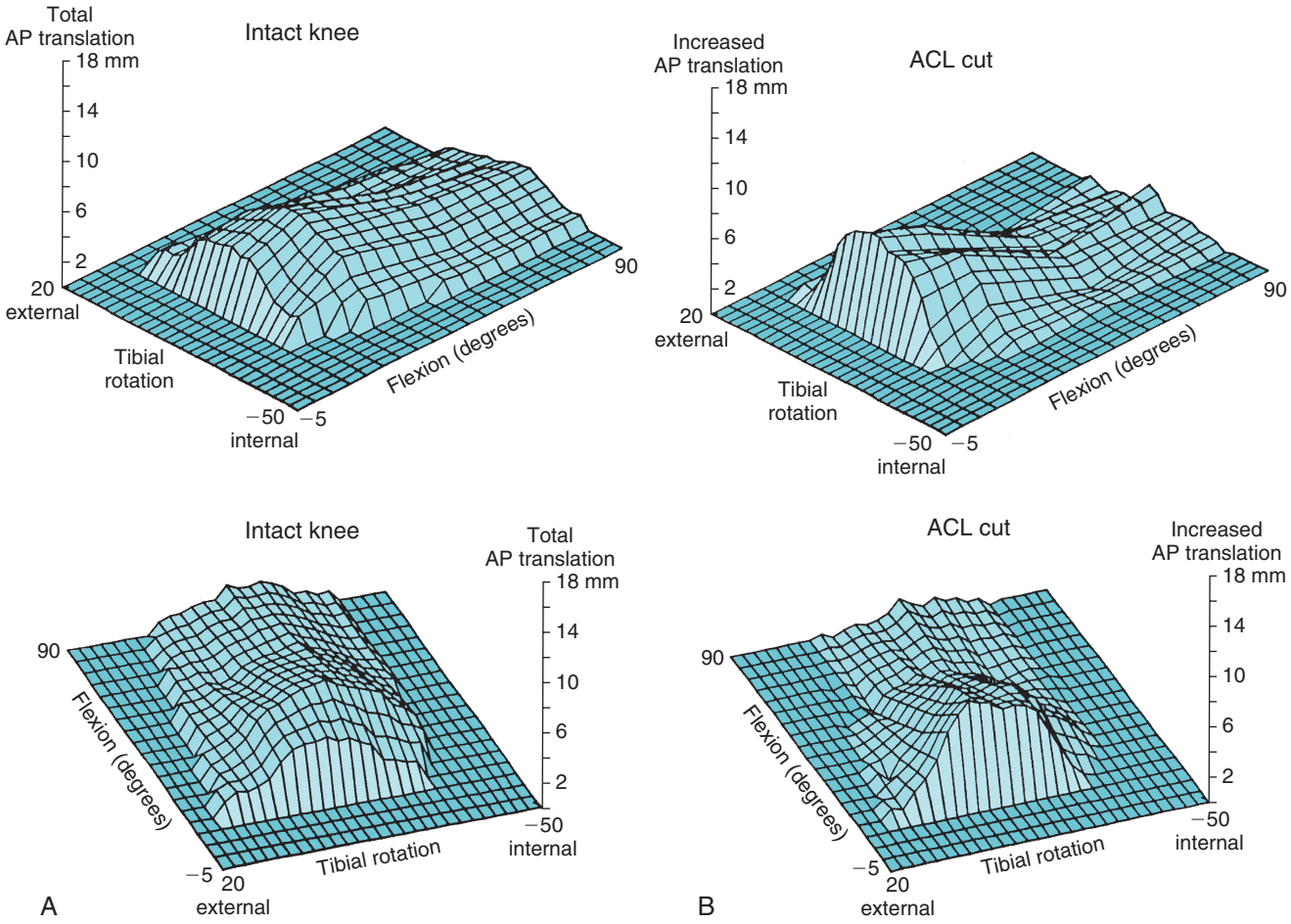


FIG 3-23 Anteroposterior (AP) translation of the human knee joint (100-N load) from 0 to 90 degrees of flexion and under the maximal limits of internal and external tibial rotation (5 N-m torque) before and after selective cutting of ligaments. **A,** Intact knee shows maximum translation at low flexion positions and neutral rotation, two views of the same plot for one knee. **B,** Increased translation caused by anterior cruciate ligament (ACL) sectioning occurs in low flexion positions, indicating other soft tissue restraints are functioning at higher knee flexion positions.

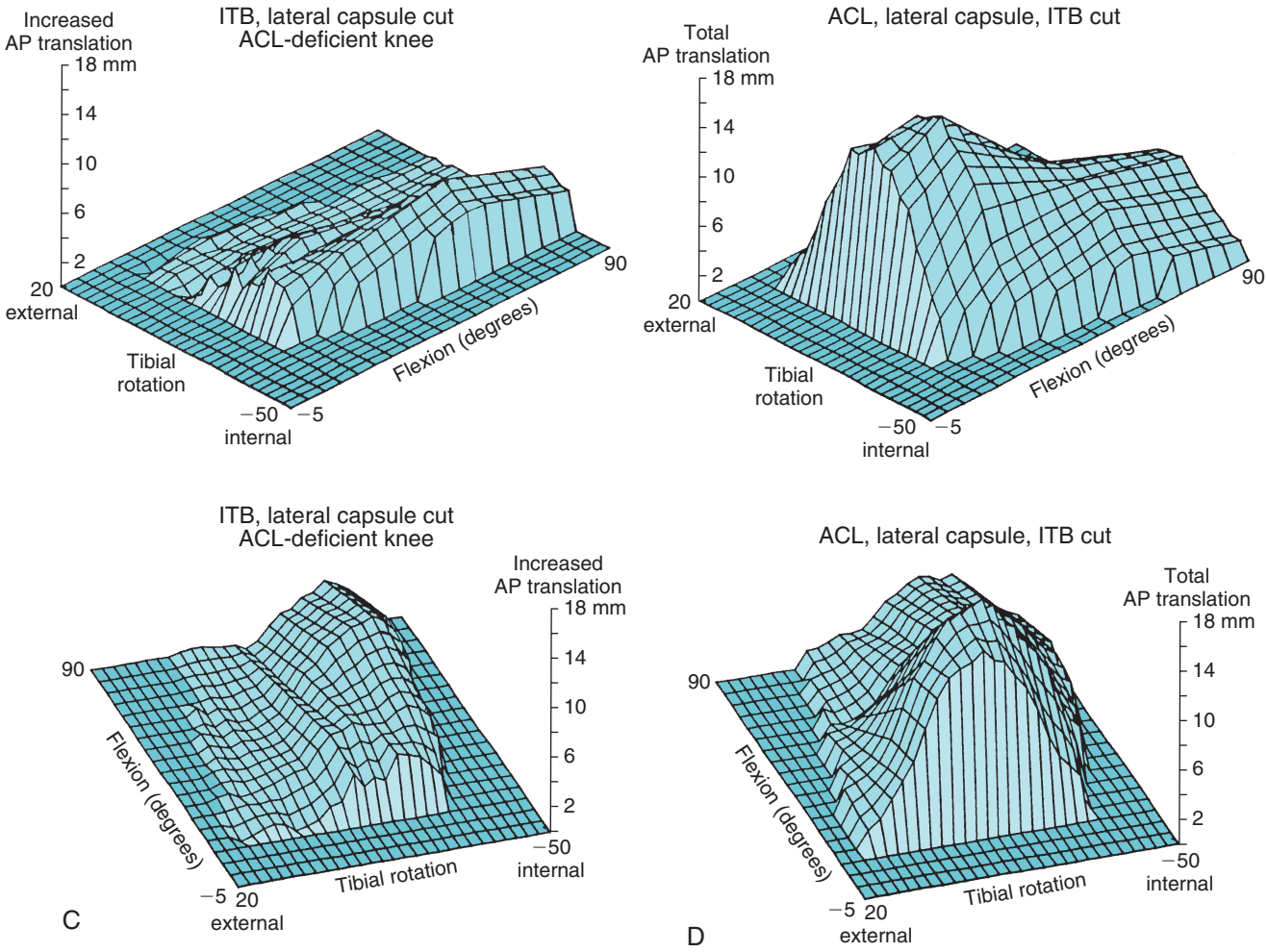


FIG 3-23, cont'd C, Further increased translation after sectioning the iliotibial band (ITB) and lateral capsule. Note the effect of sectioning these restraints is throughout knee flexion but is greatest at the higher flexion positions. This knee shows the effect of tight lateral extraarticular restraints as the initial increased translation after ACL sectioning was modest, and the translation markedly increased after the lateral structures were sectioned. **D,** The final total AP translation is shown for the ACL, lateral capsule, and ITB-sectioned knee, demonstrating major increases in translation throughout knee flexion. Increases in internal rotation of a lesser amount are also shown.

tests were done at both knee flexion angles. A ligament was cut and the test repeated. The restraint caused by the cut ligament was calculated to be the decrease that occurred in the joint restraining moment compared with the moment determined in the test before the ligament sectioning. This process was repeated after cutting other structures until the restraining moments caused by all of the ligamentous and capsular structures had been measured. The medial and lateral tests were performed in 16 knees obtained from 11 cadavers aged 18 to 55 years (mean, 36.8 years).

In six other cadaver lower limbs, the 3-dimensional motion of the knee joint was measured during the clinical examination for medial and lateral joint opening. The motions were determined first in the intact knee and then after a collateral ligament was sectioned to measure the increase in joint opening. The opposite collateral ligament was then sectioned and the increase in joint opening documented. The goal was to determine the actual motions produced in uninjured knees during a clinical examination and to evaluate the change in joint opening that occurred with cutting each collateral ligament. The knee motions were measured using the instrumented kinetic chain (Fig. 3-26),[72] which was positioned across the knee on the lateral side. The leg was positioned over the side of a table. The joint line was palpated with one hand while a force was applied at the ankle with the other hand. The force applied was not measured to conduct the examination in the normal manner. To make these measurements, it was necessary to know the position of the ends of the instrumented chain with respect to the femur and tibia. These positions were established by performing a 3-dimensional analysis using biplane radiographs.[5] Tests for reproducibility demonstrated that translational and rotational motions could be measured within ±0.5 mm and ±0.5 degrees, respectively.

The ligaments and capsular structures studied were the ACL, PCL, superficial parallel fibers of the MCL, the FCL, the popliteus musculotendinous unit (including the popliteofibular ligament [PFL]), the medial and lateral halves of the capsule (subdivided into anterior, middle, and posterior thirds), and the femorotibial portion of the ITB. The middle third of the medial capsule was considered to be the deep fibers of the MCL described by others.[71,77] The posterior third included the complex of capsular structures previously detailed[30,77]

TABLE 3-5 Comparison of Secondary Structures at Increased Posterior Displacement

	Posterolateral Capsule and Popliteus Tendon*	Medial Collateral Ligament	Posterior Medial Capsule	Fibular Collateral Ligament	Mid Medial Capsule
Mean ± SEM (%)	58.2 ± 10.1	15.7 ± 5.2	6.9 ± 3.2	6.3 ± 4.7	6.2 ± 2.4
Minimum (%)	36.7	5.6	0	0	0
Maximum (%)	82.1	29.7	14.5	20.4	11.5

Values are n = 4, posterior drawer of 19.0-25.0 mm at 90 degrees of knee flexion.
*By Duncan's multiple range test, only the posterolateral capsule and popliteus tendon were statistically different from all other structures ($P < .05$). Sectioned from femur; includes popliteofibular ligament.
SEM, Standard error of the mean.

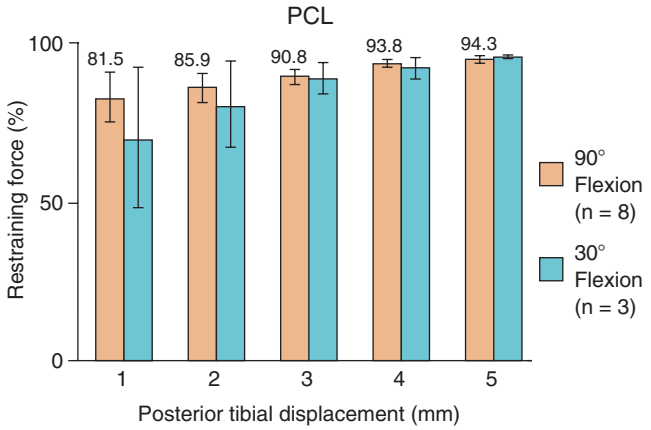


FIG 3-24 For posterior drawer in neutral tibial rotation, the percentage of total restraining force is shown for the posterior cruciate ligament (PCL) for increasing posterior tibial displacement at 90 and 30 degrees of knee flexion. Mean values are shown, ±1 standard error of the mean. Percentage values are given for 90 degrees of flexion. No statistically significant difference was observed between 90 and 30 degrees of flexion, or between 1 and 5 mm of displacement ($P > .05$). (From Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am.* 1980;62A:259-270.)

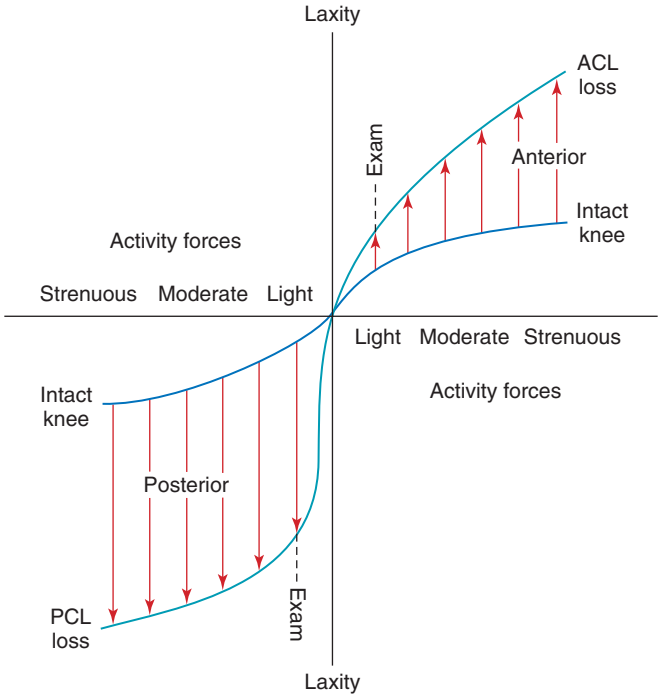


FIG 3-25 Changes in anterior and posterior laxity in one knee specimen before and after loss of the cruciate ligaments. The laxities are shown for increasing activity force. Note the small increase in anterior laxity for a clinical anterior drawer test (examination) performed with a forward pull. A large increase in laxity occurs for posterior drawer when the posterior cruciate ligament (PCL) is cut. *ACL,* Anterior cruciate ligament. (From Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am.* 1980;62A:259-270.)

and the remaining portion of the medial portion of the capsule extending to the mid popliteal region (including the oblique popliteal ligament). The lateral half of the capsule was divided into the anterior third (from the lateral margin of the patellar tendon to Gerdy's tubercle), the middle third (from Gerdy's tubercle to just anterior to the FCL), and the posterior third (the popliteus muscle-tendon-ligament unit and the rest of the capsule extending back to the mid popliteal region).

Results

The results of a typical test on an intact knee and then after sectioning the MCL are shown in Figure 3-27. The curve marked "Intact" represents behavior after conditioning but before ligaments were sectioned. The restraining moment was greater during loading (*upper curve*) than during unloading (*lower curve*) owing to the viscoelastic properties of the ligaments.

During clinical testing in which varus and valgus forces of 45 N are applied at the ankle, a moment of approximately 18 N-m is produced at the knee. These moments produced a medial and lateral joint opening in the knee shown in Figure 3-28**.** When the MCL was cut and a valgus moment applied, the medial opening increased approximately 3 mm. The secondary restraints blocked further joint opening, because they were sufficient to resist the small forces typically induced during a clinical examination. The restraining moment produced by the MCL alone is shown in Figure 3-28.

Medial Restraints

The ligaments and capsular structures resisting 5 mm of medial joint opening are shown for 5 degrees of flexion in Figure 3-29 and for 25 degrees of flexion in Figure 3-30**.** The MCL was the primary restraint at both knee flexion angles, providing 57.4% ± 3.5% of the total restraining moment at 5 degrees and 78.2% ± 3.7% at 25 degrees of flexion. The increase in contribution with flexion was caused primarily by a decrease in the contribution of the posteromedial portion of the

CRITICAL POINTS Ligamentous and Capsular Restraints Resisting Medial and Lateral Joint Opening

- The MCL is the primary restraint to medial joint opening, providing 57% of the total restraining moment at 5 degrees of flexion and 78% at 25 degrees of flexion. The increase in contribution with flexion is caused by a decrease in the contribution of the posteromedial portion of the capsule, which becomes increasingly slack as flexion occurs. The medial restraint provided by the ACL and PCL in combination is 15% of the total at 5 degrees of flexion and 13% at 25 degrees of flexion.
- The FCL is the primary restraint to lateral joint opening, providing 55% of the total restraint at 5 degrees of flexion and 70% at 25 degrees of flexion. The increased contribution of the FCL with knee flexion is because of a marked decrease in the restraint provided by the posterolateral capsule. The cruciate ligaments together provide 22% of the total lateral restraining moment at 5 degrees of flexion and 12% at 25 degrees of flexion.
- The restraints limiting lateral opening caused by the popliteus muscle tendon and ligament and of the femorotibial portion of the ITB are minimal at both knee flexion angles.
- A 5- to 8-mm increase measured clinically after an acute injury indicates significant collateral ligament injury, including the secondary restraints.
- Define the degrees of injury as first, second, or third and then estimate the millimeters of increased joint opening at 5 and 25 degrees of flexion.
- The clinician should place a finger at the joint line to estimate the millimeters of joint opening and compare the finding with the opposite knee. If axial rotation of the tibia occurs caused by inadvertent rotation of the leg during the examination, the examiner may overestimate the amount of joint opening.
- In cases of ACL rupture, the cradled position (holding the lower leg above the table) to induce varus or valgus tests should be avoided. The knee should be examined with the thigh supported by the examination table in a reduced position where the weight of the leg prevents the anterior tibial subluxation.

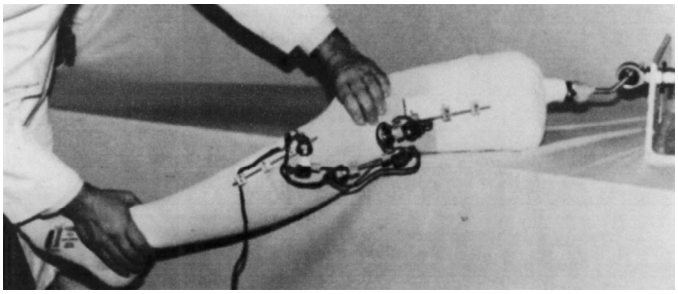


FIG 3-26 The instrumented kinetic chain, used to measure 3-dimensional joint motion, is shown mounted across the knee on a cadaver lower limb. Each end of the chain is attached to a mounting platform made from pins 3.18 mm (⅛ inch) in diameter. The platforms are attached securely to each bone by three pins that pass through the skin, underlying muscle, and bone. The femur is attached to an angle plate by means of a rod cemented in the medullary canal and a mobile ball-and-socket joint that simulates the hip. The angle plate is secured to a table with C-clamps.

capsule, which became increasingly slack as flexion occurred. The anterior and middle parts of the medial half of the capsule provided weak secondary restraint limiting medial joint opening, equivalent to 7.7% ± 1.7% of the total restraint at 5 degrees and to 4.0% ± 0.9% of the total at 25 degrees with 5 mm of opening. The posterior portion of the

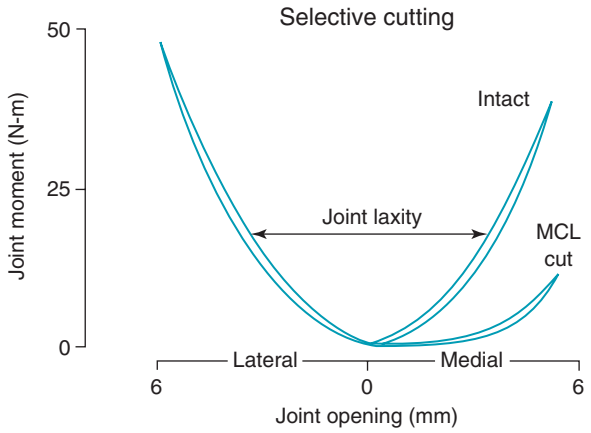


FIG 3-27 The restraining joint moment (in newton-meters) is shown for a typical intact knee and for the same knee after selective cutting of the medial collateral ligament (MCL). The test starts at the neutral position (0) with the knee intact. Six millimeters of medial opening is produced at a constant rate during 1 second. The knee then is returned to neutral and the same amount of lateral opening is produced. When the test is repeated after cutting the MCL, the restraining moment to medial opening is markedly reduced but there is no change during lateral opening. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63:1257-1269.)

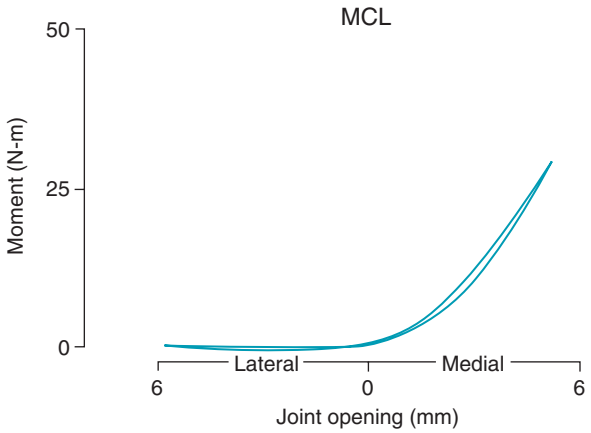


FIG 3-28 The curve for the restraining moment of the medial collateral ligament (MCL) alone versus joint opening. This curve was obtained by subtracting the curve after the ligament was cut from the curve for the intact knee shown in Figure 3-26. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am* 1981;63:1257-69.)

medial half of the capsule provided 17.5% ± 2.0% of the total restraint at 5 degrees and 5 mm of medial opening. At 25 degrees of flexion, the restraint caused by this part of the capsule dropped to 3.6% ± 0.8%. The effect of increasing the medial joint opening on the contribution of the MCL is shown in Figure 3-31**.** At 5 degrees of knee flexion, the contribution of the MCL decreased from 70.0% at 2 mm to 53.2% at 6 mm of opening.

The medial restraint provided by the ACL and PCL in combination was 14.8% ± 2.1% of the total at 5 degrees of flexion and 13.4% ± 2.7% at 25 degrees. In nine specimens, the contribution of one cruciate was separated from that of the other (Table 3-6). At 25 degrees of flexion,

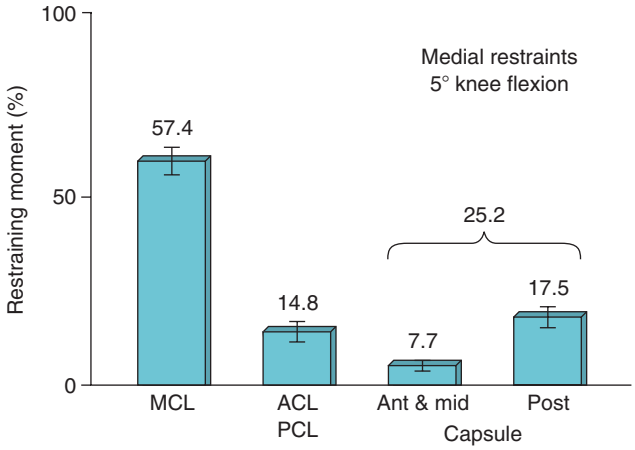


FIG 3-29 The average percent contributions to the medial restraints by the ligaments and capsule at 5 mm of medial joint opening and 5 degrees of flexion. The error bars represent ±1 standard error of the mean. *ACL,* Anterior cruciate ligament; *Ant,* anterior; *MCL,* medial crucial ligament; *PCL,* posterior crucial ligament. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63:1257-1269.)

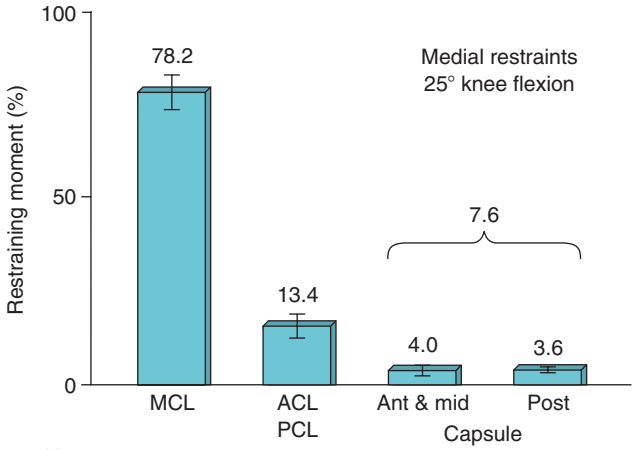


FIG 3-30 The percent restraining contributions of the medial structures at 5 mm of opening and 5 degrees of flexion. *ACL,* Anterior cruciate ligament; *Ant,* anterior; *MCL,* medial crucial ligament; *PCL,* posterior crucial ligament. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63:1257-1269.)

the PCL accounted for approximately 75% of the combined restraint exerted by the cruciate ligaments to medial opening, and the ACL accounted for 25%. This result did not depend on the order of cruciate ligament sectioning. However, at 5 degrees of flexion, the order of cruciate ligament sectioning affected the results. When the PCL was cut first, it accounted for approximately 70% of their combined restraint. When the PCL was cut after the ACL, its contribution was only 20% of their combined restraint. These findings indicate that the cruciate ligaments do not function independently of each other when the knee is near full extension.

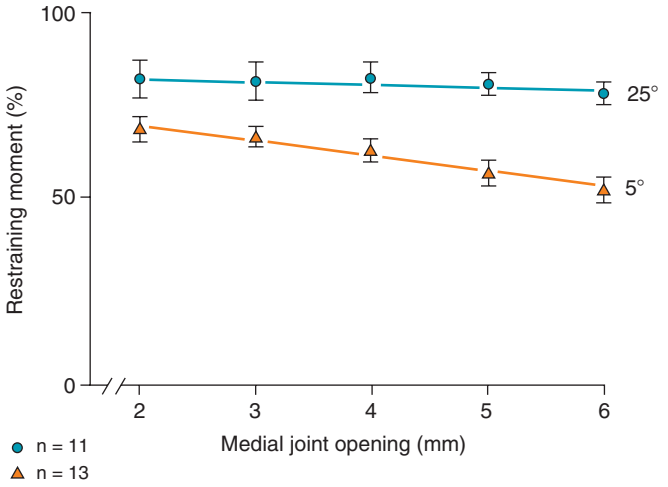


FIG 3-31 The percent contribution of the medial collateral ligament to the restraints limiting medial joint opening in the range of 2 to 6 mm. The decrease with joint opening at 5 degrees is statistically significant ($P < .005$; $r = 0.419$; n = 65). (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63:1257-1269.)

TABLE 3-6 Percentage of Restraining Moment Caused by the Cruciate Ligaments for Medial Joint Opening

Ligament	5 Degrees Knee Flexion PCL Cut Before ACL (*n* = 3)	5 Degrees Knee Flexion PCL Cut After ACL (*n* = 6)	25 Degrees Knee Flexion (*n* = 9)
ACL	5.0 ± 2.6	12.0 ± 2.9	2.4 ± 0.6
PCL	10.2 ± 1.6	2.5 ± 0.8	7.8 ± 2.5
Both	15.2 ± 3.1	14.5 ± 3.0	12.2 ± 2.6

Mean total medial restraining moment ± 1 standard error of the mean.
ACL, Anterior cruciate ligament; *PCL,* posterior cruciate ligament.

Lateral Restraints

The average contributions of the lateral ligaments, lateral half of the capsule, and cruciate ligaments to the restraining moment at 5 mm of lateral joint opening are shown in Figure 3-32 at 5 degrees of flexion and in Figure 3-33 at 25 degrees of flexion. The FCL was the primary restraint limiting lateral opening of the joint at both knee flexion angles, providing 54.8% ± 3.8% of the total restraint at 5 degrees of flexion and 69.2% ± 5.4% at 25 degrees. The increased contribution of the FCL with knee flexion was caused by a marked decrease in the restraint provided by the posterolateral capsule. There was large variability in the data for the FCL, with its contribution ranging from 34.6% to 8.37% at 5 degrees and from 40.5% to 94.7% at 25 degrees. Still, the FCL provided a restraining moment greater than the combined moments of the entire lateral half of the capsule, the ITB, the popliteus tendon, and the cruciate ligaments.

The entire lateral half of the capsule provided 17.2% of the varus restraint at 5 degrees of flexion (see Fig. 3-30) and 8.8% of this restraint at 25 degrees (see Fig. 3-31). The anterior and middle thirds of the lateral half of the capsule contributed only a small secondary restraint,

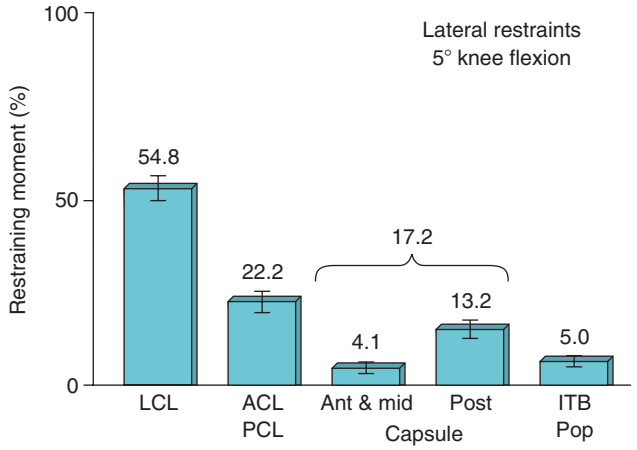


FIG 3-32 The average percent contribution to the lateral restraints by the ligaments and capsule at 5 mm of lateral joint opening and 5 degrees of knee flexion. The error bars indicate ±1 standard error of the mean. There was no tension on the iliotibial band (ITB) proximal to the lateral femoral condyle in these preparations. *ACL,* Anterior cruciate ligament; *LCL,* lateral crucial ligament; *PCL,* posterior crucial ligament; *POP,* popliteal. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63:1257-1269.)

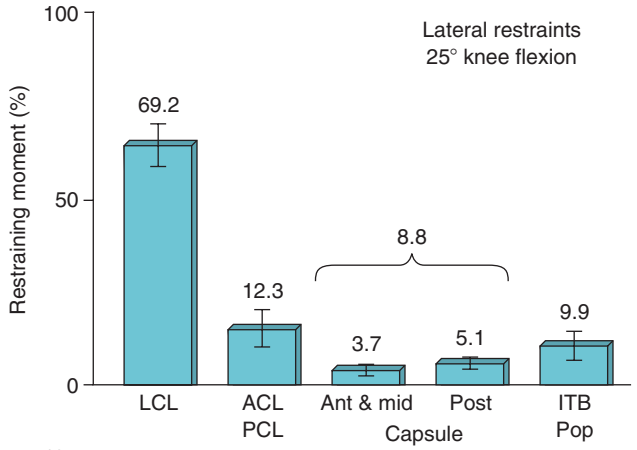


FIG 3-33 The percent contribution of the lateral structures at 5 mm of lateral joint opening and 25 degrees of knee flexion. *ACL,* Anterior cruciate ligament; *Ant,* anterior; *ITB,* iliotibial band; *LCL,* lateral crucial ligament; *PCL,* posterior cruciate ligament; *POP,* popliteal. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63:1257-1269.)

4.1% ± 1.5% at 5 degrees and 3.7% ± 1.5% at 25 degrees. The posterolateral capsule became slack with flexion and provided only 5.1% ± 1.3% of the total restraint at 25 degrees of flexion.

The cruciate ligaments together provided 22.2% ± 2.6% of the total restraining moment at 5 degrees of flexion and 12.3% ± 4.2% at 25 degrees. There was no effect on the order of cruciate ligament sectioning. However, there was large variation in these data between specimens. The combined restraint of the cruciate ligaments ranged from

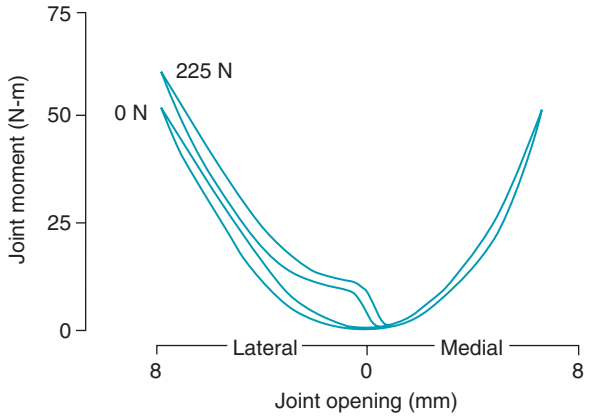


FIG 3-34 The effect of applying a 225-N force to the iliotibial tract. The force increases the lateral restraint (joint moment) and decreases lateral joint opening. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63:1257-1269.)

TABLE 3-7 Percentage of Restraining Moment Caused by the Cruciate Ligaments for Lateral Joint Opening

Ligament	5 Degrees Knee Flexion	25 Degrees Knee Flexion
ACL	19.7 ± 2.7	10.3 ± 4.1
PCL	2.7 ± 0.7	4.1 ± 1.1
Both	22.4 ± 3.0	14.4 ± 4.7

n = 11. Mean of total lateral restraint ± 1 standard error of the mean. *ACL,* Anterior cruciate ligament; *PCL,* posterior cruciate ligament.

10.7% to 36.7% at 5 degrees of flexion and from 1.9% to 45.7% at 25 degrees of flexion. The ACL provided the greater portion of the combined restraining effects (Table 3-7) at both knee flexion angles.

Iliotibial Tract, Popliteus Tendon, Biceps Tendon

The restraints limiting lateral opening caused by the ligament-like actions of the popliteus muscle tendon and ligament and of the femorotibial portion of the ITB were minimum at both knee flexion angles. Therefore, these structures were combined with the caution that the resulting data do not reflect larger in vivo restraining action of either structure owing to added in vivo muscle forces.

The effect of lateral opening on tension in the ITB and in the biceps tendon was investigated by applying a 225-N (50-lb) force to the ITB with a deadweight and pulley system. A curve of the restraining moment is shown in Figure 3-34 for an intact knee before and after the tension was applied. The tension produced an increase in the lateral restraining moment. The effect of the tension alone (Fig. 3-35) demonstrated that the applied force produced a nearly constant restraining moment, independent of the amount of lateral joint opening.

Location of Rotation Axes

The location of the axes for varus-valgus tests on the femur at 5 degrees of flexion are shown in Figure 3-36. The tibia, which moves during the test, is drawn in the neutral position, corresponding to the beginning of the varus-valgus loading test. The rotation axes are located above the joint contact area on the lateral femoral condyle for valgus displacement and above the medial contact area for varus displacement. The

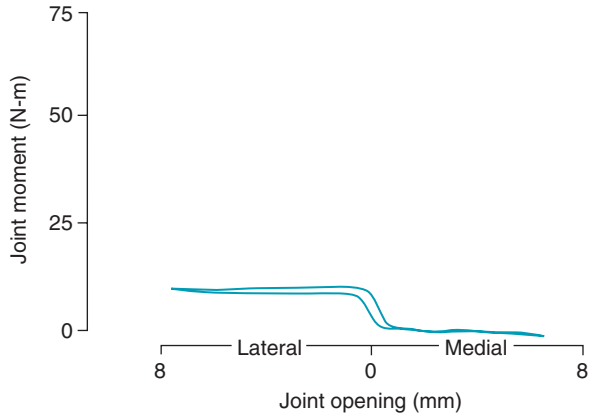


FIG 3-35 Difference curve showing the isolated lateral restraining effect of the force applied to the iliotibial tract. Note that the restraining action is independent of the amount of joint opening. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63:1257-1269.)

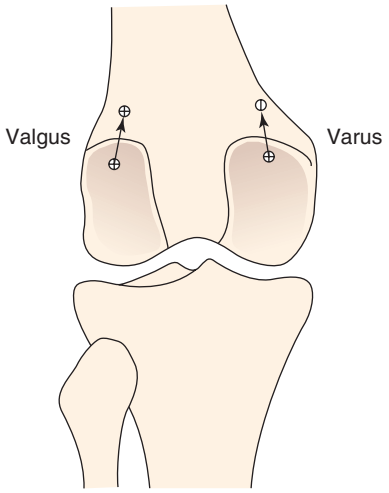


FIG 3-36 The instant centers for one-plane varus and valgus displacements of the knee at 5 degrees of flexion. The instant centers are above the joint line, indicating a sliding motion at the tibiofemoral contact region. During valgus displacement the instant center is on the lateral side and during varus displacement, on the medial side. The arrows indicate that the instant centers move proximally as the medial and lateral joint openings increase. (From Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am* 1981;63:1257-1269.)

lower points represent the rotation axes for the first half of the varus and valgus test (~0-2.5 mm of joint opening). The upper points represent the axes for the last half of each test (2.5-5 mm of opening). For the total varus and valgus motion, the axes are located near the midpoints of the lines connecting the lower and upper points.[20]

The reader should note that the positions of the axes above the joint line indicate that a tibiofemoral sliding motion occurs during the loading test. The tibia slides laterally during a valgus test in the same direction as the applied force. The opposite sliding motion occurs during a varus test as the tibia moves medially. The proximal movement of the instant center reflects an increase in the amount of medial-lateral shear movement for each degree of varus-valgus rotation during the test. The increase in the amount of shear movement per degree of rotation occurs when the rotational stiffness of the joint increases more rapidly than its shear stiffness.[20]

TABLE 3-8 Increase in Joint Opening After Sectioning of the Collateral Ligaments

	Mean ± Standard Deviation (mm)	Range (mm)
Lateral		
5 degrees flexion	0.84 ± 0.46	0.3-1.3
25 degrees flexion	2.56 ± 0.80	1.7-3.7
Medial		
5 degrees flexion	1.24 ± 0.69	1.5-3.7
25 degrees flexion	3.90 ± 1.43	2.0-5.5

n = 5. All numbers are in millimeters of joint opening; 1 mm is equivalent to approximately 1 degree of tibial angulation.

TABLE 3-9 Sprain Classification System of the American Medical Association

Sprain	Symptom	Signs	Tear Fibers
First degree	Mild	None	Minor
Second degree	Moderate	Slight abnormal motion	Partial
Third degree	Severe	Abnormal motion (3-15 mm)	Complete

Increase in medial-lateral joint opening (added by other investigators): grade I (0-5 mm), grade II (6-10 mm), grade III (11-15 mm).

Joint Motions During Clinical Examination

The increases in joint opening after the collateral ligaments were sectioned are shown in Table 3-8. The increases in motion after cutting the FCL during varus testing were 0.84 ± 0.5 mm at 5 degrees of flexion and 2.56 ± 0.8 mm at 25 degrees of flexion. The greater amount of joint opening with flexion was explained by the loss of the restraint provided by the posterior portion of the capsule and the increase in the contribution of the FCL. However, the increases in motion at both knee flexion angles were small owing to the influence of the secondary restraints under the low forces applied during the clinical examination.

The increases in medial joint opening after the MCL was sectioned during valgus testing were larger. This was caused by the larger contribution to varus-valgus restraint provided by the MCL compared with that provided by the FCL. The largest increase measured in medial joint opening was 5.5 mm in one knee at 30 degrees of flexion; however, the average increase was less than 5 mm. Therefore, only small joint openings may be demonstrated on clinical examination even when the medial or lateral primary restraint is ruptured. A 5- to 8-mm increase measured clinically after an acute injury indicates significant collateral ligament injury, including the secondary restraints. The concept of a "grade I laxity" (defined as an up to 5-mm increase in medial or lateral joint opening) as not representing a significant injury is not supported by these data. This raises the need to carefully evaluate any increase in joint opening, because this represents significant damage to the restraining function of a primary collateral ligament. The treatment aspects of acute injuries to the medial and lateral knee ligaments are discussed in Chapter 17 and Chapter 19. Table 3-9 shows the

traditional classification system of the American Medical Association (AMA) of medial and lateral ligament injury. A second-degree injury has only a few millimeters of joint opening, which is barely discernible. An increase up to 5 mm would represent a third-degree injury. Rather than use grades to classify the injury, it is more accurate to define the degrees of injury as first, second, or third and then estimate the millimeters of increased joint opening at 5 and 25 degrees of flexion. Sequential increases of even 3 mm (rather than 5 mm) have important implications of injury to additional ligament structures that, in turn, affect treatment options.

A large amount of out-of-plane tibial rotation occurred during the clinical examination. The amount of axial rotation was typically greater than the total amount of medial-lateral joint opening. In one knee, the joint opening (varus-valgus combined) near full extension was 2.5 mm and was accompanied by 4.5 degrees of axial tibial rotation. At 30 degrees of flexion, the joint opening was 6.5 mm and was accompanied by 8.2 degrees of axial tibial rotation.

The cruciate ligaments act as secondary restraints during medial and lateral opening. If one of the collateral ligaments and associated capsule is ruptured, then the cruciate ligaments become primary restraints. Because the cruciate ligaments are located in the center of the knee, close to the center of rotation, the moment arms are about one third of those of the collateral ligaments. Therefore, to produce restraining moments equal to the collateral ligaments, the cruciate ligaments must provide a force three times larger than that of the collaterals.

The ITB functions as a single unit; when removed from its proximal pelvic attachments, the femorotibial portion becomes slack and incapable of restraining lesser amounts of lateral opening. The major function of the proximal muscle fibers appears to be the transmission of the tension maintaining a tautness of the ITB.[20] There appears to be two main sources of tension in the tract[31]: the passive ligament-like tension between the iliac and femoral insertions of this structure and the active muscle forces transmitted by the tract. The passive ligament-like tension should increase during lateral joint opening. The ilium-to-tibia distance is so long, however, that lateral joint opening of a few millimeters would not be expected to produce much additional tension in the tract.[20]

Conclusion

The amount of medial or lateral joint opening detected on clinical examination is only qualitative. The clinician should place a finger at the joint line to estimate the millimeters of joint opening and compare the finding with the opposite knee. If axial rotation of the tibia occurs because of inadvertent rotation of the leg during the examination, the examiner may overestimate the amount of joint opening. Associated internal or external tibial rotation may be falsely interpreted as additional medial or lateral joint opening. The amount of medial or lateral joint opening should always be measured during arthroscopy with the gap test to verify the preoperative diagnosis.

Recognition of axial rotation is especially important when assessing medial ligament injuries. Two types of tests have been described: one in which only an abduction moment is used for medial joint opening and a second in which external rotation is produced by abducting and externally rotating the leg with the femur held stationary. The first test of medial joint opening more accurately assesses medial ligament damage and allows a diagnosis of ligament and capsular injury because it reproduces the known restraining function of structures proven under in vitro conditions. The second test, which allows a coupled medial joint opening with abduction and anterior tibial translation, may be used when there is an associated ACL rupture. The true millimeters of medial joint opening may be difficult to estimate when a coupled external rotation and anterior translation occurs.

In cases of ACL rupture, the cradled position (holding the lower leg above the table) to induce varus or valgus tests should be avoided. With the leg elevated, an anterior tibial displacement occurs.[49] The joint is partially subluxated, and a medial to lateral rocking motion can be obtained that may be misinterpreted as increased medial or lateral joint opening. To prevent this, the knee should be examined with the thigh supported by the examination table in a reduced position where the weight of the leg prevents the anterior tibial subluxation.

FUNCTION OF MEDIAL AND POSTEROMEDIAL LIGAMENTS IN ACL-DEFICIENT KNEES

The motion limits in normal knees and ACL-deficient cadaveric limbs were studied to define the role of the medial ligamentous structures in limiting anterior translation, abduction (degrees or medial joint opening), and external and internal tibial rotation.[23] The results provide a scientific basis for clinical tests for the diagnosis of combined ACL/MCL ruptures. A six-DOF instrumented spatial linkage at the knee joint was used to measure the motion limits under defined loading conditions using the techniques previously published.[72] The forces and moments in the experiment were: 100 N for anterior and posterior motion limits, 15 N-m for abduction-adduction limits, and

CRITICAL POINTS Function of Medial and Posteromedial Ligaments in ACL-Deficient Knees

- ACL sectioning alone allows small increases in internal tibial rotation and no increases in external tibial rotation. When all medial structures (ACL intact) are sectioned, the abduction limit increases to only about 7 degrees, or 7 to 8 mm of medial joint opening.
- The MCL (and deep medial capsule) limits anterior tibial translation as a secondary restraint after the ACL is ruptured. A combined ACL/MCL injury has equal anterior translation at 30 and 90 degrees, indicating the Lachman and 90-degree anterior drawer will show similar increases in anterior tibial translation.
- In the ACL/MCL-deficient knee, the Lachman test will show an absence of the normal coupled internal tibial rotation in contrast to the coupled rotation in the normal and ACL-deficient knee.
- The MCL is the primary restraint for external tibial rotation; however, the increase is small (4.6 to 8.7 degrees from 30 to 90 degrees of flexion). The increase in external rotation doubles when the PMC is also sectioned. Further increases in external rotation to approximately 15 degrees occur when the ACL is also sectioned. The results validate the importance of performing the dial tibial rotation test to determine anterior subluxation of the medial tibial plateau with medial ligament injuries.
- The combined MCL/PMC injury results in increases in external tibial rotation (9 degrees at 30 degrees of flexion), increases in internal tibial rotation (12 degrees at 30 degrees of flexion), and increases in abduction testing at 0 and 30 degrees of flexion (6 degrees and 9 degrees, respectively).
- The PMC is an important structure for stabilizing the extended knee under valgus loading (32% of the resistance).
- The posterior drawer test is performed in neutral tibial rotation to determine the maximum posterior tibial translation. When the posterior drawer is repeated in maximal internal rotation (in knees with a PCL rupture), the amount of posterior tibial translation will markedly decrease if the PMC is intact.

TABLE 3-10 Increases in Motion Limits Relative to the Intact Knee That Occurred When the Indicated Structures Were Sectioned

Limit	0 Degrees of Flexion	15 Degrees of Flexion	30 Degrees of Flexion	60 Degrees of Flexion	90 Degrees of Flexion
Anterior (mm)					
ACL	5.8 ± 0.9*	9.4 ± 1.0†	8.4 ± 1.9*	4.7 ± 2.1§	3.5 ± 1.6§
ACL + MCL	6.1 ± 2.0*	10.0 ± 2.4*	11.0 ± 2.9*	10.6 ± 3.5*	10.1 ± 4.2§
MCL + PMC	–0.5 ± 1.1	–0.3 ± 1.1	–0.5 ± 0.9	–0.1 ± 0.7	0.4 ± 1.1
ACL + MCL + PMC	8.7 ± 3.2†	12.8 ± 4.3†	14.4 ± 4.9†	14.6 ± 5.7†	12.5 ± 5.6*
External Rotation (Degrees)					
ACL	1.2 ± 1.4	0.7 ± 0.8	0.7 ± 0.6	0.7 ± 0.4	0.5 ± 0.5
MCL	2.5 ± 1.1‡	3.3 ± 1.5‡	4.6 ± 1.3*	8.0 ± 2.2*	8.7 ± 3.2‡
PMC	1.6 ± 0.9	1.2 ± 1.2	0.9 ± 1.7	0.8 ± 2.5	0.8 ± 2.4
ACL + MCL	2.3 ± 0.4†	3.2 ± 1.1*	4.6 ± 1.6*	7.3 ± 2.3*	7.5 ± 2.0*
MCL + PMC	6.8 ± 2.5‡	7.2 ± 1.9*	9.0 ± 2.0*	13.6 ± 3.0*	15.0 ± 3.6*
ACL + MCL + PMC	10.9 ± 5.8*	12.7 ± 6.2*	14.7 ± 6.5*	16.7 ± 5.9†	15.3 ± 5.1†
Internal Rotation (Degrees)					
ACL	2.9 ± 1.0*	2.2 ± 0.9‡	0.8 ± 0.9	0.5 ± 0.8	2.0 ± 2.6
MCL	0.5 ± 0.5	1.4 ± 0.7	2.1 ± 1.2	1.8 ± 0.3‡	1.5 ± 0.4*
PMC	3.4 ± 2.4	4.0 ± 2.3	2.7 ± 1.7	1.3 ± 0.7	1.4 ± 1.4
ACL + MCL	3.6 ± 1.5‡	3.5 ± 1.4‡	2.3 ± 1.3	2.4 ± 0.8*	2.1 ± 1.4
MCL + PMC	6.3 ± 5.8	11.6 ± 3.4*	9.3 ± 2.2*	3.9 ± 2.4	2.9 ± 1.5
ACL + MCL + PMC	12.7 ± 6.5*	13.2 ± 3.3§	10.4 ± 2.1§	4.5 ± 1.1§	3.3 ± 1.2†
Abduction (Degrees)					
ACL	0.4 ± 0.2‡	0.8 ± 0.5	0.6 ± 0.6	0.1 ± .3	0.0 ± 0.3
MCL	1.5 ± 0.9	3.3 ± 0.8*	4.1 ± 0.8‡	4.5 ± 0.8†	3.8 ± 1.0*
PMC	0.4 ± .3	0.2 ± 0.6	0.4 ± 0.3	0.0 ± 0.9	0.4 ± 0.5
ACL + MCL	2.5 ± 1.1‡	5.4 ± 2.6‡	7.1 ± 3.6‡	8.1 ± 4.0§	7.1 ± 2.8‡
MCL + PMC	4.6 ± 1.9‡	6.0 ± 1.4*	6.6 ± 0.9§	5.8 ± .2†	4.8 ± 1.1*
ACL + MCL + PMC	9.1 ± 4.6*	12.7 ± 4.8†	14.4 ± 5.0†	14.2 ± 4.5†	12.1 ± 4.0†

Values are given as mean ± standard deviation. ACL + MCL (6 donors); MCL + PMC (6 donors); ACL + MCL + PMC (9 donors).
*$P < .01$.
†$P < .001$.
‡$P < .05$.
§$P < .0001$.
ACL, Anterior cruciate ligament (6 donors); *MCL*, superficial medial collateral ligament (6 donors); *PMC*, posteromedial capsule, including the posterior oblique ligament (6 donors).

5 N-m for internal-external tibial rotation limits. After the motion limits were determined in the intact cadaveric knee, the ACL, MCL, and PMC were sectioned in different patterns to determine function when cut alone or after one of the other ligament structures. The ligaments cut were the ACL, superficial long fibers of the MCL (including deep medial one third meniscofemoral but not meniscotibial), and the entire PMC, including the posterior oblique portion.

The increases in motion limits are shown in Table 3-10. The changes in the anterior translation limits following the ligament sectioning procedures are shown in Figure 3-37. The typical pattern of a major increase in anterior translation at low flexion angles compared with high flexion angles was statistically significant ($P < .001$). Note that subsequent sectioning of the MCL resulted in major increases in anterior translation at high flexion angles, with the amount of anterior translation equal at low flexion angles. This means that major increases in anterior translation at 90 degrees of knee flexion indicate that the secondary restraints are also insufficient. When the ACL was intact, there was no increase in anterior translation even when all of the medial ligament structures were sectioned.

The changes in coupled internal and external tibial rotation during the anterior translation and abduction loading tests are shown in Table 3-11. The anterior loading produced a coupled internal tibial rotation, as expected. The coupled internal tibial rotation decreased after the ACL was sectioned, but still remained. However, sectioning the MCL produced a loss of the coupled internal rotation. This indicates the importance of the MCL in maintaining a rotation point for the coupled internal rotation to occur; this is lost with MCL insufficiency, as already discussed. In pivot shift tests with a combined ACL/MCL injury, the magnitude of anterior tibial subluxation results in a grade III pivot shift (tibial impingement). In the abduction (valgus) test for medial joint opening, as long as there is an intact ACL, a coupled internal tibial rotation occurs. However, with an ACL and MCL injury, this internal tibial rotation with abduction is lost and there is an associated increase in external tibial rotation. These subtle changes in internal tibial rotation with combined ACL/MCL injuries are important, because the obligatory coupled rotation of anterior translation-internal tibial rotation is lost, which can be detected on clinical examination.

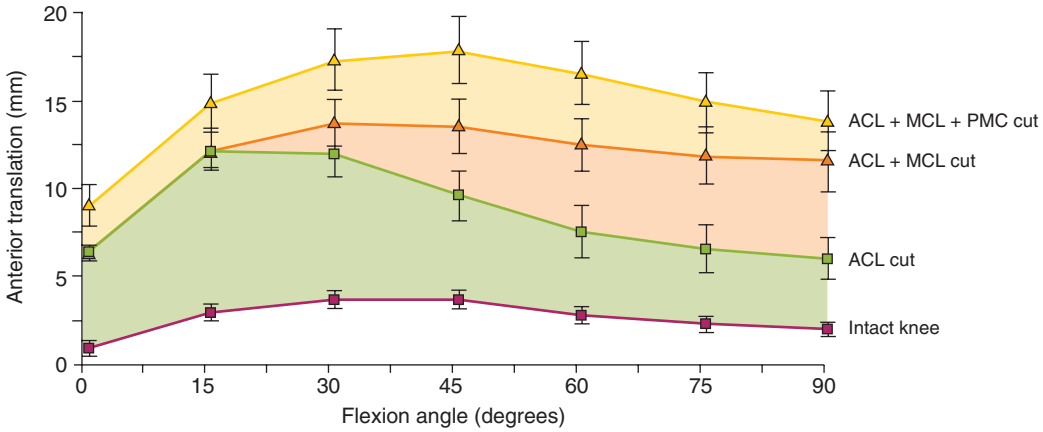


FIG 3-37 The anterior translation limits (*bottom curve*) when a 100-N anterior force was applied to control intact knees (11 donors). Sectioning the anterior cruciate ligament (ACL cut) increased the anterior limits more at 15 and 30 degrees of flexion than at 90 degrees of flexion (six donors). When the superficial medial collateral ligament (MCL) was subsequently cut (ACL + MCL cut), the anterior limit further increased in the flexed knee (six donors). Subsequent cutting of the posteromedial capsule (PMC) (*top curve*) produced an additional 2.4- to 4-mm increase over that for the ACL and MCL injury (nine donors). Error bars show the standard error of the mean. (From Haimes JL, Wroble RR, Grood ES, Noyes FR. Role of the medial structures in the intact and anterior cruciate ligament-deficient knee. Limits of motion in the human knee. *Am J Sports Med.* 1994;22:402-409.)

TABLE 3-11 Mean Degrees of Coupled Rotation During Anterior Translation and Abduction Tests for Intact Knees and After Ligament Sectioning

	ANTERIOR TEST FLEXION ANGLE		ABDUCTION TEST FLEXION ANGLE		
	30 Degrees	90 Degrees	0 Degree	15 Degrees	30 Degrees
Intact	–8.6	–10.6	–2	–4.1	–6.9
ACL	–5.4	–5	–3.2	–7	–9.1
MCL	–11.7	–14.7	1.4	6.4	5.9
ACL + MCL	0.6	0	–0.5	–2.5	–4.2

Negative numbers represent internal rotation and positive numbers represent external rotation. These numbers are the change in tibial rotation from the position of the tibia in the intact knee during passive flexion to the position of the tibia after application of anterior forces or abduction moments. Intact (11 donors); ACL cut (6 donors); MCL cut (6 donors); ACL + MCL cut (6 donors).
ACL, Anterior cruciate ligament; *MCL*, medial collateral ligament.

The increase in the external tibial rotation limit with ligament sectioning is shown in Figure 3-38. Sectioning of the MCL produced major increases in external tibial rotation that increased with each subsequent ligament sectioning. The MCL acted as the primary restraint to external tibial rotation at all flexion angles. Cutting just the PMC (ACL, MCL intact) did not result in any increase in external tibial rotation (see Table 3-10).

The increase in the internal tibial rotation limit is shown in Figure 3-39. Note that the internal tibial rotation limit increases in the intact knee with knee flexion. ACL sectioning produced small increases in internal rotation (<3 degrees) at 0 and 15 degrees of knee flexion (see Table 3-10). Sectioning the PMC alone had no effect on internal tibial rotation; however, PMC sectioning after MCL and ACL sectioning produced a major increase in the internal limit from 0 to 45 degrees of knee flexion.

The changes in the abduction rotation limits in the intact knee and with ligament sectioning are shown in Figure 3-40. The MCL was the primary restraint; however, the data show only small increases in abduction (medial joint opening) with complete MCL sectioning, with further increases in the motion limits after the PMC was sectioned. The ACL cut allowed for even further increases in abduction, indicating that it is a secondary restraint after the medial ligaments (MCL, PMC) are cut.

The conclusions of this cadaveric study on the function of the ACL and medial ligament structures applied to the clinical diagnosis and function of ligament injuries are:

1. ACL sectioning alone allows only small increases in internal tibial rotation and no increases in external tibial rotation. When all medial structures (ACL intact) were sectioned, the abduction limit increased to only about 7 degrees, or 7 to 8 mm of medial joint opening. This suggests that partial to complete ACL tears are required for further increases to occur in medial joint opening (see Table 3-10).
2. The MCL (and deep medial capsule) limits anterior tibial translation as a secondary restraint after the ACL is ruptured. A combined ACL/MCL injury has equal anterior translation at 30 and 90 degrees, indicating the Lachman and 90-degree anterior drawer tests will show similar increases in anterior tibial translation, instead of only the major increase at 30 degrees of knee flexion.
3. In the ACL- and MCL-deficient knee, the Lachman test will show an absence of the normal coupled internal tibial rotation in contrast to the coupled rotation in the normal knee and the ACL-deficient knee.
4. The MCL is the primary restraint for external tibial rotation; however, the increase is small (4.6 degrees to 8.7 degrees from 30 to 90 degrees of flexion). The increase in external rotation doubles when the PMC is also sectioned. Further increases in external rotation to approximately 15 degrees occur when the ACL is also sectioned. The results validate the importance of performing the dial tibial rotation test (see Chapter 15 and Chapter 17) to determine anterior subluxation of the medial tibial plateau with medial ligament injuries.

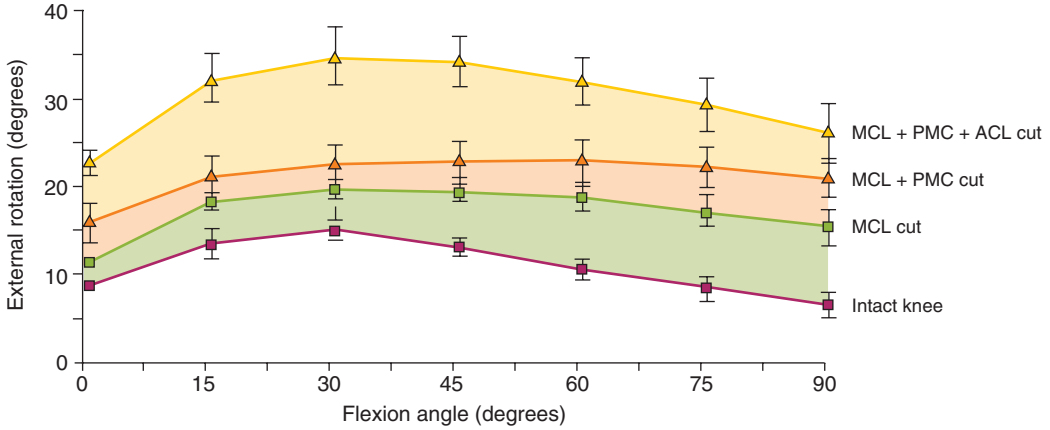


FIG 3-38 The external rotation limits in the intact knee (*bottom curve*) first increased with flexion to 30 degrees and then decreased with further flexion (11 donors). Cutting just the superficial medial collateral ligament (MCL cut) increased the external rotation limits more in flexion than in extension (16 donors). Further cutting of the posteromedial capsule (PMC [MCL + PMC cut]) produced a further increase in the external limit at all flexion angles, but the increase was again greater in flexion than in extension. Cutting the superficial MCL, the PMC, and the anterior cruciate ligament (ACL) allowed for a large increase in the external limit, particularly from 15 to 45 degrees of flexion (*top curve*). (From Haimes JL, Wroble RR, Grood ES, Noyes FR. Role of the medial structures in the intact and anterior cruciate ligament-deficient knee. Limits of motion in the human knee. *Am J Sports Med.* 1994;22:402-409.)

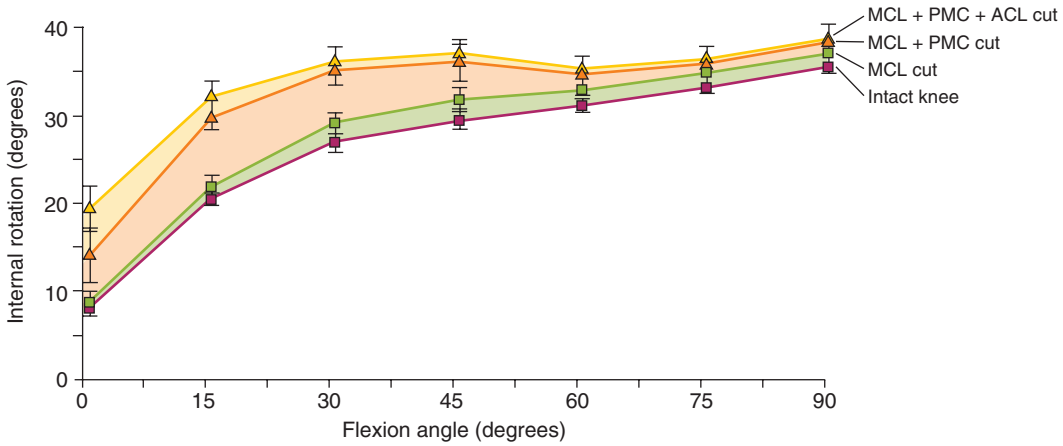


FIG 3-39 The internal rotation limits of the intact knee (*bottom curve*) increased progressively as the knee was passively flexed (11 donors). Cutting the superficial medial collateral ligament (MCL [MCL Cut]) produced only a small increase in the internal rotation limits (six donors). Cutting the MCL and posteromedial capsule (PMC [MCL + PMC Cut]) caused large increases in the internal rotation limits from 0 to 45 degrees of flexion (six donors). Cutting the MCL, the PMC, and the anterior cruciate ligament (ACL) (*top curve*) caused similarly large increases in the internal limits from 0 to 45 degrees of flexion relative to the intact knee (six donors). However, these increases were not significantly different from those seen with the MCL and PMC cut. (From Haimes JL, Wroble RR, Grood ES, Noyes FR. Role of the medial structures in the intact and anterior cruciate ligament-deficient knee. Limits of motion in the human knee. *Am J Sports Med.* 1994;22:402-409.)

5. The combined MCL/PMC injury results in increases in external tibial rotation (9 degrees at 30 degrees of flexion), increases in internal tibial rotation (12 degrees at 30 degrees of flexion), and increases in abduction testing at 0 degrees and 30 degrees of flexion (6 degrees and 9 degrees, respectively). The increase in internal tibial rotation was previously recognized by Mueller[44] and is an interesting finding not commonly reported.

The results of the authors' studies are in agreement with other published data in cadaveric knees. Robinson and coworkers[68] studied the superficial medial collateral ligament (SMCL), the deep medial collateral ligament (DMCL) and the PMC and measured the changes in motion limits under AP drawer, valgus, and internal-external rotation loads by sequential MCL cutting in 18 cadaveric knees. These authors reported that the PMC limited valgus, internal rotation, and posterior drawer in extension, resisting 42% of a 150-N drawer force when the tibia was in internal rotation (Figs. 3-41 to 3-44). The SMCL resisted valgus at all angles and was dominant from 30 to 90 degrees of flexion, plus internal rotation in flexion. The DMCL resisted tibial anterior translation of the flexed and externally rotated knee and was a secondary restraint to valgus.

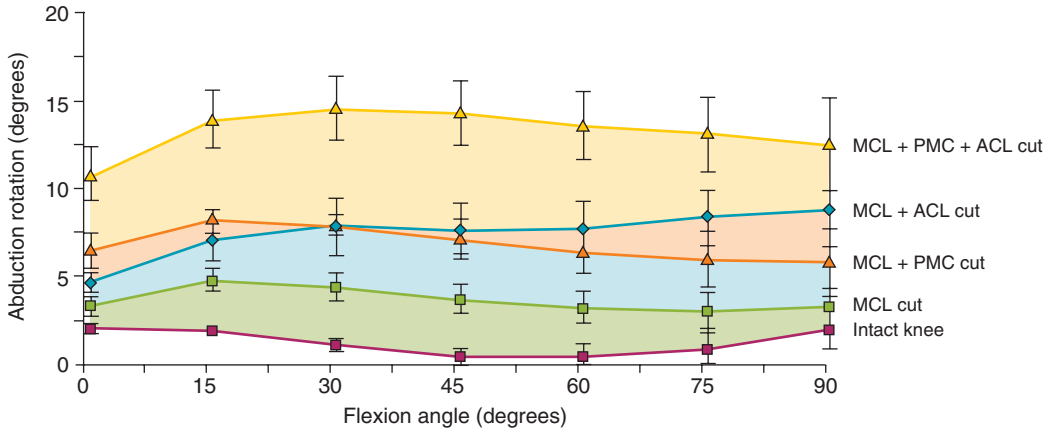


FIG 3-40 The abduction rotation limits (valgus opening) of the intact knee (*bottom curve*; 11 donors). Cutting only the medial collateral ligament (MCL cut) produced a small increase (approximately 2 to 4 degrees) in the abduction limit from 15 to 75 degrees of flexion. Cutting the anterior cruciate ligament (ACL [MCL + ACL cut]) increased the abduction limit (six donors). Cutting the posteromedial capsule (PMC) in addition to the MCL (MCL + PMC cut) with the ACL intact allowed for a further small but consistent increase (2 to 3 degrees) over the superficial MCL alone (six donors). When compared with the intact knee, this injury combination increased the abduction limit approximately 6 to 7 degrees at both 15 and 30 degrees of flexion. Subsequent cutting of the ACL (*top curve*) caused a large increased in the abduction limits at all flexion angles (nine donors). (From Haimes JL, Wroble RR, Grood ES, Noyes FR. Role of the medial structures in the intact and anterior cruciate ligament-deficient knee. Limits of motion in the human knee. *Am J Sports Med.* 1994;22:402-409.)

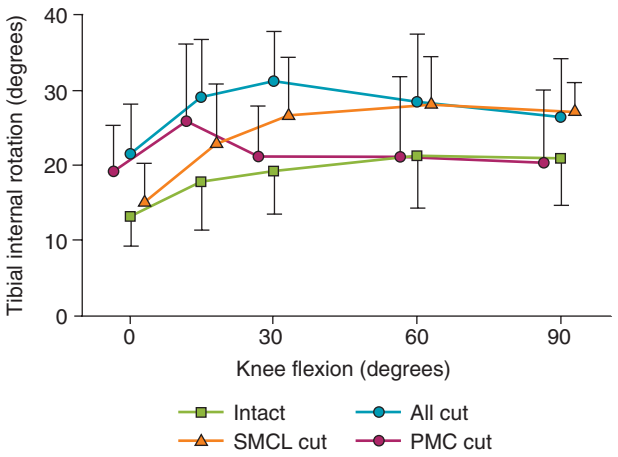


FIG 3-41 Tibial internal rotation motion limits with the knee intact (n = 18) and cutting the superficial medial collateral ligament (SMCL) alone (n = 4), posteromedial capsule (PMC) alone (n = 4), and SMCL, deep medial collateral ligament, and PMC together (n = 14). These data show the reciprocal action of the SMCL and PMC restraining internal rotation at different angles of tibiofemoral flexion. (From Robinson JR, Bull AM, Thomas RR, Amis AA. The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity. *Am J Sports Med.* 2006;34:1815-1823.)

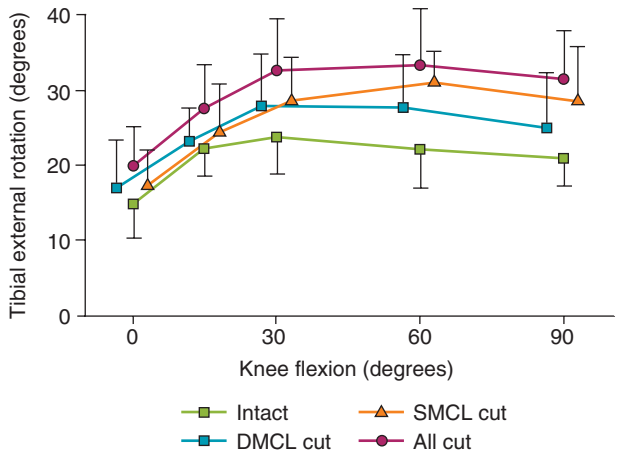


FIG 3-42 Tibial external rotation motion limits with the knee intact (n = 18) as well as changes caused by cutting either the superficial medial collateral ligament (SMCL) alone (n = 4) or the deep medial collateral ligament (DMCL) alone (n = 6) or after cutting both the whole MCL and the posteromedial capsule (n = 14). (From Robinson JR, Bull AM, Thomas RR, Amis AA. The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity. *Am J Sports Med.* 2006;34:1815-1823.)

Robinson and coworkers[68] reaffirmed that the PMC is an important structure for stabilizing the extended knee under valgus loading (32% of the resistance). With knee flexion, the PMC slackens and the MCL becomes the dominant restraint. In the extended knee, with posterior drawer and internal rotation, the PMC tightens based on its attachments at the femur (just posterior to the adductor tubercle) and the posteromedial aspect of the tibia resisting 42% of the posterior load.

In the bumper model of ligament behavior previously discussed, applying an internal tibial rotation tightens the PMC and SMCL, thereby increasing their resistance to posterior tibial displacement. The internal tibial rotation also tightens the ITB and midlateral capsule. In essence, the tibia is placed in a highly constrained position with AP translation blocked by lateral and medial extraarticular structures.

The posterior drawer test for PCL rupture is performed in neutral tibial rotation to determine the maximum posterior tibial translation. When the posterior drawer is repeated in maximal internal rotation (in knees with a PCL rupture), the amount of posterior tibial translation will markedly decrease if the PMC is intact. This can be used as a test to reaffirm that the medial secondary restraints are

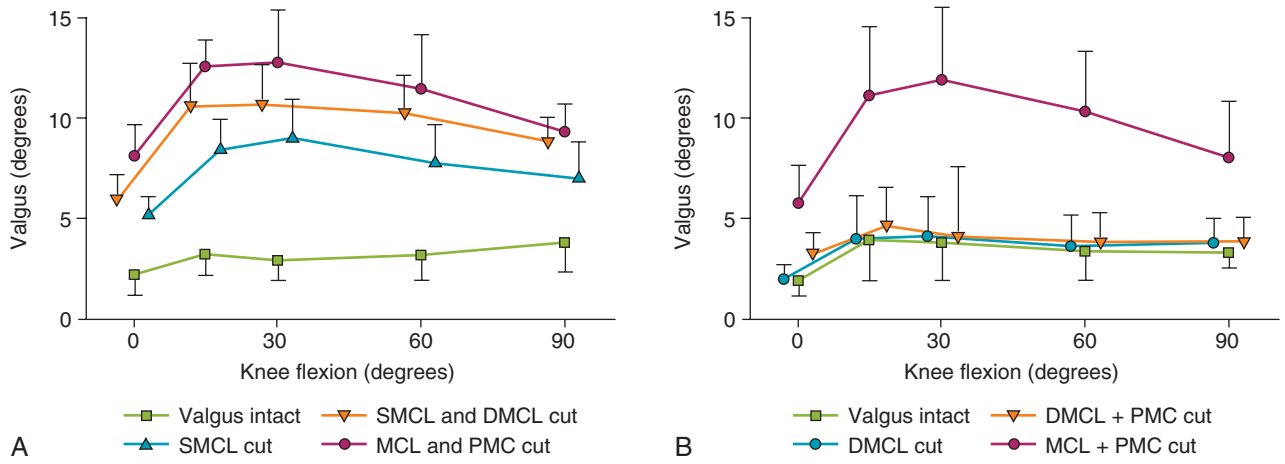


FIG 3-43 A, Valgus rotation produced by a 5 N-m moment of the intact knee and after sequential division of the posteromedial structures, superficial medial collateral ligament (SMCL), then deep medial collateral ligament (DMCL), then posteromedial capsule (PMC; $n = 4$). **B,** Valgus rotation with the knee intact and after sequential division of the posteromedial structures, DMCL, then PMC, then SMCL ($n = 6$). (From Robinson JR, Bull AM, Thomas RR, Amis AA. The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity. *Am J Sports Med.* 2006;34:1815-1823.)

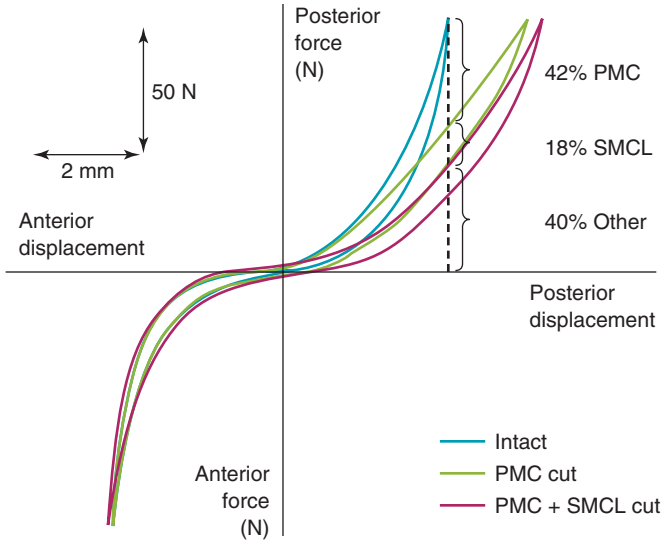


FIG 3-44 Force-displacement test: mean load versus displacement curves for intact, posteromedial capsule (PMC)-deficient, and PMC + superficial medial collateral ligament (SMCL)-deficient knees tested at 0 degrees of flexion with fixed tibial internal rotation. Load share calculated for 100-N posterior displacement force ($n = 4$). (From Robinson JR, Bull AM, Thomas RR, Amis AA. The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity. *Am J Sports Med.* 2006;34:1815-1823.)

disrupted. However, more accurate medial joint opening tests at 5 and 25 degrees of flexion provide the same and frequently more meaningful data.

In regard to the anatomic description in these biomechanical experiments, Robinson and associates[69] dissected the MCL and capsular structures in 20 cadaver knees and reported on the anatomy of the SMCL, DMCL, and PMC. In the PMC, there were oblique fibers referred to as *capsular condensations* that attached at the posterior margin of the SMCL femoral attachment at the femoral epicondyle, proceeding in a distal direction to blend in with the capsule and semimembranosus tendon sheath expansions. These capsular fibers tightened with internal tibial rotation, and the entire PMC tightened with knee extension. The authors reported that the three distinct bands corresponding to the posterior oblique ligament (POL) described by Hughston and Eilers[30] could not be identified, preferring instead to use the nomenclature of the PMC.

Griffith and associates[17] conducted a study on the static function of the medial knee ligament structures in 24 cadaveric knees and emphasized the intricate relationship among the medial ligaments in resisting applied valgus and internal and external rotation torques. A comparison of their results with results of our study[20] show some discrepancies in the magnitude of medial joint opening and degrees of external rotation and internal rotation with ligament sectioning (Fig. 3-45 and Fig. 3-46). It is important to view the results of both studies because they reflect the significant inherent variability from one specimen to another in cadaveric tests. This is further reflected in the bumper model explanations previously described. Overall, both studies are more in agreement than disagreement on the loading relationship of the medial components. Of note, Griffith and associates'[17] study does divide the SMCL into distal and proximal sections in terms of function. These authors reported the proximal division of the SMCL as the primary valgus stabilizer; however, we question this conclusion. Sectioning the distal division also produced major increases in valgus rotation and the proximal SMCL was never sectioned as the first structure. In addition, another study by Griffith and associates[18] on force measurements in the SMCL proximal and distal divisions under valgus loading showed statistically significant resisting forces in the distal SMCL.

EFFECT OF SECTIONING THE MCL AND PMC ON POSTERIOR TIBIAL TRANSLATION

Ritchie and colleagues[66] studied in 14 cadaver knees the contribution of various structures in the PCL-deficient knee in resisting posterior tibial translation. Single-plane posterior drawer tests were performed with the knee in neutral tibial rotation and in 20 degrees of internal tibial rotation. The authors reported that with the knee in internal tibial rotation, posterior displacement was significantly less compared with that in neutral rotation when the SMCL was sectioned. The results showed that the SMCL was responsible for a decrease in posterior tibial

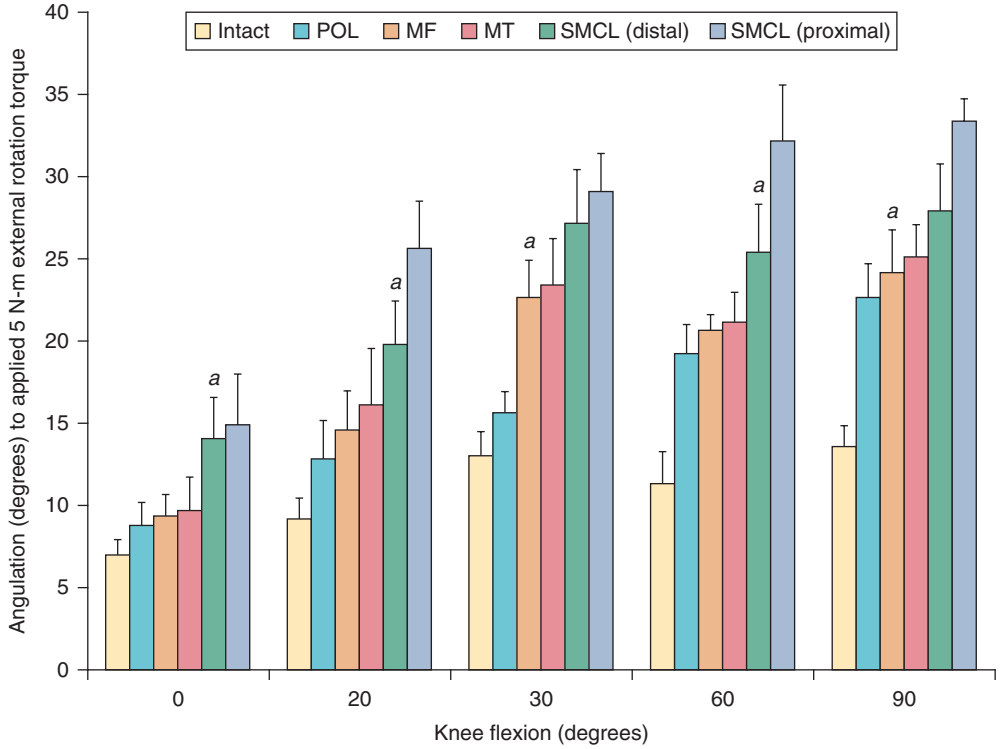


FIG 3-45 Knee angulation changes resulting from an applied external rotation torque (5 N-m) for each group of eight sectioned knees. Testing conditions for group 1 (sectioning of the posterior oblique ligament [POL] first). *a,* Significant difference compared with the intact knee (note that all sequential sectioning states are significantly different compared with the intact knee). Error bars indicate the standard error of the mean. *MF,* Meniscofemoral attachment of deep medial collateral ligament; *MT,* meniscotibial attachment of deep medial collateral ligament; *SMCL,* superficial medial collateral ligament. (From Griffith CJ, LaPrade RF, Johansen S, et al. Medial knee injury: part 1, static function of the individual components of the main medial knee structures. *Am J Sports Med.* 2009;37:1762-1770.)

translation in the PCL-deficient knee and not the PMC, including the POL.

ROLE OF THE POL

In a cadaveric study using a robotic testing system, Petersen and coworkers[65] examined the restraint of the SMCL, the DMCL, the POL, and the PMC in resisting posterior tibial translation after PCL sectioning. The study reported that the POL had a much larger role than the SMCL and DMCL in resisting posterior tibial translation and internal tibial rotation. It should be noted that these two structures were first sectioned; no studies were done when the POL was sectioned first. This indicates there could be a sectioning artifact introduced in the study. Even so, there are posteromedial oblique capsular fibers from the medial femoral condyle to the tibia, just posterior to the SMCL, that resist internal tibial rotation and posterior tibial translation (after PCL sectioning). The study concluded that there are discrete oblique fibers that form the middle arm of the POL described by Hughston and Eilers.[30] Of interest in this cadaveric study was the finding that a valgus loading of the knee joint close to knee extension (with PCL deficiency) produced an increased posterior tibial translation of the medial compartment with absence of the POL and PMC.

Robinson and associates[69] conducted a cadaveric study of the medial and posteromedial structures and could not identify a distinct separate POL structure, but they did identify an oblique portion of the PMC where fibers could be tensioned under internal tibial rotation loading. Robinson and coworkers[68] and Haimes and associates[23] studied the contribution of the PMC, which included the POL. Robinson and coworkers[68] reported that the PMC resisted 28% of the posterior tibial load when the tibia rotated freely in the extended knee, which rose to 42% when the tibia was subjected internal rotation. These authors concluded that the PMC resisted posterior tibial translation close to full extension, and less so with knee flexion, which relaxes the PMC. With knee flexion, the SMCL resisted posterior tibial translation.

The role of the POL (along with the SMCL) in resisting internal and external tibial rotation was further studied by Griffith and colleagues[17,18] and Wijdicks and coworkers[78] and is discussed further in Chapter 19 in reference to the dial test for diagnosis.

In knees with chronic PCL instability and associated medial and posteromedial ligament and capsular injury, the integrity of all the structures should be restored. Specific tests for increased internal tibial rotation using the dial test are performed.

VARIABILITY AMONG CLINICIANS DURING CLINICAL KNEE LIGAMENT TESTING

There is a well-appreciated difficulty in quantifying the amount of tibial displacements and rotations in the clinical knee examination, and the potential exists for considerable variability to occur among examiners. For this reason, any attempt to provide objective

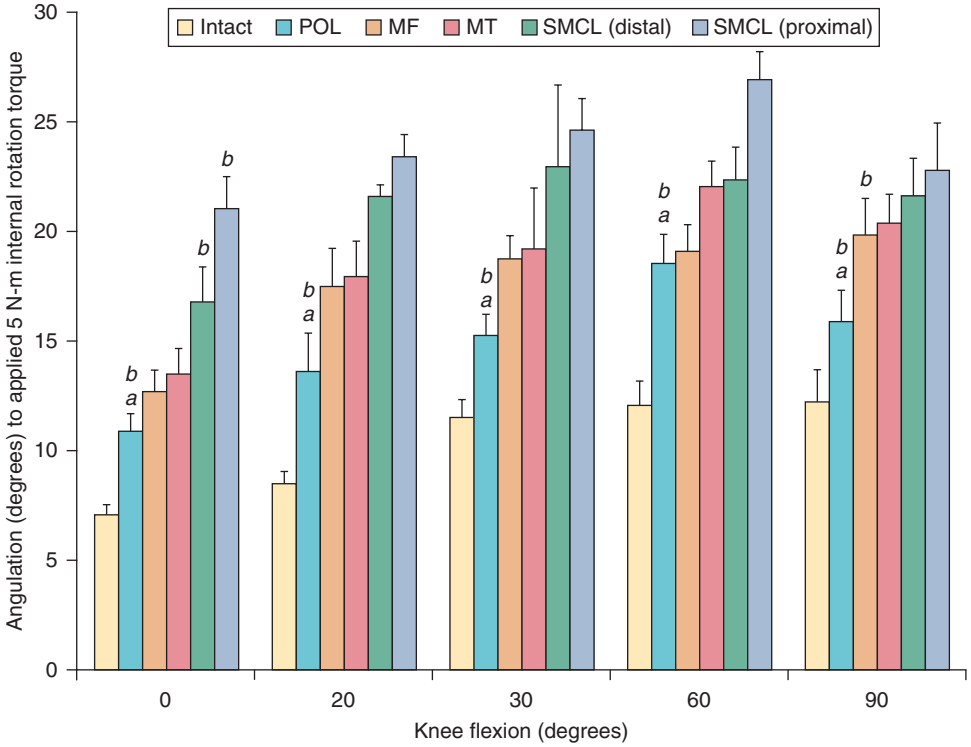


FIG 3-46 Knee angulation changes resulting from an applied internal rotation torque (5 N-m) for each group of eight sectioned knees. Testing conditions for group 1 (sectioning of the posterior oblique ligament [POL] first). *a,* Significant difference compared with the intact knee (note that all sequential sectioning states are significantly different compared with the intact knee). *b,* Significant difference compared with the previous sectioning state. Error bars indicate the standard error of the mean. *MF,* Meniscofemoral attachment of deep medial collateral ligament; *MT,* meniscotibial attachment of deep medial collateral ligament; *SMCL,* superficial medial collateral ligament. (From Griffith CJ, LaPrade RF, Johansen S, et al. Medial knee injury: part 1, static function of the individual components of the main medial knee structures. *Am J Sports Med.* 2009;37:1762-1770.)

CRITICAL POINTS Variability Among Clinicians During Clinical Knee Ligament Testing

- An investigation was conducted with 11 experienced knee surgeons to determine differences in clinical examination testing techniques, accuracy in estimating knee displacements, and skill in diagnosing specific ligament injuries in knees with multiple abnormal motion limits.
- Wide variability existed among examiners in the starting position (knee flexion, tibial rotation) for AP displacement during the Lachman test and in the amount of tibial translation and rotation induced.
- Variability existed in the starting position for the pivot shift test and in the amounts of anterior tibial translation and internal tibial rotation produced. Many examiners induced coupled motions of anterior tibial translation and internal tibial rotation to produce anterior tibial subluxation without constraining or enhancing either motion.
- Most estimates were within 3 mm of the measured values in the laboratory during the medial joint abduction test. The examiners performed the test at a different flexion angle and reached a different final tibiofemoral position in both the intact knee and the ACL/MCL-sectioned knee.
- Large variations were found in the amount of internal and external tibial rotation induced in the ACL/MCL-sectioned knee. Each examiner performed the test at a different knee flexion angle and reached a different final rotation position.
- Seven examiners incorrectly diagnosed an injury to the posterolateral structures after the ACL and MCL were sectioned.
- The pivot shift test is qualitative in nature and imprecise in determining the results of ACL reconstructive procedures.
- Examination test techniques must be standardized regarding the test conditions so that examiners conduct knee examinations in a similar manner.
- The diagnosis of rotatory subluxations is highly subjective and requires a careful assessment of the AP position of the medial and lateral tibial plateaus relative to the femur.

measurements, such as knee arthrometer or stress radiographs (even with these test limitations), is believed to be more accurate than comparing manual examination results among various clinicians.

An investigation was conducted with 11 experienced knee surgeons to determine differences in clinical examination testing techniques, accuracy in estimating knee displacements, and skill in diagnosing specific ligament injuries in knees with multiple abnormal motion limits.[50,54] Knee joint positions and abnormal motions were measured in right-left cadaveric knees by a 3-dimensional instrumented spatial linkage. A comparison was made of the clinicians' estimate of the knee motion limits and subluxations with the actual measured values. The 3-dimensional limits of knee motion were measured in the laboratory

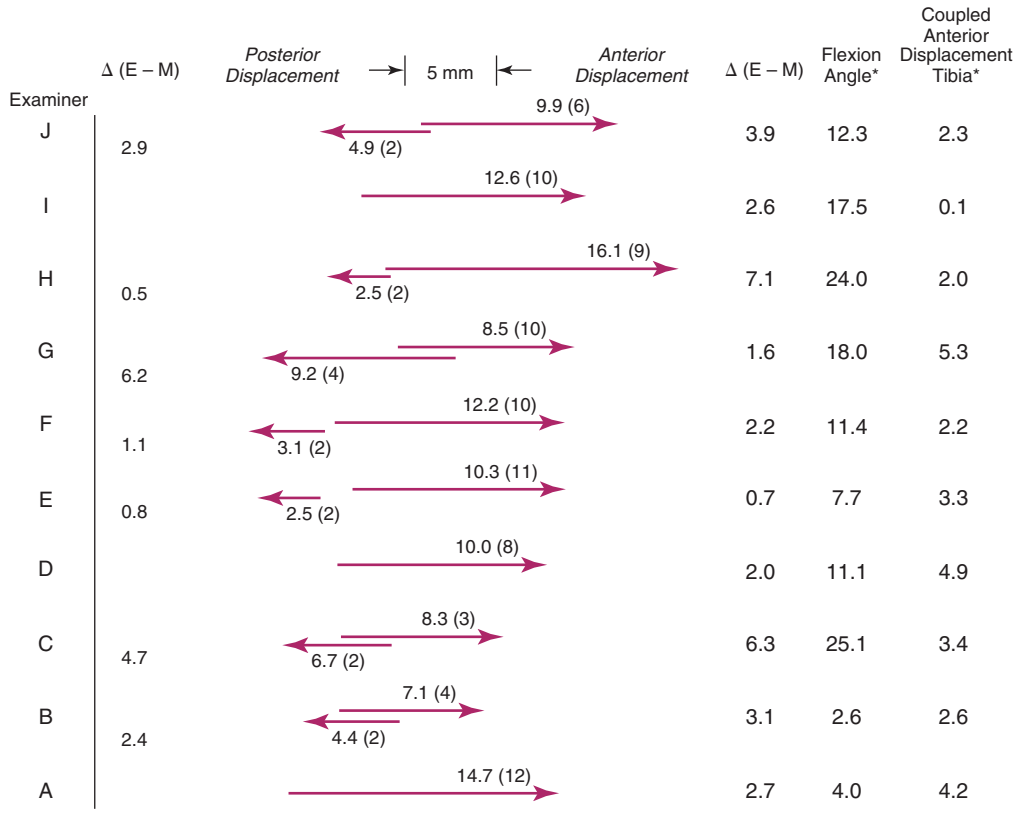


FIG 3-47 The instrumented spatial linkage measured values for anterior and posterior displacement for each examiner. The numbers above and below each bar give the measured displacement; the examiner-estimated values are given in parentheses. Starting position flexion angles and the coupled external rotation for the anterior displacement test are given for each examiner. *Δ (E – M),* Difference between estimated and measured instrumented spatial linkage value (examiner's estimated value). *Measured during anterior displacement test. (From Noyes FR, Cummings JF, Grood ES, et al. The diagnosis of knee motion limits, subluxations, and ligament injuries. *Am J Sports Med.* 1991;19:163-171.)

under defined loading conditions before and after the clinicians' examination.

Anteroposterior Displacement

Wide variability existed among examiners in the starting position of knee flexion and tibial rotation for AP displacement during the Lachman test (Fig. 3-47), and for the amount of tibial translation and rotation induced. Although some of the clinicians displaced the knee to the maximal displacement limits obtained in the laboratory, others failed to do so by a wide margin. The conclusion was reached that there was a wide variation in the loads applied among the examiners during the tests.

Pivot Shift Testing

The starting position for the pivot shift test varied among examiners but was typically close to 5 degrees extension (Fig. 3-48). As the knee was flexed, varying amounts of anterior tibial translation and internal tibial rotation were produced. During flexion, the maximal amount of internal tibial rotation was achieved first, followed by the maximal amount of anterior tibial translation. Although the amount of anterior translation of the lateral tibial plateau was similar among examiners, large differences existed among the clinicians (range, 6-16.9 mm) in the amount of maximum anterior translation of the medial tibial plateau. Examiners who produced the greatest amount of internal tibial rotation during the pivot shift test also significantly limited the amount of anterior translation of the medial tibial plateau ($R = -.79$, $P < .01$).

The maximal amount of anterior tibial translation and the limits to anterior and posterior translation produced by each examiner are shown in Figure 3-49. The normal and abnormal limits of tibial translation are shown before and after combined ACL and MCL ligament sectioning. The maximal amount of anterior translation (central point) ranged from 10 to 18 mm among examiners, and the maximal amount of anterior subluxation of the lateral tibial plateau ranged from 14 to 19.8 mm.

The mean value for maximal internal tibial rotation induced during the pivot shift test was 15.8 degrees ± 3.6 degrees (range, 11-24 degrees). Maximal internal rotation occurred at an average knee flexion angle of 15.6 degrees ± 5.2 degrees (range, 5-23 degrees). The limits to internal and external tibial rotation are shown in Figure 3-50. Two examiners exceeded the normal intact internal tibial rotation limit obtained under 5 N-m of torque. Only a slight increase occurred in the degrees of internal tibial rotation after the ACL and MCL were cut. Increases in external tibial rotation limits were also measured after ACL/MCL sectioning, which occurred during the tibial reduction phase of the pivot shift maneuver.

The tibial reduction phenomenon involved a posterior tibial translation and external tibial rotation. Three examiners (C, F, and I) produced the reduction phase with posterior tibial translation, uncoupling this motion from external tibial rotation. Four examiners (A, B, C, and

F) continued to flex the knee after reduction to about 80 degrees of flexion. Five examiners accentuated the reduction event by producing the maneuver with 20 degrees or less change in knee flexion, which resulted in the steepest decline in the translation and rotation curves.

A few examiners demonstrated variability during the pivot shift test in regard to enhancement of internal tibial rotation (Fig. 3-51 and Fig. 3-52). The millimeters of anterior translation of the medial, central, and lateral points varied depending on how the test was performed.

Medial-Lateral Joint Space Opening

During abduction and adduction rotation testing, the examiners were instructed to begin the tests with the femoral condyle in contact with the tibial plateau. Data from the medial joint space abduction test demonstrated that most of the examiners' estimates were within 3 mm of the actual measured values in the laboratory (Fig. 3-53). The starting flexion angle averaged 11.6 degrees (range, 3.1-21.3 degrees). Each examiner performed the tests at a different flexion angle and reached a different final tibiofemoral position in both the intact knee and the ACL/MCL-sectioned knee (Fig. 3-54).

Internal-External Tibial Rotation

Large variations were found among examiners in the amount of internal and external tibial rotation induced during testing of the ACL/MCL-sectioned knee. Although most of the examiners estimated the total amount of internal tibial rotation to within 5 degrees of that measured in the laboratory, only one examiner provided such an estimate for the total amount of external tibial rotation. The knee flexion angle at the start of the test ranged from 1.9 to 35.3 degrees. Each examiner performed the test at a different knee flexion angle and reached a different final rotation position.

Medial-Lateral Compartment Translations During External Tibial Rotation

After sectioning the ACL and MCL, the amount of external tibial rotation increased from 17.8 degrees (intact knee) to 22.1 degrees. Most of

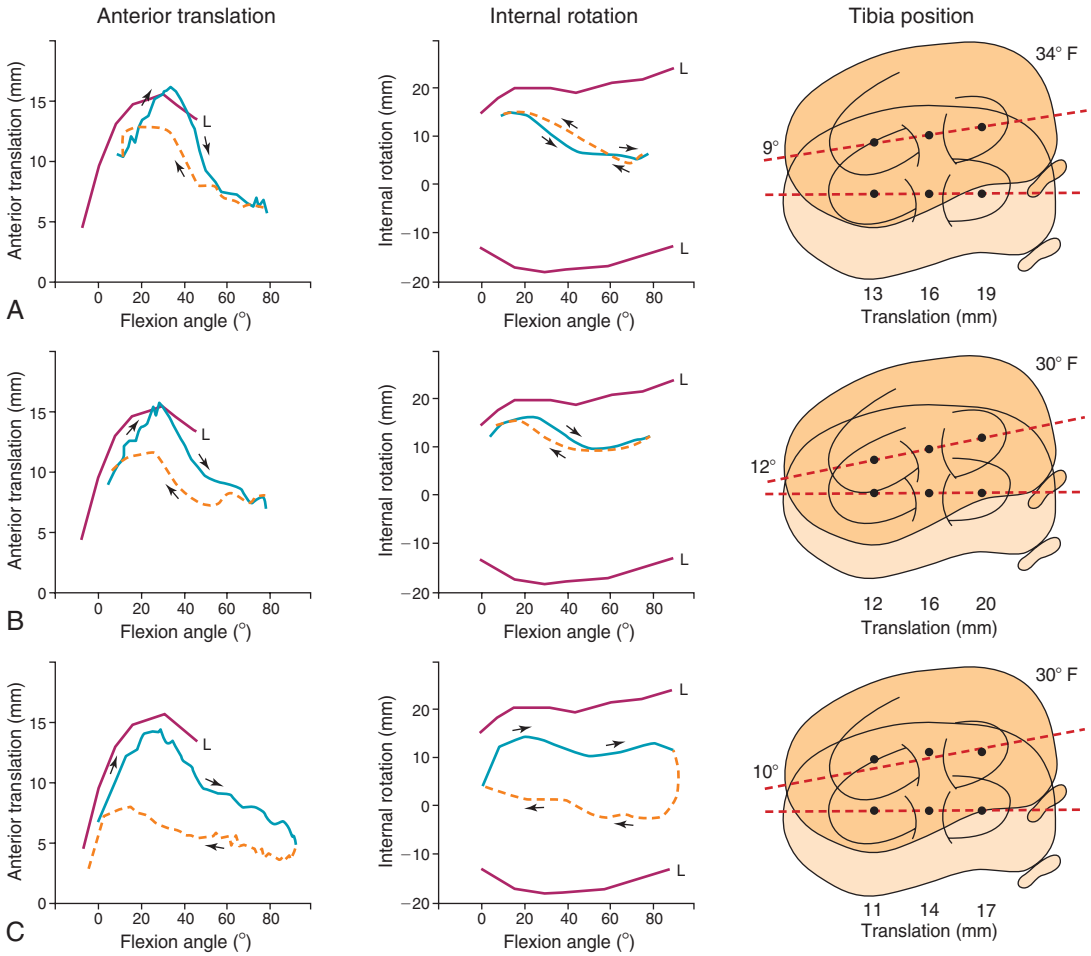


FIG 3-48 The tibial translations and rotations are shown for six examiners (**A** to **F**) during the pivot shift test. The limit curves (L) for 100 N of anterior translation and 5 N-m of the tibial rotation are superimposed on the clinical test results. The test follows the arrow sequence of knee flexion to reach a maximum anterior subluxation, the reduction event, followed by knee extension to return to the starting position of the test. The tibial plateau drawings show the position of maximum anterior subluxation (based on tibial center reference point). The millimeters of anterior translation for the medial, central, and lateral tibial reference points are shown (subluxated position from neutral position). *F,* Flexion. (From Noyes FR, Grood ES, Cummings JF, Wroble RR. An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. *Am J Sports Med.* 1991;19:148-155.)

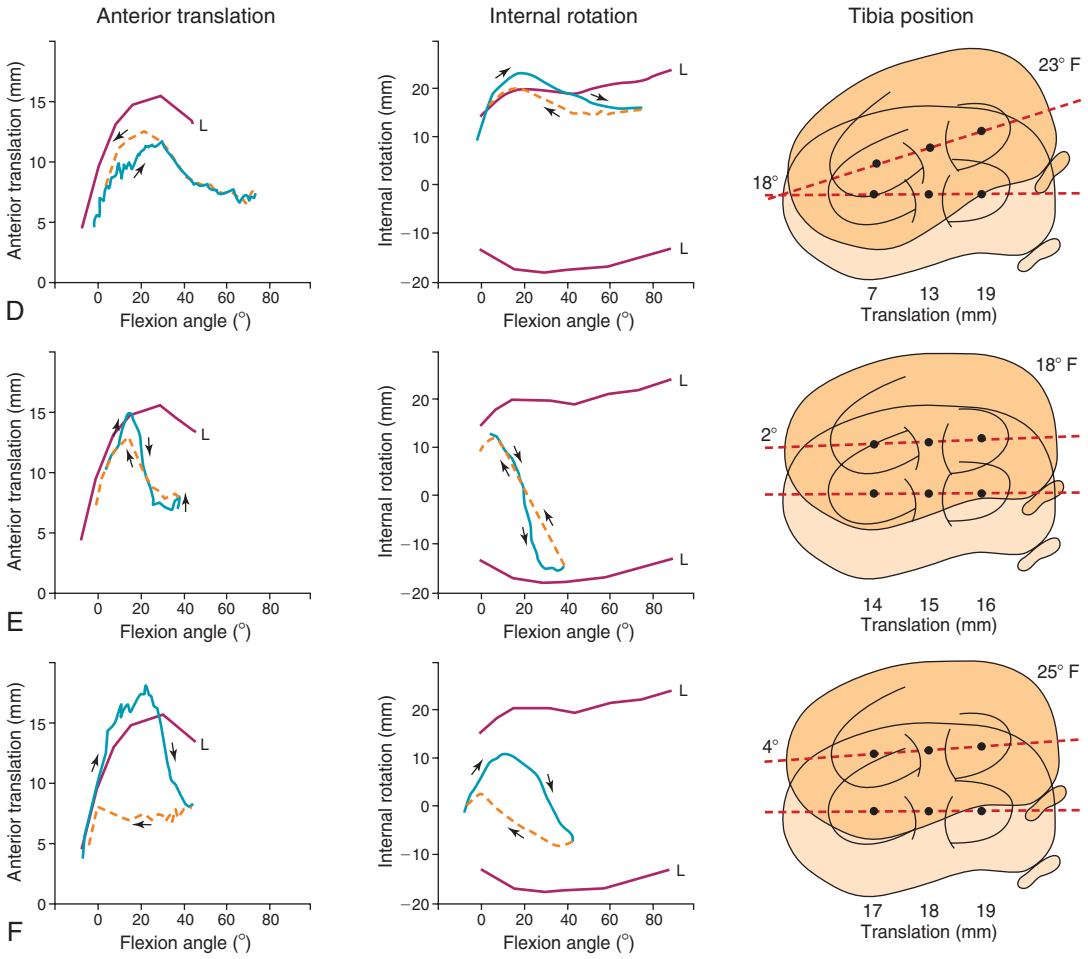


FIG 3-48, cont'd

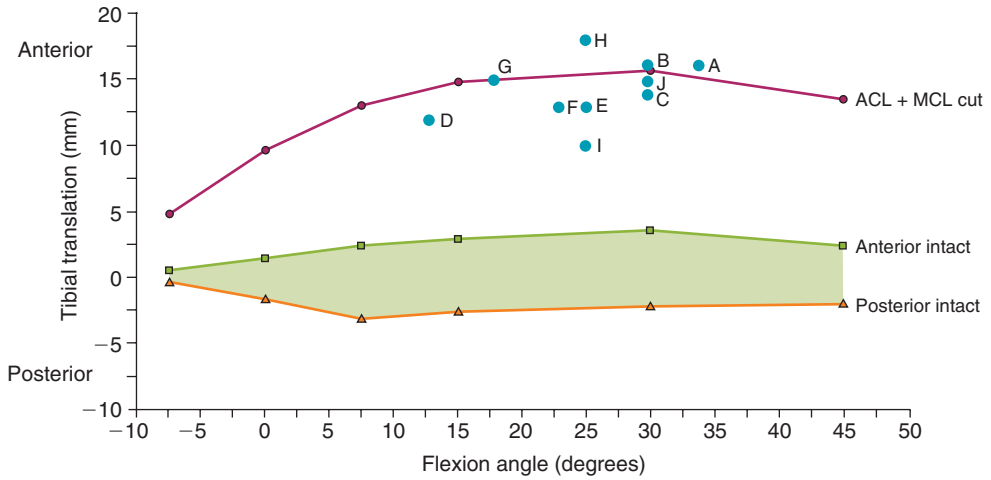


FIG 3-49 The anterior and posterior limits (central point) of tibial translation with a 100-N force are shown before and after ligament cutting. The circles represent the point where the maximum amount of anterior translation occurred for each examiner (*A* to *J*). *ACL,* anterior cruciate ligament; *MCL,* medial collateral ligament. (From Noyes FR, Grood ES, Cummings JF, Wroble RR. An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. *Am J Sports Med.* 1991;19:148-155.)

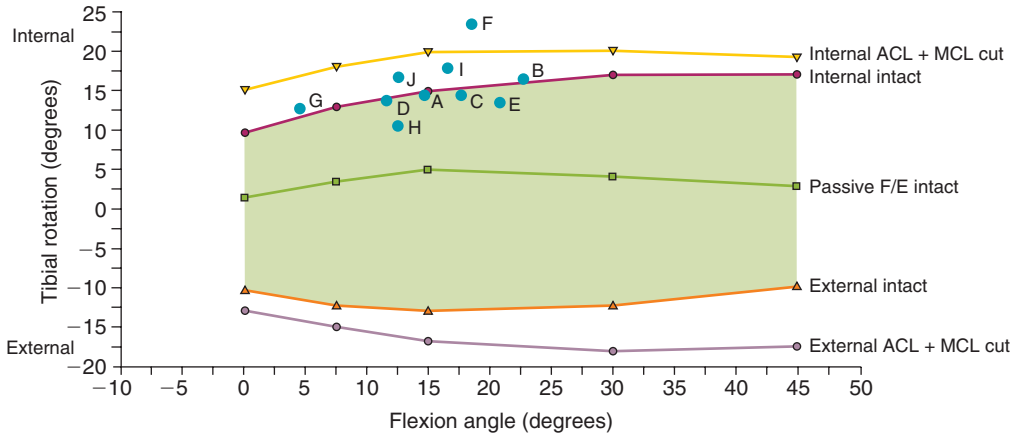


FIG 3-50 The internal and external limits of tibial rotation with a 5 N-m torque are shown before and after ligament cutting. The maximal amount of internal rotation is graphed for each examiner (*A* to *J*). *ACL,* anterior cruciate ligament; *MCL,* medial collateral ligament. (From Noyes FR, Grood ES, Cummings JF, Wroble RR. An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. *Am J Sports Med.* 1991;19:148-155.)

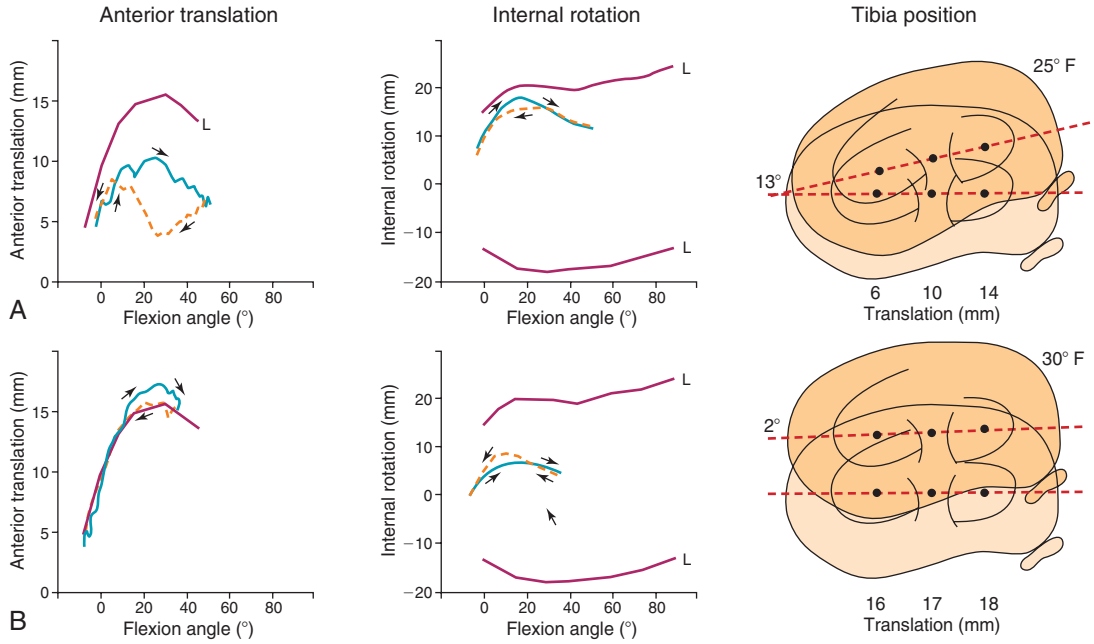


FIG 3-51 Two methods of tibial positioning are shown: (1) by enhancing internal rotation during the pivot shift test and (2) by not enhancing internal tibial rotation. The enhanced internal tibial rotation limited anterior translation of the tibia. *F,* Flexion; *L,* Limit curve. (From Noyes FR, Grood ES, Cummings JF, Wroble RR. An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. *Am J Sports Med.* 1991;19:148-155.)

the examiners produced an increase in anterior translation of the medial tibial plateau during the external rotation test. The displacement of the medial and lateral tibial plateaus in both the intact and ACL/MCL-sectioned states are shown in Figure 3-55. The average center of tibial rotation in both states was in the lateral tibiofemoral compartment. The lateral shift in the axis of tibial rotation is demonstrated in Figure 3-55, *B*, along with the increase in anterior displacement (range, 3.0-8.5 mm) of the medial tibial plateau. Seven of the 11 examiners incorrectly diagnosed an injury to the posterolateral structures, even though the lateral tibial plateau did not displace further posteriorly.

Study Limitations and Conclusions

Limitations existed in these studies, including the use of cadaver limbs which do not represent actual clinical conditions. Although whole lower limbs were used, with the hip replaced with a ball- and socket-joint, the muscles and capsular structures of the hip were removed, which may have affected femoral rotations. The forces or torques applied to the limb by each examiner were not directly measured but were inferred by comparing the joint displacements obtained in the clinical tests with those documented in the laboratory under defined loading conditions. The pivot shift test technique used by many examiners more closely replicated that which would be used while patients

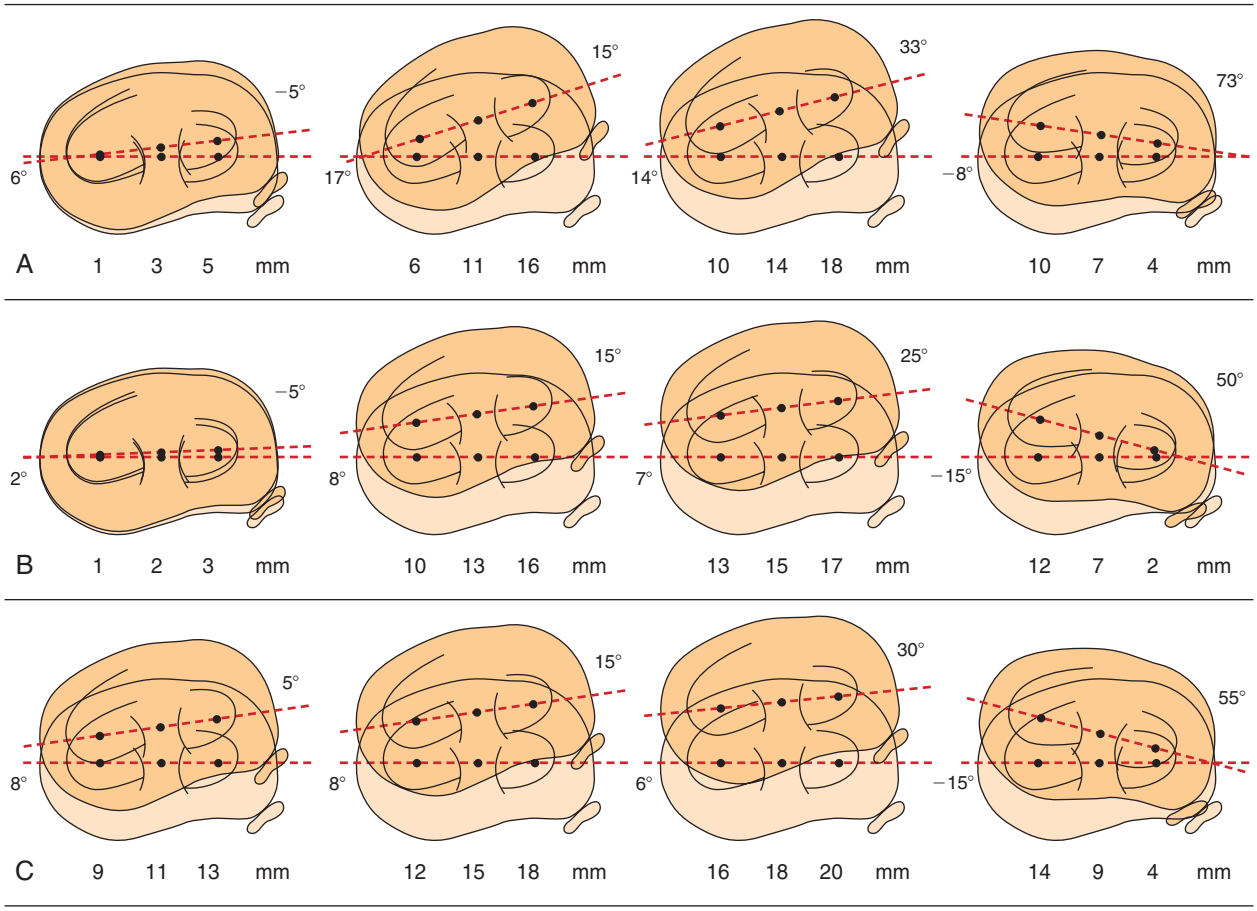


FIG 3-52 **A,** The pivot shift test is performed by first enhancing internal rotation. The test is then repeated in **B,** with the examiner not purposely enhancing internal rotation, and in **C,** with the tibia attempted to be held in a more externally rotated position. In actuality, the tibia is not externally rotated in **B** and **C** until the end of the test. The millimeters of anterior translation of the medial, central, and lateral points vary depending on how the test is performed. (From Noyes FR, Grood ES, Cummings JF, Wroble RR. An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. *Am J Sports Med.* 1991;19:148-155.)

are under anesthesia and not during a clinical examination. The gentler techniques, such as those induced during the flexion-rotation drawer test, avoid pain and apprehension although still induce a subluxation-reduction phenomenon.

The investigation demonstrated that many examiners induced coupled motions during the pivot shift test of anterior tibial translation and internal tibial rotation to produce anterior tibial subluxation without constraining or enhancing either motion. These examiners produced a greater anterior subluxation of the medial and lateral tibial plateaus than those who induced greater amounts of internal tibial rotation, which significantly decreased anterior subluxation of the medial tibial plateau ($P < .01$, Fig. 3-56). The recommendation can, therefore, be made to avoid intentional enhancement of internal tibial rotation when performing this test to allow the tibia to subluxate in the least constrained manner.

The variability demonstrated among examiners in the maximal amount of anterior tibial subluxation produced during the pivot shift test may affect the final grade assigned. It is certainly possible that one examiner would rate a knee as a grade II, and another examiner who applied a smaller force would rate the same knee as a grade I. Thus, the pivot shift test must be considered qualitative in nature and imprecise in determining the results of ACL reconstructive procedures. These results determined the need for a clinical testing device that could measure the anterior and posterior subluxations of the medial and lateral tibial plateaus under controlled loading conditions.

The tests for mediolateral joint space opening demonstrated wide variation among examiners in the starting position of the tibiofemoral compartment during abduction-adduction rotation testing. The medial or lateral tibiofemoral compartment must be in the closed position initially in order for the examiner to be able to accurately estimate the amount of joint space opening.

Even though variation existed among examiners in the estimated displacements, 9 of the 11 clinicians correctly diagnosed the ACL/MCL injury. However, numerous errors were made in the diagnosis of other ligament injuries, most notably, to the posterolateral structures. An increase in external tibial rotation was interpreted by many examiners to be a result of a posterior subluxation of the lateral tibial plateau and, therefore, injury to the posterolateral structures. The abnormality was actually an anterior subluxation of the medial tibial plateau, created by sectioning the ACL and MCL. To avoid this misdiagnosis, the examiner should palpate the medial and lateral tibial plateaus and their position relative to the femoral condyle in the maximum position of external and internal tibial rotation.[58,60] Because this provides only a qualitative estimate, the need exists for instrumented or radiographic

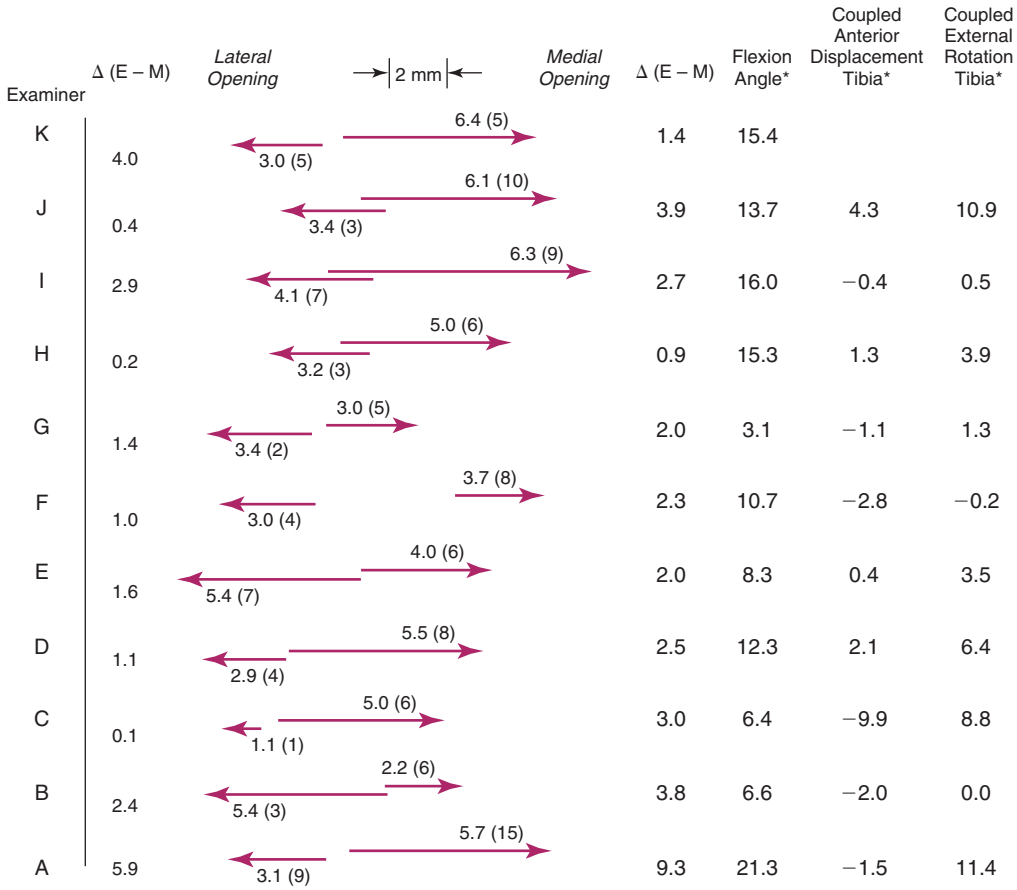


FIG 3-53 Instrumented spatial linkage measured values for the medial and lateral joint space opening in the abduction-adduction rotation test for each examiner (*A* to *K*). The numbers above and below each bar give the measured displacement, and the estimated value for each examiner are in parentheses. Starting position flexion angles, coupled anterior tibial displacement, and the coupled external rotation for the abduction rotation test are given for each examiner. *Δ (E – M),* Difference between estimated and measured instrumented spatial linkage value (examiner's estimated value). *Measured during medial joint space opening test. (From Noyes FR, Cummings JF, Grood ES, et al. The diagnosis of knee motion limits, subluxations, and ligament injuries. *Am J Sports Med.* 1991;19:163-171.)

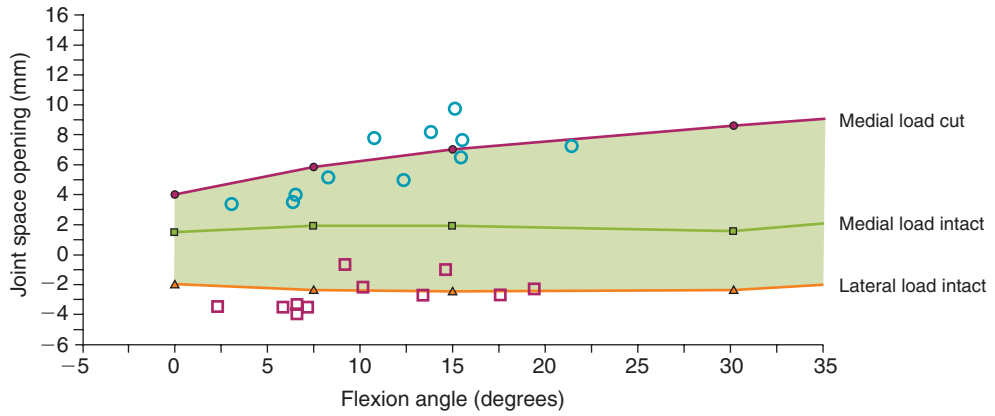


FIG 3-54 The curves show the limits of medial and lateral joint space opening (*vertical axis*) when a 20 N-m force was applied to the knee for both the intact and sectioned states. The *circles* represent individual examiner final positions for the medial test on the anterior cruciate ligament/medial collateral ligament (ACL/MCL)-sectioned knee. The squares represent individual examiner final positions for the lateral test on the ACL/MCL-sectioned knee. (From Noyes FR, Cummings JF, Grood ES, et al. The diagnosis of knee motion limits, subluxations, and ligament injuries. *Am J Sports Med.* 1991;19:163-171.)

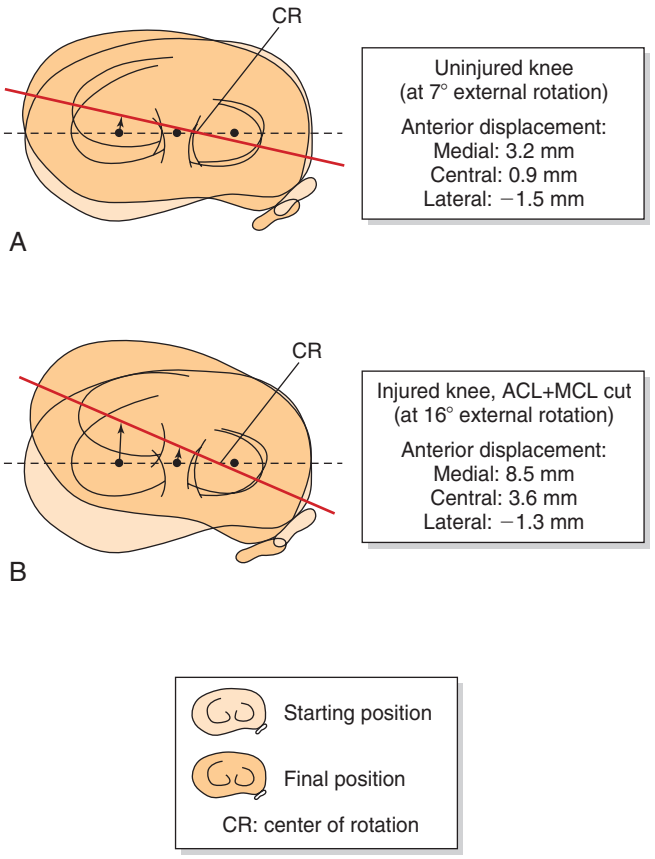


FIG 3-55 External rotation test in the uninjured knee (**A**) and after sectioning the anterior cruciate ligament (ACL) and medial collateral ligament (MCL) (**B**). The increase in external tibial rotation is shown (7 to 16 degrees). The figures show the increase in anterior displacement of the medial tibial plateau and the lateral shift in the axis of tibial rotation. (From Noyes FR, Cummings JF, Grood ES, et al. The diagnosis of knee motion limits, subluxations, and ligament injuries. *Am J Sports Med.* 1991;19:163-171.)

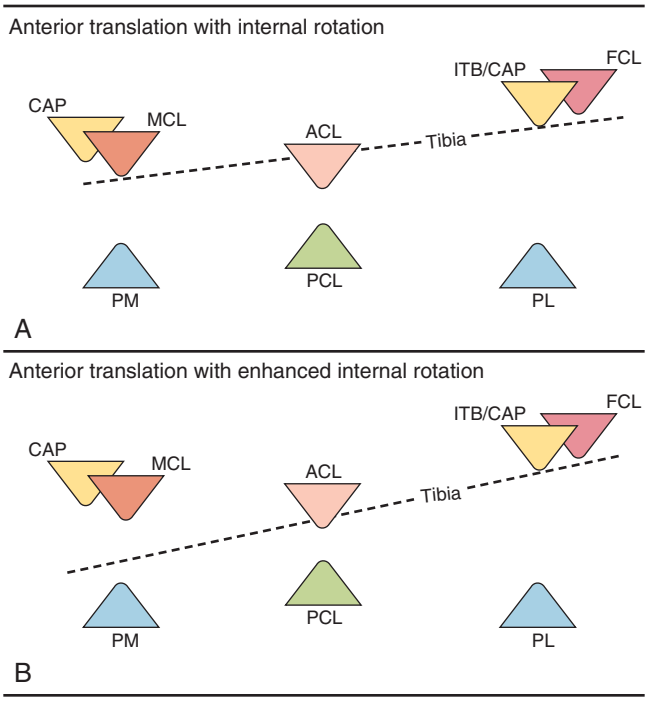


FIG 3-56 The bumper model of the knee joint is shown for the pivot shift test at approximately 20 degrees of knee flexion. The central anterior cruciate ligament (ACL) bumper is not shaded, indicating ACL disruption. The tibial position line extends past this point, being limited by the medial and lateral bumpers. **A,** An anterior translation is combined with internal tibial rotation to reach a maximum anterior subluxation of the medial and lateral tibiofemoral compartments, resisted by the medial and lateral ligament restraints. **B,** Enhanced internal tibial rotation reduces the anterior translation of the central tibial region medial tibiofemoral compartment. *CAP*, Capsule; *FCL,* fibular collateral ligament; *ITB/CAP*, iliotibial band + lateral capsular structures; *MCL*, medial collateral ligament; *PCL,* posterior cruciate ligament; *PL*, posterolateral structures; *PM*, posteromedial structures. (From Noyes FR, Grood ES, Cummings JF, Wroble RR. An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. *Am J Sports Med.* 1991;19:148-155).

methods to diagnose more accurately the complex rotatory subluxations of the knee joint.

Based on these investigations, the following conclusions and recommendations were reached: (1) examination test techniques must be standardized regarding the test conditions so that examiners conduct knee examinations in a similar manner; (2) wide variations among clinicians regarding how knee tests are performed may not allow the comparison of knee motion limits; (3) instrumented teaching models should be developed to increase reproducibility among examiners; (4) reliable quantification of clinical testing in the form of knee arthrometry or stress radiography should be required for reporting clinical results; and (5) the diagnosis of rotatory subluxations is highly subjective and requires a careful assessment of the AP position of the medial and lateral tibial plateaus relative to the femur.

DEFINITION OF TERMS FOR KNEE MOTIONS, POSITIONS, AND LIGAMENT INJURIES

Considerable discrepancy exists in the orthopedic literature in the implied meanings of many terms commonly used to describe knee motions, positions, and ligament injuries. As a result, confusion may develop when clinicians communicate or compare the results of studies. In addition, the use of precise terminology is essential in the development of a valid ligament classification system, as described earlier in this chapter. In recognition of this problem, surgeons and scientists from two institutions conducted a study and made recommendations regarding the definitions of medical and engineering terms commonly used to describe the motion and position of the knee observed during clinical testing.[58]

A systematic format was adopted to (1) categorize the terminology used in major articles on knee ligament injuries; (2) compare terms used in the selected articles to determine whether unique definitions had evolved over time through common usage; (3) review and compare definitions of these terms from a variety of primary, secondary, and tertiary sources; and (4) provide a recommendation for use of these terms in the orthopedic literature. Dictionaries were considered primary sources,[26,74] textbooks were considered secondary sources,[37] and published articles were considered tertiary sources. Terms that had controversial or multiple definitions in the orthopedic literature were classified according to the least ambiguous meaning based on simplicity and clarity.

CRITICAL POINTS Definition of Terms for Knee Motions, Positions, and Ligament Injuries

- Considerable discrepancy exists in the orthopedic literature in the implied meanings of many terms commonly used to describe knee motions, positions, and ligament injuries.
- Motion and displacement of the knee are described by the combination of (1) the change in orientation of the tibia and (2) the motion or displacement of some reference or base point on the tibia.
- *Translation* refers to the motion of a rigid body and not of a point. The use of this term to refer to a point has evolved from general usage. The location of the reference point for translation may be chosen arbitrarily. However, the amount of translation depends on which point is selected; any associated rotation could cause the reference points to move differently.
- *Laxity* indicates slackness or lack of tension in a ligament. Laxity may be normal or abnormal; abnormal laxity may be congenital or result from an injury. The adjective *abnormal* should be used to indicate when laxity is pathologic. Because the word *laxity* has many different meanings (in English), more precise terms should be used when possible to describe abnormalities in motion or position of the knee joint.
- *Instability* frequently indicates a condition (physical sign) that is characterized by abnormal displacement of the tibia and describes an anatomic structure, such as ACL instability. It is preferable to describe the specific defect of the ligament or structures and to provide separately the abnormal displacements of the tibia.
- Considerable confusion exists regarding the definition of terms used to describe rotatory instability of the knee, such as anterolateral, posterolateral, anteromedial, and posteromedial. While some authors use these terms to describe abnormal motions, others use them to describe an abnormal position of the knee joint.
- The goal of the examination of the knee joint is to determine the motions, limits of motion, and initial and final positions of the joint that result from specified loading conditions. The outcome of the test should include the motions of the knee that occur, the abnormal motion limits, and the final tibiofemoral position.

The definitions of terms used to describe positions of the knee (position, dislocation, and subluxation) are shown in Table 3-12, and the terms used to describe motion of the knee (motion, displacement, translation, rotation, range of motion, limits of motion, coupled displacement and motion, constrained and unconstrained motion, force, moment, laxity and instability) are shown in Table 3-13. The terms used to describe injury to the knee (sprain, rupture, and deficiency) are shown in Table 3-14.

Note that motion and displacement of the knee are described by the combination of (1) the change in orientation of the tibia and (2) the motion or displacement of some reference or base point on the tibia. The change in orientation is quantified by the rotation of the tibia about the three independent axes (flexion-extension rotation, internal-external rotation, abduction-adduction rotation) and the motion or displacement of the reference point on the tibia. The flexion-extension axis is located in the femur, and its orientation relative to the femur does not change. The internal-external rotation axis is located in the tibia, and its orientation relative to the tibia does not change. The abduction-adduction axis is perpendicular to both the flexion and tibial rotational axes, and its orientation can change relative to both bones. The term *translation* in its purest form refers to the motion of a rigid body and not of a point. Therefore, the use of the term *translation* to refer to a point has evolved from general usage.

The location of the reference point for translation may be chosen arbitrarily. However, the amount of translation depends on which point is selected; any associated rotation could cause the reference points to move differently. The reference point frequently used to describe translation of the knee is located midway between the medial and lateral margins of the joint. Some investigators use a point on the tibial condyle that is midway between the spines of the intercondylar eminence.

The range and limits of knee flexion/extension are commonly defined in the literature by three numbers that denote maximum hyperextension, the zero or neutral point, and maximum flexion. For example, 5-0-145 describes a knee that goes from 5 degrees hyperextension to 145 degrees of flexion. A knee that lacks 15 degrees from full (0 degree) extension would be described as 0-15-145.

Most clinical examination tests are performed in a constrained manner in which the motion of the knee joint is restricted. For instance, in the abduction and adduction tests, the coupled external or internal tibial rotations are blocked by the examiner to determine the medial and lateral joint openings that are caused only by the abduction-adduction motion. An advantage of a constrained test is that the specific motions are known and may be reproduced in the laboratory, allowing the primary and secondary ligamentous restraints to be experimentally determined. During the Lachman test, the examiner may constrain the amount of coupled internal rotation of the tibia. In the pivot shift test, the motions are unconstrained to allow maximal subluxation of the lateral tibiofemoral compartment. The specific ligaments and the importance of each in limiting the final position will depend on how these tests are performed. We described earlier in this chapter the diagnostic information obtained during both constrained and unconstrained tests on the knee joint under known forces, motions, and displacements.

When applied to a ligament, the term *laxity* is used to indicate slackness or lack of tension—a lax ligament. Ligaments may purposely be made slack in an uninjured knee by positioning the tibia so that the distance between the femoral and tibial attachments is shortened. Laxity may be normal or abnormal; abnormal laxity may be congenital or result from an injury. The adjective *abnormal* should be used to indicate when laxity is pathologic. In the orthopedic literature, the term *laxity* is also used to indicate looseness of a joint or some amount of motion that results from the application of forces and moments. One source defines laxity as "either normal free motion or greater than normal free motion, as of a joint."[36] The problem with this term is that the specific type of motion is not stated. For instance, the term *anterior laxity of the knee* may refer to the combined motions of both anterior translation and tibial rotation, or just to the amount of anterior tibial translation. If the latter is true, it is preferable to use the term *anterior translation*, thus avoiding ambiguity and allowing the millimeters of anterior tibial translation that occurred under defined loads to be reported. If the amount of anterior translation reported is the difference between the injured and contralateral knee, this should always be indicated.

Because the word *laxity* has many different meanings, more precise terms should be used, when possible, to describe abnormalities in motion or position of the knee joint. *Laxity* should be used only in a general sense to indicate slackness or lack of tension in a ligament. When referring to motion of the knee, it is preferable to describe the specific motion.

In the orthopedic literature, the term *instability* is commonly used to indicate a condition (physical sign) that is characterized by abnormal displacement of the tibia. This term is also commonly used to describe an anatomic structure, such as ACL instability. It is preferable to describe the specific defect of the ligament or

TABLE 3-12 Definitions of Terms Used to Describe Positions of the Knee

Term	Etymology	Primary Source Definition	Secondary, Tertiary Source Definitions	Comments
Position	From Latin *ponere*, to put, to place	(1) Of the human body: bodily posture or the arrangement of parts of the body (body segment) as used for a particular examination or surgical procedure. (2) Of a point: the location of a point with respect to a reference system. (3) Of a rigid body: the position of a point or particle in the body and the orientation of the body.	The location of a point on the tibia, such as the medial tibial spine, can be described by three translational coordinates: anteroposterior, mediolateral, and proximodistal. These coordinates indicate where the point is located with respect to a reference coordinate system on the femur. The *orientation of a body* refers to how it is rotated relative to other body segments. The orientation of the tibia relative to the femur is described by the angles of flexion-extension, abduction-adduction (or varus-valgus rotation), and internal-external rotation.	The position of the tibia is crucial to correctly diagnose knee ligament injuries. The starting position of the tibia during clinical tests determines the tension in each of the ligamentous and capsular structures. The final position of the tibia when maximum subluxation has been reached determines which ligaments are injured.
Dislocation	From Latin *de*, away from; *locare*, to place	An abnormal position of the osseous structures forming a joint, such that there is no longer contact between the normally opposed, articulating surfaces. Synonym: luxation	The term *dislocation* has been used to indicate a complete noncontact position of either the medial and the lateral tibiofemoral compartments or the patellofemoral joint. This term can also be used to describe a noncontact position of only the medial or lateral tibiofemoral compartment.	Dislocations of the knee joint are typically classified according to the final tibial position: anterior, posterior, medial, lateral, or rotatory.
Subluxation	From Latin *sub*, under, beneath; *luxare*, to put out of joint	A partial dislocation in which there is an abnormal position of the osseous structures forming the joint; however, a portion of the opposing articulating surfaces is still in contact.	*Subluxation* has been used to indicate an incomplete or partial dislocation. This term has been used synonymously with abnormal motion. However, *subluxation* represents a position of the joint and not its motion. It is therefore incorrect to use this term to indicate abnormal motion.	Identifying and quantifying subluxation is difficult because the term does not have units. The clinician must describe a subluxation according to the position of the tibia relative to the femur. Rotatory subluxations are described by the rotation of the tibia and the position of any point on the tibia. Or, the anteroposterior position of a point may be specified on the medial and lateral tibial plateaus.

structures and to provide separately the abnormal displacements of the tibia (including the known loading conditions that lead to the diagnosis).

The term *sprain* is usually defined as an injury to a ligament in which portions of the ligament are torn but not completely disrupted.[1,8,36] The AMA's classification system sorts ligament injuries into three categories: first-, second-, and third-degree sprains, as previously described in Table 3-9.

The goal of the examination of the knee joint is to determine the motions, limits of motion, and initial and final positions of the joint that result from specified loading conditions. The examiner should specify the conditions under which the test is conducted, including the position of the patient and the knee joint and the loads applied. The outcome of the test reported includes the motions of the knee that occur, the abnormal motion limits, and the final tibiofemoral position, as discussed earlier in this chapter. A change in any of the test conditions may alter the interpretation of the outcomes and the final diagnosis of the anatomic structure that is injured.

Considerable confusion exists regarding the definition of terms used to describe rotatory instability of the knee, such as anterolateral, posterolateral, anteromedial, and posteromedial. Although some authors use these terms to describe abnormal motions, others use them to describe an abnormal position of the knee joint. In this textbook the authors use these terms to describe an abnormal position (subluxation) of the medial or lateral compartment with the sense (direction) indicated.

Video Content

Video 3-1

TABLE 3-13 Definitions of Terms Used to Describe Motion of the Knee

Term	Etymology	Primary Source Definition	Secondary, Tertiary Source Definitions	Comments
Motion	From Latin *movere*, to move	The act or process of changing position.	The motion of an object is described by specifying its velocity or the rate and direction with which it is changing position.	The sequential positions of an object in motion compose the path of the motion. The net effect of a motion can be quantified in two ways: (1) by describing the distance that an object travels along its path and (2) by describing the displacement between the starting and the ending points of its path, without regard to the details of the intervening motion.
Displacement	From Old French *des*, away; *placer*, to place	The net effect of a motion. The change in position of a body or particle between two points along its path without regard to the path followed.	The *displacement* of a rigid body is the change in its position regardless of the path it follows. It can be described by the change in position of any particle (also termed *translation*), along with the change in orientation (also termed *rotation*) of the rigid body.	Displacement may be described as a combination of three translations and three rotations, each of which corresponds to a degree of freedom. The standard international unit of translation is the meter; the unit of rotation is the radian or the degree.
Translation	From Latin *trans*, across; *ferre*, to carry	A type of motion or displacement of a rigid body in which all lines attached to it remain parallel to their original orientation. A type of motion by which all points in the body move along paths parallel to each other. All points move with the same speed and in the same direction.	*Translation* describes the motion of the tibia with respect to the femur, which consists of three independent components: mediolateral translation, anteroposterior translation, and proximodistal translation.	A body that follows a curved path undergoes translation if its orientation does not change during the motion. If the direction of motion is constant, the body moves in a straight path. If the direction changes with time, the body follows a curved path. The points of motion should not be referred to as translations; points displace, not translate. The standard international unit of translation is the millimeter.
Rotation	From Latin *rotare*, to turn	A type of motion or displacement in which all points on a body move about an axis as a center or a motion in which one point is fixed. The axis is commonly termed the *axis of rotation*.	During rotation, the points on a body have different directions of motion and different speeds. At each instant, the points move in circles about the axis of rotation. Rotations are composed of three independent degrees of freedom that occur about one of three axes: flexion-extension rotation, internal-external rotation, and abduction-adduction rotation.	Motion and displacement of the knee are described by the combination of (1) the change in orientation of the tibia and (2) the motion or displacement of some reference or base point on the tibia. The change in orientation is quantified by the rotation of the tibia about the three independent axes. The motion is often referred to in the literature as *translation of the tibia*.
Range of motion	From Old French *ranc*, row	The displacement that occurs between the two limits of movement for each degree of freedom.	Common use of *range of motion* in the knee is to describe the amount of rotation that may occur. There is also a *range of motion* for each of the translational and rotational degrees of freedom.	Range of motion depends on the loads applied to the knee. For motions other than flexion-extension, the range of motion generally depends on the angle of flexion of the knee. The range of anteroposterior translation depends on the angle of flexion and the position of tibial rotation in which the knee is placed before a measurement is made.
Limits of motion	From Latin *limes*, boundary	The extreme positions of movement possible for each of the six degrees of freedom.	Two limits, in opposite directions, are required to define range of motion. A total of 12 limits of motion exist in the knee, 2 for each of the 6 independent degrees of freedom.	Specifying the limits of motion provides additional information not provided by the range of motion. The range and limits of knee flexion-extension are commonly defined by three numbers that denote maximum hyperextension, the zero or neutral point, and maximum flexion.

TABLE 3-13 Definitions of Terms Used to Describe Motion of the Knee—cont'd

Term	Etymology	Primary Source Definition	Secondary, Tertiary Source Definitions	Comments
Coupled displacement and motion	From Latin *copula*, bond	A displacement or motion in one or more degrees of freedom that is caused by a load (force or moment) applied in another degree of freedom.	The amount of coupled motion depends on (1) where the force is applied to the tibia, and (2) whether the center of rotation is constrained or allowed to move freely. The type and amount of coupled motion that occur during clinical testing depend on the mechanical properties of the knee and the magnitude and direction of loads applied by the examiner.	An example of coupled motions that occur during clinical testing is external rotation when a posteriorly directed force is applied to the tibia and internal rotation when an anteriorly directed force is applied to the tibia.
Constrained (and unconstrained) motion	From Latin *con*, together; *stringere*, to draw tight	To restrict the motion of a (mechanical) body in a particular mode.	The motion of the knee joint may be allowed to occur freely (*unconstrained*) or it may be restricted (*constrained*). If the motion is unconstrained, the tibia displaces into its maximum position. Constrained tests limit the amount of motion that occurs.	An example of an unconstrained clinical test is the external rotation dial test. Typically, motions of external rotation and posterior translation of the tibia occur. The examiner does not constrain these motions but allows the joint to displace to its maximum subluxation.
Force	From Latin *fortis*, brave, strong	The influence on a body, such as a push or pull, that accelerates (changes either the speed or the direction of motion) or deforms (changes either the size or the shape) the body.	A force has three properties: (1) an orientation or line of action, (2) a sense, forward or backward, along its line of action, and (3) a magnitude, which is expressed in newtons (N).	The effect of a force depends on its three properties and its point of application. If an anteriorly directed force is applied to the tibia, the resulting tibia motion depends on where the force is applied and its magnitude. The direction of the force is the combination of its orientation (along the anteroposterior axis) and its sense (anterior).
Moment	From Latin *momentum*, movement	The influence on a body that causes an angular (rotational) acceleration of the body.	A *moment* has three properties: (1) an orientation, or line of action, (2) a sense, clockwise or counterclockwise, about its line of action, and (3) a magnitude, which is measured in newton-meters. The magnitude of the moment is directly proportional to the magnitude of the force that produces it and to the perpendicular distance to the line of action of the force (moment arm).	When indicating the moment at the knee, it is essential to state the axis about which the moment is determined, because the magnitude of the moment will depend on where the axis is located and on the orientation of the axis.
Laxity	From Latin *laxare*, to relax, slacken	(1) Slackness or lack of tension (a characteristic of a ligament) and (2) looseness, referring to a normal or an abnormal range of motion of a joint.	In the orthopaedic literature, *laxity* has two general meanings: (1) a slackness in a ligament or lack of tension and (2) looseness of a joint. Synonym (as applied to joint motion): play.	The clinical examination for laxity of the knee joint ligaments involves determining the abnormal displacement of the tibia and the position that can be induced by the application of forces and moments. The clinical findings are used to infer the extent of injury to the ligaments and capsular structures (abnormal laxity).
Instability	From Latin *in*, not; *stabilitas*, firmness, steadiness	A condition of a joint characterized by an abnormal increased range of motion (mobility) caused by injury to the ligaments, capsule, menisci, cartilage, or bone.	In the orthopedic literature, *instability* is used to describe (1) an episode of giving-way (symptom) and (2) a condition of abnormal mobility (play) of the joint (physical sign). *Instability* should be used only in a general manner to indicate abnormal displacement of the tibia that occurred owing to an injury.	Functional instability may result in partial collapse of the knee or a subjective sensation. The term *instability* should not be used to indicate a giving-way reinjury or an anatomic structure (e.g., instability of the ACL).

TABLE 3-14 Definitions of Terms Used to Describe an Injury of a Ligament in the Knee

Term	Etymology	Primary Source Definition	Secondary, Tertiary Source Definitions	Comments
Sprain	Possibly from Old French *espreindre*, to squeeze; from Latin *exprimere*, to squeeze or press out	An injury to joint ligaments that stretches or tears ligament fibers but does not completely disrupt the ligament (its continuity remains intact).	Most common definition is an acute injury of a ligament with a partial tear but without a complete rupture or loss of function of the ligament.	If a sprain is classified as a third-degree sprain (according to the classification of the American Medical Association), it is preferable to include the term *third degree* to indicate a complete tear of the ligamentous fibers.
Rupture	From Latin, *rumpere*, to break	A tear or tearing apart.	Usually indicates complete tearing of a ligament and loss of function. Synonym: tear	The term *partial* indicates an incomplete ligament rupture in which some function remains. If the term *partial* is not used, the word *rupture* indicates a complete disruption. It is the loss of function of a ligament that defines a tear, not the property of continuity.
Deficiency	From Latin *deficere*, to fail	The state or condition of lacking a substance, quality, or characteristic essential for completeness.	The term *deficiency* is used to (1) describe a knee in which a ligament is absent and (2) indicate when a loss of function of a ligament has occurred. Synonym: insufficiency	*Deficiency* is a general term that indicates that a defect exists but does not specify the extent of the injury. The clinician or author must therefore specify the extent of the defect. The presence of a positive pivot shift or abnormal anterior tibial displacement defines the deficiency of the ligament.

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4

Knee Ligament Function and Failure

Frank R. Noyes, Edward S. Grood

OUTLINE

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VIDEO CONTENT

Video 3-1 Comprehensive Knee Exam: Clinical Rationale and Diagnosis

LIGAMENT FIBER LENGTH-TENSION PROPERTIES

In the early writings of Fick in 1911,[25] the description of ligaments having fibers grouped into bands was presented, along with the concepts that not all fibers of a ligament would be tense at one time. Fick also noted that knee flexion angle played an important role in determining which fibers were under tension and those that were slack. Since then, numerous publications have appeared that demonstrate how ligament fiber tension and function depends on the initial length and attachment site and on the specific joint position of both flexion-extension and tibial rotation.[30,34,35,78] These concepts are important because they form the basis for the placement of knee ligament grafts and provide insight into the concepts of single- and double-bundle anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) reconstruction. In addition, the ligament fiber length-tension properties form the basis for the tensioning rules regarding knee flexion and load applied for ligament grafts at surgery. Major disagreement still exists among investigators on these points, as is discussed in this chapter.

It is first important to understand the length-tension behavior of individual ligament fibers. The viscoelastic properties of ligament fibers allow them to initially undergo elongation under load in resisting joint displacements. The tension developed in the ligament fibers depends on its tibiofemoral attachment site, initial length, initial joint position, and subsequent joint displacement. In Figure 4-1, a force-versus-length curve is shown for human ACL fibers. The "L0" point describes the initial loading of the ligament fiber; when the ligament bone attachment distance of the fiber is less than L0, the fiber is slack. The fiber functions only when the distance between the fiber attachment sites reaches the length of the fiber to initiate loading. The fiber functions only within a narrow elongation or strain, which has been estimated at strains of 5% or less.[21] Failure of the individual fiber begins in the upper range estimated at the 8% level of strain.

Collagen fibers are not highly elastic and demonstrate failure at relatively low levels of elongation or strain. Because ligament fibers function only within a small range of lengths and the fiber lengths vary with knee rotations and translations, these fiber length patterns can be measured under in vitro conditions. Beynnon and coworkers[5-7] have measured fiber length patterns in vivo (described further in Chapter 10).

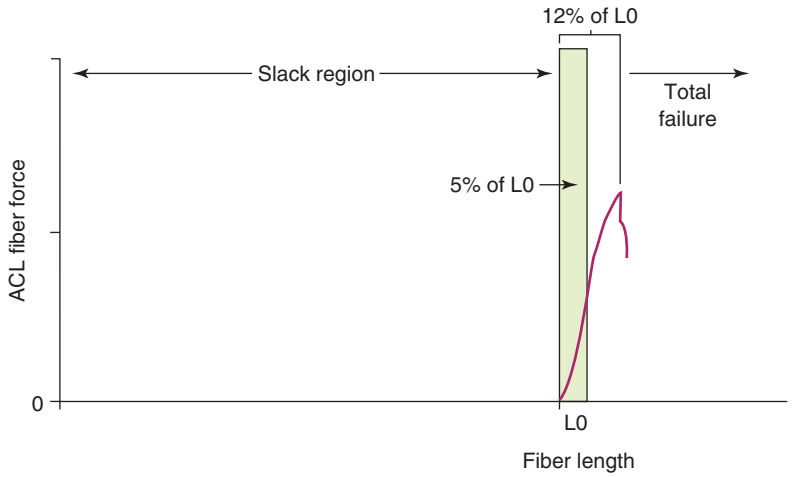


FIG 4-1 Force-length curve for human anterior cruciate ligament (ACL) fibers. Fiber force is shown as a function of the distance between attachments (length). In vivo functional activities are thought to occur within the shaded region, which corresponds to fiber strain of only 5%. (From Grood ES. Placement of knee ligament grafts. In Finerman GA, Noyes FR, eds. *Biology and Biomechanics of the Traumatized Synovial Joint: The Knee as a Model.* Rosemont, IL: American Academy of Orthopaedic Surgeons; 1992-393-417.)

CRITICAL POINTS Ligament Fiber Length-Tension Properties

- Numerous publications demonstrate how ligament fiber function depends on the initial length and attachment site and the specific joint position of both flexion-extension and tibial rotation.
- These concepts form the basis for the placement of knee ligament grafts, provide insight into single- and double-bundle cruciate reconstructions, and form the basis for the tensioning rules regarding knee flexion and load applied for ligament grafts at surgery.
- The tension developed in ligament fibers depends on its tibiofemoral attachment site, initial length, initial joint position, and subsequent joint displacement.
- Fibers function only when the distance between the fiber attachment sites reaches the length of the fiber to initiate loading.
- Collagen fibers are not highly elastic and demonstrate failure at relatively low levels of elongation or strain.

CRITICAL POINTS How Ligament Fiber Microgeometry Determines Ligament Function and Failure

- The 3-dimensional microgeometry of ligament fibers is only partially understood on a macroscopic and ultrastructural level.
- The arrangement of ligament fibers in a parallel manner such as the MCL, FCL, or a tendon provides a structure with a high maximum load to failure because the majority of the fibers are loaded in a symmetrical manner and share the loading profile. The structure will fail at a relatively small displacement.
- The capsular structures are designed to provide a low stiffness, allowing elongation or compliance, which is built into their microgeometry. Failure of capsular structures can be difficult to detect as a microtearing process occurs throughout the entire capsule. Before ultimate failure of the capsule, the microfailure process produces a residual elongation or slackening.
- The length-tension behavior and failure pattern of the ACL and PCL are also dissimilar, with different fiber regions brought into the loading based on the position of the knee.

HOW LIGAMENT FIBER MICROGEOMETRY DETERMINES LIGAMENT FUNCTION AND FAILURE

The 3-dimensional microgeometry of ligament fibers is only partially understood on a macroscopic and ultrastructural level. From a macroscopic level, Figures 4-2 to 4-5 show the concepts of how ligament fibers determine functional properties and the mechanisms of ligament failure. Figure 4-2 shows a stress-strain curve for a typical collagen fiber. The initial toe region involves straightening of the collagen fibers, followed by a linear region. At the end of the linear region, failure of individual collagen fibers occurs, which progresses to final failure of the whole structure. Note that the total fiber strain to failure is only 8% in this illustration. Figure 4-3 shows the effect on the structural properties of a ligament on increasing the cross-sectional area. There is an increase in stiffness and ultimate force to failure. Figure 4-4 shows the effect of different lengths of a collagen structure under load, both having the same cross-sectional area. In the illustration, there is a 50% decrease in stiffness in the ligament that is twice as long. This effect has been noted in ACL semitendinosus-gracilis tendon (STG) reconstructions where aperture fixation of the graft directly at the tunnel site may improve mechanical properties of the graft in addition to decreasing graft-bone tunnel motion. Figure 4-5 shows the effect of fiber microgeometry on structural properties. The finger trap illustration shows a major decrease in stiffness and ultimate strength because the collagen fibers are not loaded in a symmetric manner.

The arrangement of ligament fibers in a parallel manner such as the medial collateral ligament (MCL), fibular collateral ligament (FCL), or a tendon provides a structure with a high maximum load to failure because the majority of the fibers are loaded in a symmetric manner and share the loading profile. The structure will fail at a relatively small displacement, as is true for the MCL and FCL. Alternatively, the capsular structures are designed to provide a low stiffness, allowing elongation or compliance, which is built into the microgeometry, similar to that shown in the illustration of the finger trap in Figure 4-5. Certain portions of the capsule may have an arrangement in which some fibers exist in a more parallel array, such as the posterior oblique ligament of the posteromedial capsule. Failure of capsular structures

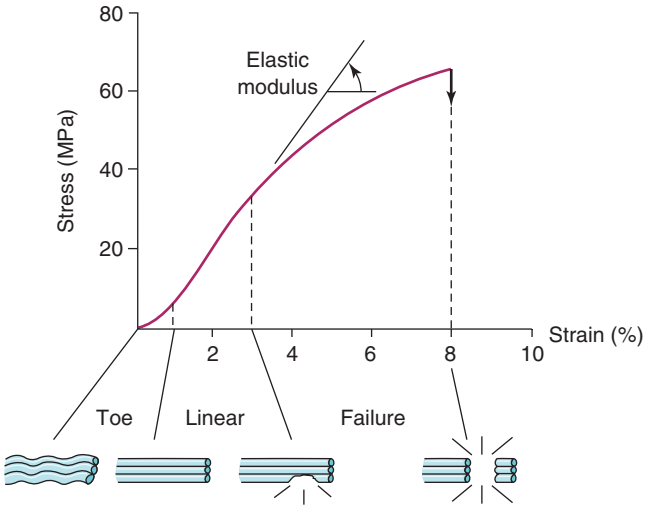


FIG 4-2 Example of a typical normalized stress-strain curve for collagen. The resulting curve provides mechanical (material) parameters that are independent of tissue dimensions. (From Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. In Hutton R, ed. *Exercise and Sports Science Review,* vol. 6. Philadelphia: Franklin Institute Press; 1978;125-182.)

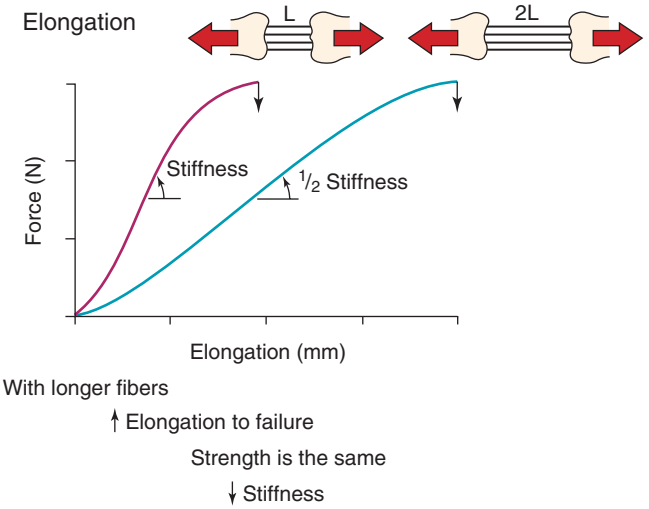


FIG 4-4 The influence of original length of tissue fibers on the shape of the load-deformation curve. (From Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. In Hutton R, ed. *Exercise and Sports Science Review,* vol. 6. Philadelphia: Franklin Institute Press; 1978-125-182.)

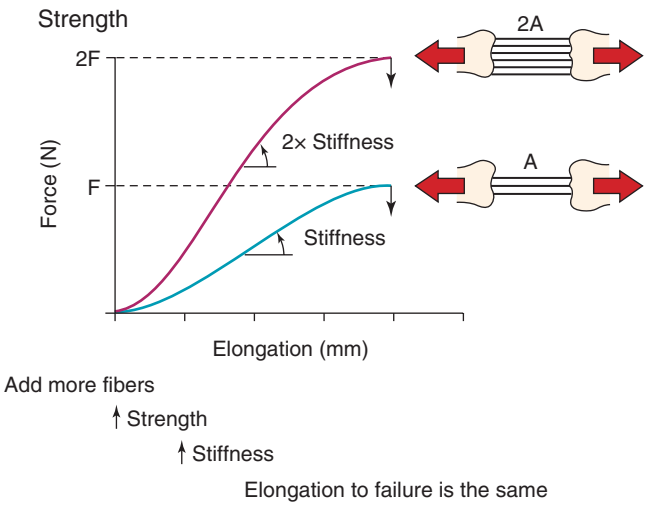


FIG 4-3 The effects of increasing tissue cross-sectional area on the shape of the load-deformation curve. (From Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. In Hutton R, ed. *Exercise and Sports Science Review,* vol. 6. Philadelphia: Franklin Institute Press; 1978-125-182.)

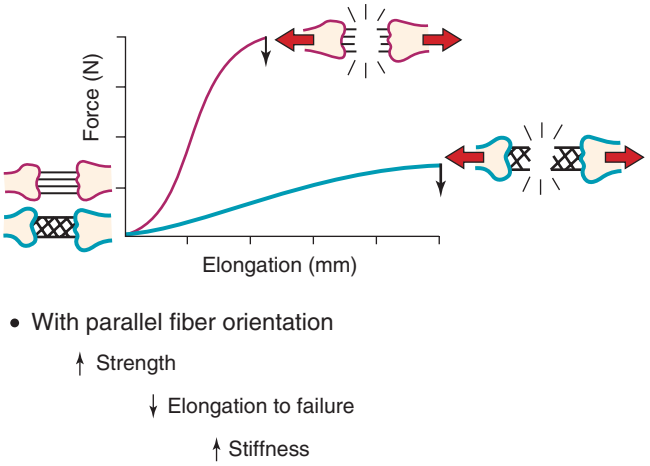


FIG 4-5 The effect of altering the collagen fiber alignment is shown. Parallel collagen fibers are loading uniformly, resulting in structural properties of increased strength, decreased elongation to failure, and increased stiffness in contrast to the oblique fiber orientation representing joint capsular tissues.

can be difficult to detect because a microtearing process occurs throughout the entire capsule. The capsule may appear slack and elongated without an obvious failure or the capsule may be avulsed off its femoral or tibial attachment and the failure site identified and repaired at surgery. Before ultimate failure of the capsule, the microfailure process produces a residual elongation or slackening that, in chronic knee injuries, may require plication procedures to restore tension and function. An example is plication of posteromedial or posterolateral capsular structures so that they will function in full extension and resist knee hyperextension. The length-tension behavior and failure pattern of the ACL and PCL are also dissimilar, with different fiber regions brought into the loading based on the position of the knee.

An example of the force elongation properties of the MCL and medial capsular structures is shown in Figure 4-6. This example is from a rhesus primate knee, in which the medial structures were loaded in uniaxial tension. The high failure load of the MCL compared with the capsular structures is shown. The capsule undergoes a failure process that is somewhat continuous because different portions of the less stiff capsule are brought into the loading sequence and fail, without an abrupt failure.

An example of a scanning electron microscopic analysis of failure of the ACL ligament is shown in Figure 4-7. In this series of experiments, the ACL of a rhesus primate knee was loaded to one half of its expected failure load. Scanning electron microscopic examination showed that some portions of the fiber bundles had separated and had lost some of their normal wavy attachment. This is not an artifact, because normal ACL fibers will show a wavy appearance. In

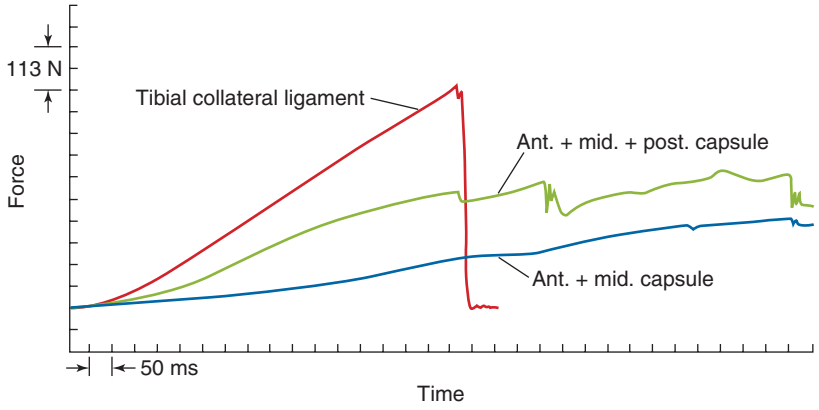


FIG 4-6 Typical oscillograph record of force versus time for failure tests on the medial collateral ligament (MCL) and two capsular preparations. A constant distraction rate was used, so the time axis is proportional to specimen elongation. The MCL supports the largest forces and fails abruptly. This is in contrast to the progressive failure of the ACL. Note the reduction in stiffness that occurs for both the MCL and the capsule before significant failure indicated by the sudden drop in resisting force. This is indicative of a progressive microfailure process, which occurs before macroscopic failure. *Ant.,* Anterior; *mid.,* middle; *post.,* posterior. (From Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. In Hutton R, ed. *Exercise and Sports Science Review,* vol. 6. Philadelphia: Franklin Institute Press; 1978:125-182.)

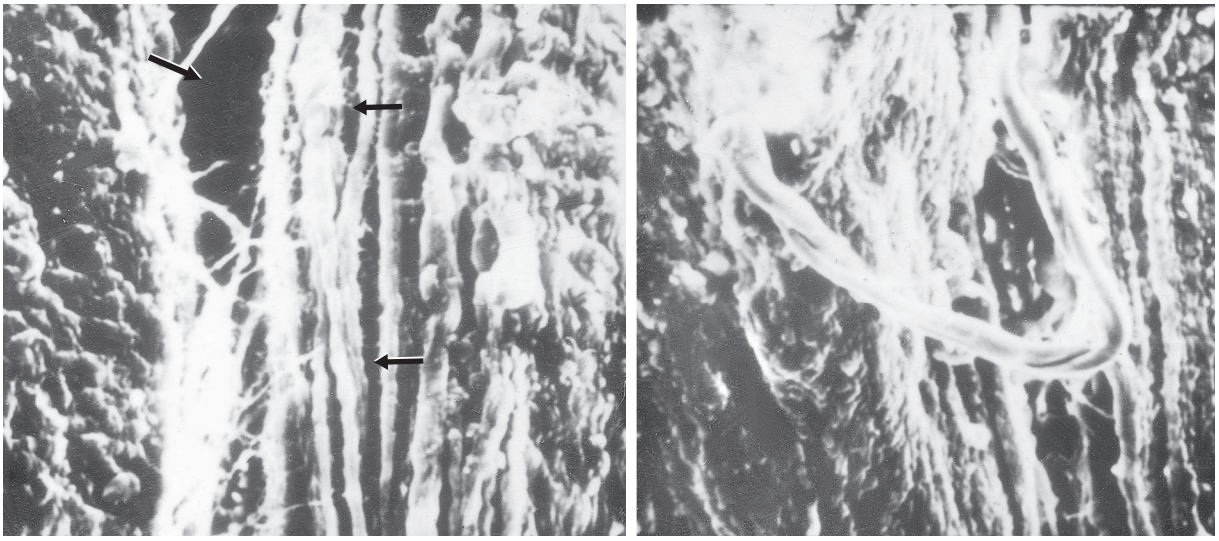


FIG 4-7 Scanning electron microphotographs of an anterior cruciate ligament after it was loaded to one half its anticipated maximum load without evidence of failure. Microfailure occurs. A whole fiber bundle completely ruptured is shown at left (*arrows*). Separation of fibers within a bundle is shown at right. (From Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. In Hutton R, ed. *Exercise and Sports Science Review,* vol. 6. Philadelphia: Franklin Institute Press; 1978:125-182.)

certain portions of the ACL, there is complete failure of individual fibers that were brought into the loading sequence owing to their fiber length at the knee position selected for the loading test. In Figure 4-8, failure of a major fiber bundle is shown with failure of the individual fibers at different places within the fiber. Note that failure of a small vessel has also occurred at the site of fiber failure, which is unusual given the expected elongation that vessels undergo before ultimate failure.

IMPORTANCE OF FEMORAL ATTACHMENT ON LIGAMENT LENGTH-TENSION PATTERNS

Many factors determine ligament length patterns during knee motion; however, one of the most sensitive factors is the fiber's femoral attachment (even more so than the tibial attachment). This concept is highly important for understanding ACL and PCL ligament fiber function and the location of ligament grafts for reconstruction.

The effect of the femoral attachment described by Grood and associates[30] is illustrated in Figure 4-9. In this model, the tibial attachment is assumed to be stationary, and flexion of the knee occurs about a fixed center of rotation (CR). The location of the CR is at the average rotation center of the human knee joint. A fiber that attaches anterior to the CR, such as fiber F_a, will lengthen with knee flexion up to 90 degrees as it rises up to the top of the circle and thereafter shortens with knee flexion. The opposite effect is shown by fiber F_d, which shortens with knee flexion and, at 90 degrees of flexion, would start to lengthen. The length patterns of the fibers are shown in the accompanying graph. This shows the complex length pattern of cruciate ligament fibers and is in marked contrast to more simplified descriptions that the ACL anteromedial fibers lengthen with knee flexion and the



FIG 4-8 Scanning electron photomicrograph of a collagen fiber bundle at the plane where failure occurred. The failure of collagen fibers at multiple levels within the fiber bundle demonstrates the pull-apart failure process. The *arrows* indicate a rich supply of vessels lying on the surface of the fiber bundle with perpendicular branches supplying the interior of the fiber bundle. (From Noyes FR, Grood ES, Nussbaum NS, Cooper SM. Effect of intra-articular corticosteroids on ligament properties. A biomechanical and histological study in rhesus knees. *Clin Orthop.* 1977;23:197-209.)

CRITICAL POINTS Importance of Femoral Attachment on Ligament Length-Tension Patterns

- Many factors determine ligament length patterns during knee motion; however, one of the most sensitive factors is the fiber's femoral attachment (even more so than the tibial attachment).
- The length-tension pattern of cruciate ligament fibers is complex and is in marked contrast to more simplified descriptions that the ACL anteromedial fibers lengthen with knee flexion and the posterolateral fibers lengthen with knee extension.
- A ligament functions with fibers of different lengths and their loading, which depends on attachment site characteristics.
- There is an approximate region in the ACL and PCL at which one region lengthens with knee flexion, another region shortens, and fibers between these two regions undergo less elongation. However, there are major differences among investigations regarding where these regions are located.
- Our data concluded that the line for the ACL is primarily oriented in a proximal to distal direction and that fibers anterior to the line become longer in flexion and that posterior fibers become shorter.
- The region for the line for the PCL is oriented in an anterior to posterior direction, with distal fibers becoming longer with knee flexion and proximal fibers lengthening with knee extension.
- The effects of changing the tibial attachment of an ACL graft in cadaveric specimens were investigated. Moving the fiber attachment on the tibia in a medial to lateral direction had only a small effect on fiber length and normalized length patterns. In contrast, moving the fiber in an anterior to posterior direction had a strong effect on fiber length.
- The placement of an ACL graft in an anterior to posterior location within its femoral footprint has significant effects in determining the tension and loading conditions of the graft. The placement of a PCL graft in a proximal to distal femoral direction has similar profound effects on its length-tension behaviors.
- The ACL or PCL graft should be tensioned at the knee flexion angle under which the graft will be at its longest length. Tensioning a graft at a flexion range in which the graft is in its shortest position would be expected to produce failure of portions of the graft as it elongates at a different knee flexion position.

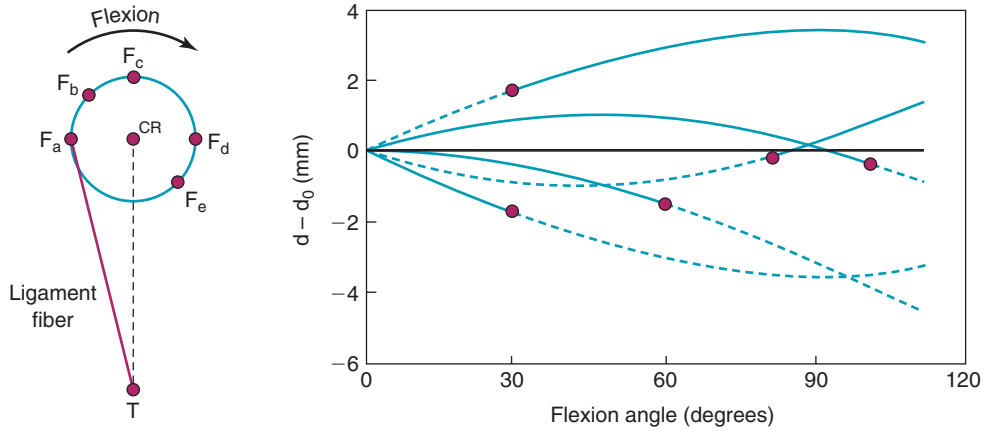


FIG 4-9 Length patterns are determined by the femoral attachment location. A ligament fiber is shown with tibial attachment (T) and femoral attachment (F_a). Other femoral attachments are represented by points F_b through F_e. The femur is assumed to flex about a fixed center of rotation (CR). The graph shows how the distance between attachments (d) referenced to the distance between attachments at 0 degrees (d_o) varies with flexion to 120 degrees. The curves are solid in the region over which the ligament fiber is tense and dotted in the region over which it is slack. The functional region is obtained by assuming the fiber is strained 5% at its maximum length. (From Grood ES. Placement of knee ligament grafts. In Finerman GA, Noyes FR, eds. *Biology and Biomechanics of the Traumatized Synovial Joint: The Knee as a Model.* Rosemont, IL: American Academy of Orthopaedic Surgeons; 1992:393-417.)

posterolateral fibers lengthen with knee extension, which is a gross oversimplification. The circle model is still only an approximation because the knee does not have a fixed CR; this provides an additional complexity in the analysis of ACL and PCL fiber function.

Contour plots are used to simplify the description of ligament length changes; a typical contour map is shown in Figure 4-10.[35] A single contour line expresses all of the attachments that would produce the same maximum fiber strain. The region bound by the contour line with the smallest strain (2% elongation) provides the most isometric femoral attachments. Note in Figure 4-10 that the tibiofemoral separation distance increases dramatically anterior to the contour line, and correspondingly, the length decreases posterior to the line with knee flexion. It should also be noted that the concept of ligament isometricity is a misnomer because it is not expected that a ligament shows this behavior with a set minimal strain or elongation during knee flexion, as already discussed. A ligament functions with fibers of different lengths and their loading, which depends on attachment site characteristics. The disadvantage of the contour map is that the length of the individual native ligament fibers is not represented, and therefore it is unknown at what point the ligament fibers in any region are tense or slack. The contour map is most useful to show the length changes that would occur for ligament grafts placed at certain positions within the ACL and PCL attachment sites at the maximum elongation or strain of the graft. In addition, note the knee position at which the graft is tensioned to not produce excessive graft elongation, which would either overconstrain the joint or result in graft failure.

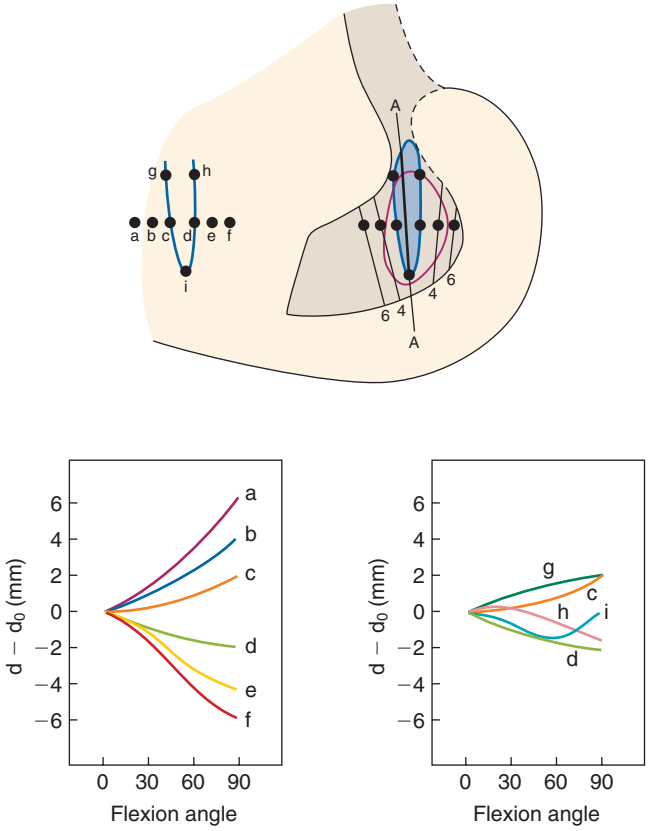


FIG 4-10 Typical contour plot for the anterior cruciate ligament. This figure was determined for knee flexion from 0 to 90 degrees while an anterior force of 100 N was applied to the tibia. The tibial attachment sites used in the analysis were located in the geometric center of the ACL's tibial insertion. (From Hefzy MS, Grood ES, Noyes FR. Factors affecting the region of most isometric femoral attachments: Part II. The anterior cruciate ligament. *Am J Sports Med.* 1989;17:208-216.)

A number of studies show there is an approximate region in the ACL or PCL at which one region lengthens with knee flexion, another region shortens, and fibers between these two regions undergo less elongation.[9,30,32,33,35,68,78] However, there is a major discrepancy in the investigations regarding where the regions are located within the cruciate ligaments. Our data and those of others[78] have concluded that the line for the ACL is primarily oriented in a proximal to distal direction and that fibers anterior to the line become longer in flexion and posterior fibers become shorter (Fig. 4-11; see also Fig. 4-10). The region for the line for the PCL, in contrast, is oriented in an anterior to posterior direction, with distal fibers becoming longer with knee flexion and proximal fibers lengthening with knee extension. Thus, the line that divides the shortening and lengthening regions has a completely different orientation for the ACL than the PCL. This is one of the most basic concepts of how ligament fibers function. Many current illustrations for ACL femoral attachment sites incorrectly show that the proximal fibers lengthen with knee flexion and distal fibers lengthen with knee extension. In fact, there are fibers within the ACL proximal and distal femoral attachment regions, governed by the contour plot behavior (see Fig. 4-10), that do not show this reciprocal tension behavior with knee flexion and extension. The data for these studies are not based on true fiber attachment separation distances, and these differences have rather profound effects on where ACL and PCL grafts are placed and tensioned. The PCL fiber length-tension behaviors under loading are shown in Chapter 15.

It should be noted that both Sidles and colleagues[78] and Hefzy and coworkers[35] reported that the contour maps describing fiber elongation patterns were strongly dependent on whether an anterior or posterior displacement load was applied to the tibia and the contour maps provided were under loading conditions for the respective ACL or PCL. A more complete description of contour maps for the femoral and tibial attachments is provided for the reader,[30,35,78] and the effect of tibial attachment sites is discussed in Chapters 7 and 15.

The effects of changing the tibial attachment of an ACL graft in cadaveric specimens is shown in Figure 4-12. The six ACL fiber locations on the tibia all originate at the approximate center of the ACL femoral attachment. Moving the fiber attachment on the tibia in a medial to lateral direction had only a small effect on fiber length and normalized length patterns. In contrast, moving the fiber in an anterior to posterior direction had a strong effect on fiber length. An anterior shift of the tibial attachment of 7.5 mm increased the fiber length by 5 to 8 mm. An anterior tibial attachment resulted in the fiber length behavior to become tauter in flexion. In Figure 4-13, the strong effect of moving the femoral attachment location in an anterior to posterior location on changing the length with knee flexion is shown. The location of the tibial insertion site is unchanged. The effect of moving the femoral attachment in a proximal to distal direction is shown in Figure 4-14. The more distal attached fibers were markedly shortened and had a concave length pattern, whereas the longer proximal fibers had a slight convex pattern. In summary, these studies show the complex behavior of the cruciate ligaments in which individual fibers and fiber regions are loaded to resist coupled motions of tibial translation and rotation. For the surgeon, the placement of a graft for the ACL in an anterior to posterior location within its footprint has significant effects in determining the tension and loading conditions of the graft as demonstrated. As is discussed in Chapter 15, placing the PCL graft in a proximal to distal direction has similar profound effects on its length-tension behaviors. The surgeon does have the ability to approximately select the range of knee flexion (low flexion, high flexion positions) under which the graft will be at its longest length and, therefore, should

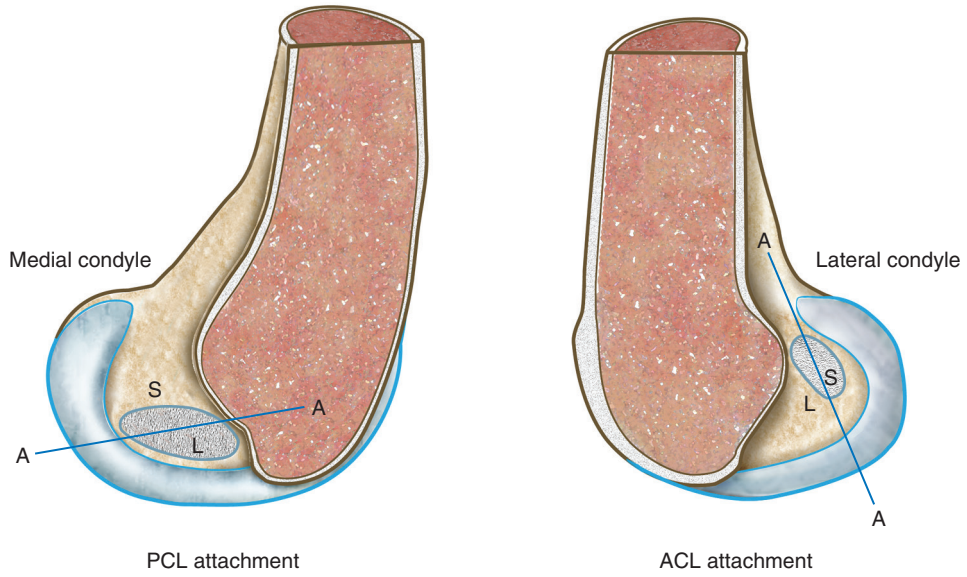


FIG 4-11 The division of the femoral ligament attachment into fibers that shorten (S) and lengthen (L) with knee flexion (reverse with knee extension). The line A to A, dividing the regions, has a different orientation for the two cruciate ligaments. Small errors in placement along the direction of the line have only small effects on length patterns. The approximate location of the line in reference to the posterior cruciate ligament (PCL) and anterior cruciate ligament (ACL) footprint is shown, with the qualification that the line changes its orientation with knee flexion. In contrast, placement errors perpendicular to the line cause large changes in length patterns. (Modified from Grood ES. Placement of knee ligament grafts. In Finerman GA, Noyes FR, editors. *Biology and Biomechanics of the Traumatized Synovial Joint: The Knee as a Model.* Rosemont, IL: American Academy of Orthopaedic Surgeons; 1992:393-417.)

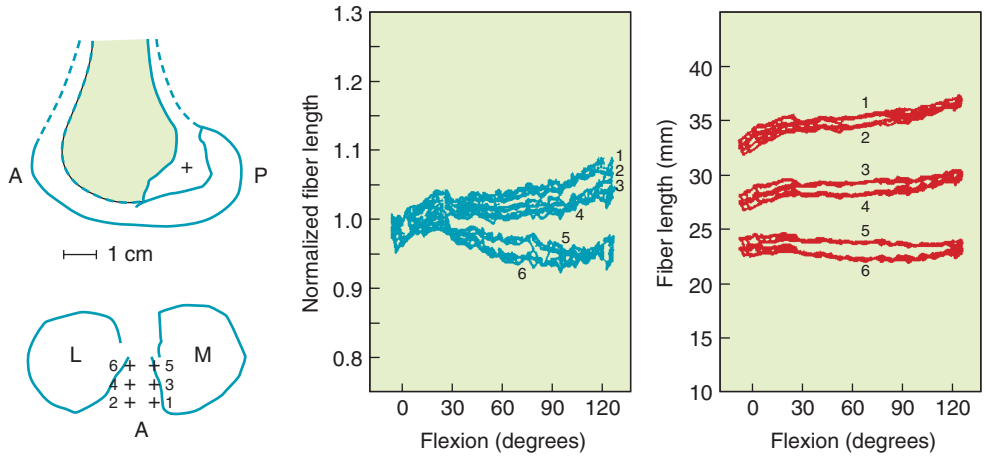


FIG 4-12 Sensitivity of fiber-length patterns to tibial attachment location in a cadaveric specimen. *A,* Anterior; *L,* lateral; *M,* medial; *P,* posterior. (From Hefzy MS, Grood ES. Sensitivity of insertion locations on length patterns of anterior cruciate ligament fibers. *J Biomech Eng.* 1986;108:73-82.)

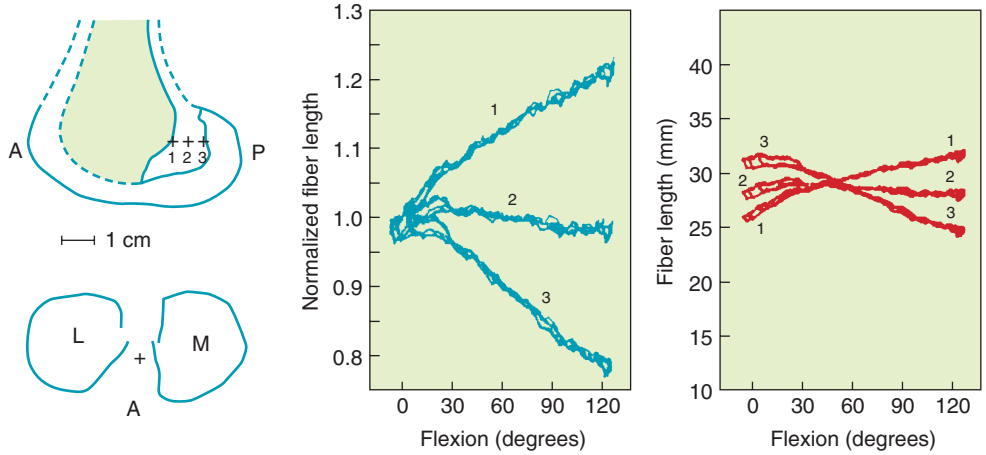


FIG 4-13 Sensitivity of fiber-length patterns to femoral attachment location in a cadaveric specimen. *A,* Anterior; *L,* lateral; *M,* medial; *P,* posterior. (From Hefzy MS, Grood ES. Sensitivity of insertion locations on length patterns of anterior cruciate ligament fibers. *J Biomech Eng.* 1986;108:73-82.)

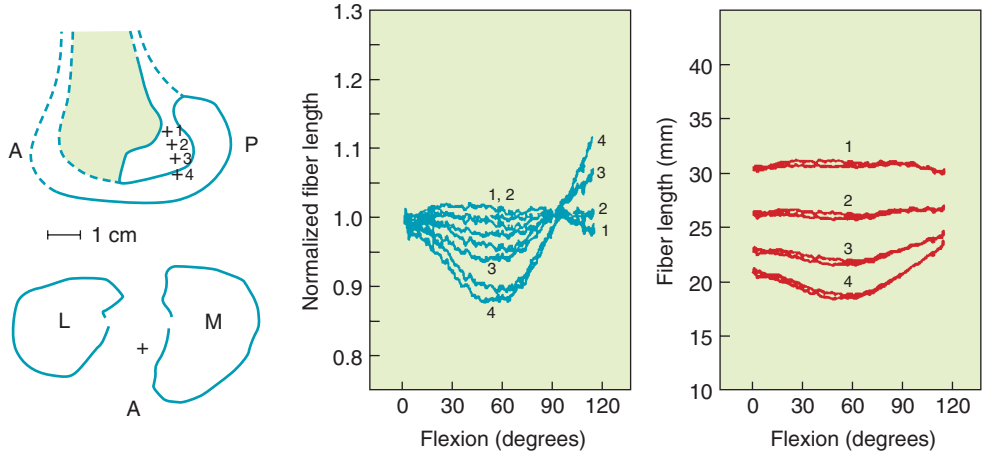


FIG 4-14 Sensitivity of fiber-length patterns to femoral attachment in a cadaveric specimen. Shown are the femoral attachments near the anteroposterior midline of the anterior cruciate insertion. *A,* Anterior; *L,* lateral; *M,* medial; *P,* posterior. (From Hefzy MS, Grood ES. Sensitivity of insertion locations on length patterns of anterior cruciate ligament fibers. *J Biomech Eng.* 1986;108:73-82.)

be tensioned at this position. Tensioning a graft at a flexion range at which the graft is in its shortest position would be expected to produce failure of portions of the graft as it elongates at a different knee flexion position. Within each graft, there will be asymmetric loading of the graft fibers. The contour plots show the different fiber elongations of fibers in the center of the graft compared with the fibers at the periphery of the graft. The concept of placing more than one graft is designed to allow adjustments to more closely simulate ligament fiber behaviors, although it is probable that the surgeon is adding collagen fibers to fill the ACL or PCL footprint and that native cruciate fiber behavior is never achieved.

In agreement with Grood and associates' studies, Markolf and colleagues[51] reported in a cadaveric in vitro biomechanical study that positioning the femoral ACL tunnel in an anterior to posterior direction is more critical in terms of graft forces and function than a proximal to distal direction.

LIGAMENT FIBER LENGTH-TENSION PATTERNS AND BURMESTER CURVES

As already discussed, one of the primary scientific bases for ligament fiber function and graft placement is the measurement or computation of fiber length patterns. An alternative approach for determining ligament function proposed by Menschik[54,55] is frequently referenced in the literature. This approach is based on the four-bar model of ACL and PCL ligament function shown in Figure 4-15, first proposed by Strasser,[81] and on the mathematical theory for knee motions developed by Burmester.[10] This mathematical theory was developed to determine all pairs of femoral and tibial attachments that remain the same distance apart (isometric) as the knee is moved through small (infinitesimal) motions. The pairs of attachment points are represented by the two curves shown in Figure 4-16, one for all possible femoral attachments and one for all possible tibial attachments, which are described as a cubic curve because of their mathematical form. A single tibial and femoral attachment of a ligament is obtained by drawing a straight line through the instant center of knee flexion controlled by the four-bar mechanism where the cruciate links cross each other. The MCL tibial and femoral isometric attachments are the points at which a line crosses the tibial and femoral cubics.

CRITICAL POINTS Ligament Fiber Length-Tension Patterns and Burmester Curves

- Mathematical theory developed to determine all pairs of femoral and tibial attachments that remain the same distance apart (isometric) as the knee is moved through small (infinitesimal) motions.
- The pairs of attachment points are represented by a curve for all possible femoral attachments and a second curve for all possible tibial attachments.
- There are important scientific objections to using this model to define ligament function and possible graft attachment locations.
  - Shape of the curves depends on the knee flexion angle that is chosen; different curves can be computed for different flexion angles.
  - The curves are based on small knee motions. There are tibial attachment locations that are as isometric that are not on the Burmester curve when a wider range of knee motion is considered.

The Burmester curves have been used by many authors to explain the attachment locations of the collateral ligaments and capsular structures, and references are available proposing these curves explain ligament function.[59] However, there are important scientific objections to using this model to define ligament function and possible graft attachment locations. The shape of the curves depends on the knee flexion angle chosen, and different curves can be computed for different flexion angles (see Fig. 4-16). Menschik[54,55] published the curves for 43 degrees of flexion without providing the specific criteria used for computing the curves at this particular position of knee flexion. We computed the curves for other flexion angles that differed markedly in shape and had different sites for the attachment of the collateral ligaments that may not be close to their anatomic attachment (see Fig. 4-16). In addition, the Burmester curves are based on small knee motions, and it has been determined that there are tibial attachments locations that are as isometric that are not on the Burmester curve when a wider range of knee motion is considered.

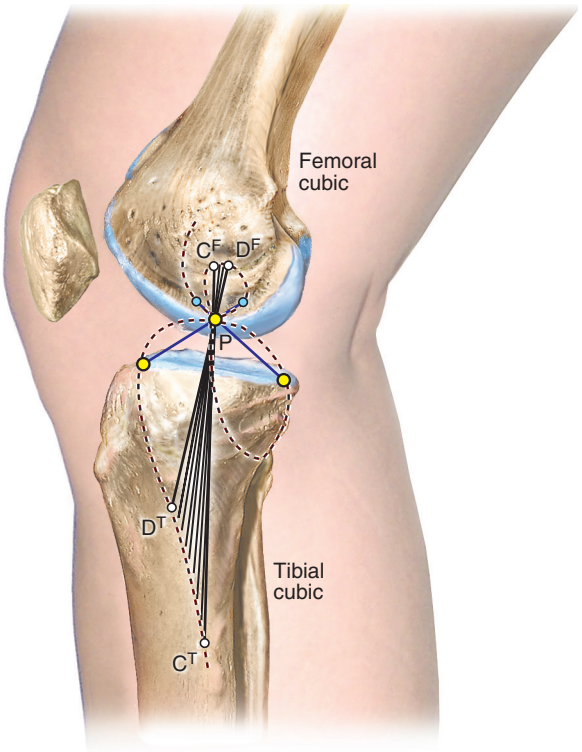


FIG 4-15 Burmester curves for the four-bar mechanism. There are two separate curves, a femoral cubic (C^F) and a tibial cubic (C^T). Pairs of nearly isometric attachments can be obtained by passing a line through instant center (P) and extending the line until it crosses both cubics. The points C^F and C^T where the line crosses the cubics are nearly isometric. Other pairs of nearly isometric attachments, such as D^F and D^T, can be found by rotating the line about the instant center. The lines shown here represent theoretical fibers of the medial collateral ligament.

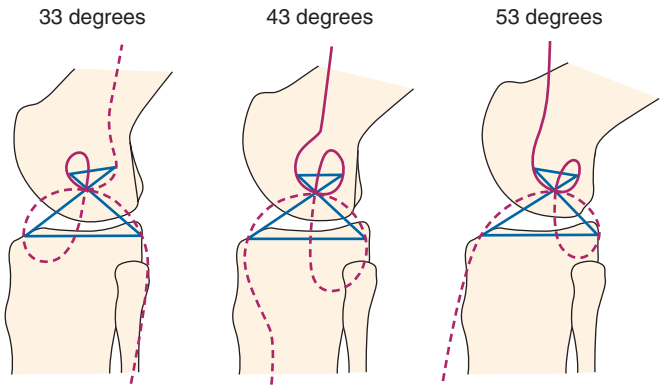


FIG 4-16 Burmester curves computed for flexion angles of 33, 43, and 53 degrees. The curves for 43 degrees of flexion are nearly identical to the curves published by Menschik[54,55] and Mueller.[59] Note that most of the tibial cubic for 33 degrees and 53 degrees of flexion is not on the tibia and thus they are not possible ligament attachments. (From Grood ES. Placement of knee ligament grafts. In Finerman GA, Noyes FR, editors: *Biology and Biomechanics of the Traumatized Synovial Joint: The Knee as a Model*. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1992:393-417.)

MECHANICAL PROPERTIES OF LIGAMENTS

The ligaments of the knee have unique anatomic and mechanical characteristics that cannot be generalized from one ligament to another. The mechanical behavior of ligaments depends on the material properties of the fibers, the geometric arrangement of collagen fibrils[20,23,71] and fiber bundles (as already described), the proportion of different types of fibrous constituents, and the effect of the surrounding ground substance.[20,29,39,58,69] The ligament insertion site and underlying bone are additional portions of the ligament unit that must be considered when evaluating overall mechanical properties.

One approach for investigating each component of a ligament unit is to use a bone-ligament-bone specimen, such as a femur-ACL-tibia complex (FATC) preparation. This allows the mechanical properties of all of the components of the ligament unit to be studied together. The combined interaction of the components determines the properties of the entire structure in vivo. The problem still exists in loading the bone-ligament-bone unit in a manner that allows in vitro data to be

CRITICAL POINTS Mechanical Properties of Ligaments

The mechanical behavior of ligaments varies and depends on the material properties of the fibers, the geometric arrangement of collagen fibrils and fiber bundles, the proportion of different types of fibrous constituents, the effect of the surrounding ground substance, the ligament insertion site, and underlying bone.

Effect of Strain Rate on Mechanical Properties

- Strain rate describes the rate of deformation used in mechanical studies (length change/initial length per unit of time).
- Significant difference in the predominant mode of failure of the specimens tested at the fast strain rate compared with those tested at the slow rate. At the fast rate, two thirds of the specimens demonstrated a ligamentous failure and 28% failed by tibial avulsion fracture. At the slow rate, 57% of the specimens failed by tibial avulsion fracture and 29% failed by ligamentous failure.
- Under slow strain rate conditions, the bone-insertion area of the tibia was the weakest component. At the fast strain rate, representing the more physiologic loading condition, the ligament and bone components were more balanced as to strength properties and failed at a similar maximum load and energy to failure.

Analysis of Failure-Mode Mechanisms

- Mechanism of failure usually involves both the bony and ligamentous components in a progressive manner until complete failure occurs.
- Ligamentous failure occurs by an initial tensile failure of collagen fibers, followed by a pulling-apart shear failure of the disrupted fibers. Rupture of collagen fiber bundles also occurs throughout the ligament.

The study showed for the first time that an ACL-ligament-bone preparation failed at a higher load and at greater elongation, and absorbed significantly more energy, at a fast rate of deformation than at a slow rate, which is important for interpreting in vitro ligament biomechanical studies.

The visual determination of continuity of a ligament at surgery provides an inadequate determination of the extent of ligament damage that has actually occurred and its functional capacity.

The fibrocartilaginous zone at the ligament insertion site is believed to be advantageous in producing a gradual change in mechanical properties, decreasing the stress-concentration effect of the ligament's insertion into the stiffer bone structure.

extrapolated to in vivo loading conditions. This represents a problem because there are so many different in vivo loading conditions at the time of ACL failure; it is simply not possible to reproduce these conditions in the laboratory. There is less of a problem in studying the effect of one factor or variable on the mechanical properties of a ligament-bone unit because the same loading conditions are used throughout the experiment.

Effect of Strain Rate on Mechanical Properties

The strain rate describes the rate of deformation used in mechanical studies (length change/initial length per unit of time). We have conducted a series of fast and slow strain rate tests on ACL bone-ligament-bone specimens in rhesus monkeys.[63] A slow rate of deformation was chosen to represent the strain rates used in many prior in vitro experiments. A fast rate of deformation was chosen to represent the physiologic in vivo loading conditions to which ligaments may be subjected. The ligament units were tested as right-left pairs at the two strain rates to exclude animal variability. The femur and tibia were at an angle that corresponded to 45 degrees of knee flexion to allow as nearly uniform loading of the ligament as possible. In this experiment, a distraction of the joint was produced. An alternative loading sequence would be to induce anterior translation. Both of these loading profiles have been used experimentally.

Dividing the extension rate by the initial length of the ligament produced approximate strain rates of 0.662 sec^{-1} at the fast rate and of 0.00662 sec^{-1} at the slow rate, a 100-fold difference. At the fast rate, the ligament underwent the initial 15% to 20% elongation in approximately 0.25 seconds.

An example of a load-versus-time record from a typical test at the fast strain rate is shown in Figure 4-17. The curve demonstrates an initial concave toe region, followed by a fairly linear region up to the first significant failure. At this point, the load is termed the *linear load* because it denotes the approximate point at which the ligament preparation enters into the major failure region. Minor failures occur first, with a drop in load. Decreases in load after the linear load indicate successive failures until complete failure, at which time the load falls to zero. The maximum load occurs in the major failure region. The time axis is proportional to the relative displacement of the grips and represents elongation of the ligament after the compliance of the testing device and the grips are computed. Because the extension rate is known, specimen elongation at the linear load, maximum load, and zero load (complete failure) is determined. The area under the load-deformation curve indicates the energy absorbed by the specimen up to complete failure. The slope of the curve in the linear region provides the approximate stiffness of the preparation. It was not possible in this experiment to calculate the cross-sectional area of the ACL with any degree of reproducible accuracy. Force values are reported as load rather than stress (force per unit area). Alternative experiments, discussed later, employ other testing configurations in which ligament strain is measured by sensitive optic techniques.

The anterior cruciate bone-ligament-bone specimens showed a complex and varied mode of failure. These included avulsion of minor to major bone fragments from insertion sites, failure at the bone-ligament interface without bone avulsion, and ligament failure that occurred initially by tensile pull-apart failure of fiber bundles and then by shear failure among the disrupted fibers. The predominant mode of failure of each specimen was classified as one of the following: (1) ligamentous failure, (2) tibial avulsion failure, (3) combined ligament failure/tibial avulsion fracture, (4) femoral avulsion fracture, or (5) combined ligament failure/femoral avulsion fracture.

A statistically significant difference was found in the predominant mode of failure of the specimens tested at the fast strain rate compared with those tested at the slow rate ($P < .05$, Fig. 4-18). At the fast rate, two thirds of the specimens demonstrated a ligamentous failure and 28% failed by tibial avulsion fracture. At the slow rate, 57% of the specimens failed by tibial avulsion fracture and 29% failed by ligamentous failure.

The results of the strain rate properties according to the modes of failure are shown in Table 4-1. Under slow strain rate conditions, the bone-insertion area of the tibia was the weakest component, demonstrated by the reduced maximum load and energy absorbed to failure. At the fast strain rate, representing the more physiologic loading condition, the ligament and bone components failed at a similar maximum load and energy. The overall difference in strength properties was

CRITICAL POINTS Effects of Immobilization and Disuse on Ligament Biomechanical Properties

We conducted a study on primates to determine the effect of altered activity levels on the mechanical properties of ligaments.

- The results showed that 8 weeks of immobilization produced a marked decrease of nearly one half of the maximum failure load and significant weakening of a functional ligament unit.
- The decrease in strength properties was associated with resorption of haversian bone and weakening of the cortex beneath the ligament's insertion site at both the tibia and femur.
- An exercise program had little effect in preventing the decline in the strength properties of the ligament unit during immobilization and only partial recovery in strength properties occurred after 20 weeks of resumed activity.
- Following immobility, an extended period of time may be required before the functional capacity of a ligament unit returns to normal.
- Disuse-induced changes following fracture or ligament reconstruction may extend well into the time period after which normal activity has been resumed by the patient

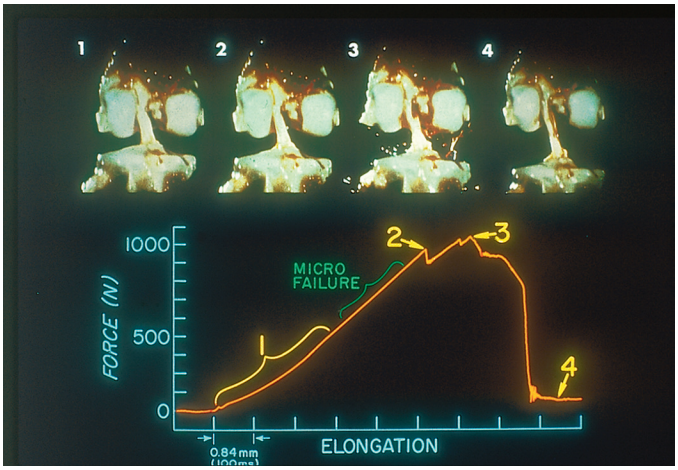


FIG 4-17 Oscillograph record of force versus time for a tension test to failure of a rhesus femur-ACL-tibia preparation. A constant distraction rate was used so that the time axis was proportional to specimen elongation. The images, obtained from high-speed videos taken during the test, show the preparation at four stages of the test. (From Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. In Hutton R, editor. *Exercise and Sports Science Review,* vol 6. Philadelphia: Franklin Institute Press; 1978-125-182.)

TABLE 4-1 Strain Rate Results by Failure Mode

Strain Rate	*n*	Failure Mode	Maximum Load (kgf)	Strain to Maximum Load (%)	Energy (kgf-cm)	Strain to Failure (%)
Fast	21	Ligamentous	92.8 ± 17.5	51.4 ± 7.5	39.8 ± 8.9	61.0 ± 8.9
	9	Tibial avulsion fx	100.0 ± 19.3*	51.6 ± 7.0*	38.4 ± 13.2	55.0 ± 12.4
Slow	8	Ligamentous	93.0 ± 10.6	47.8 ± 6.0	39.9 ± 9.7†	59.0 ± 9.3†
	16	Tibial avulsion fx	84.1 ± 2*	45.6 ± 7.4*	30.9 ± 9.3†	50.9 ± 8.0†

From Noyes FR, DeLucas JL, Torvik PJ. Biomechanics of anterior cruciate ligament failure: an analysis of strain-rate sensitivity and mechanisms of failure in primates. *J Bone Joint Surg Am.* 1974;56:236-253.
*Mean value significantly different from that of the same failure mode at the other strain rate.
†Mean value significantly different from that of other failure mode at the same strain rate.
Fx, Fracture.

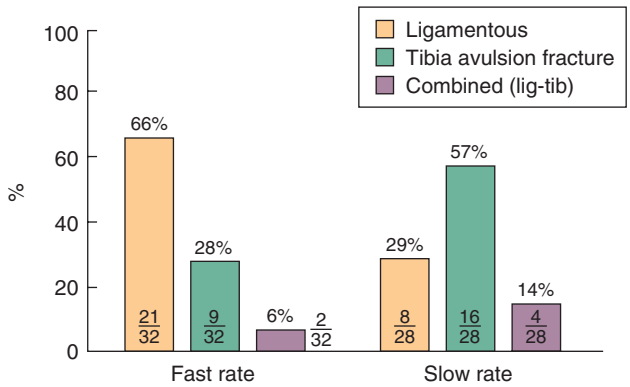


FIG 4-18 The major mechanism of specimen failure is shown for 32 knees tested at the fast strain rate and 28 knees tested at the slow strain rate. The difference in specimen failure at the two strain rates is statistically significant ($P < .05$). (From Noyes FR, DeLucas JL, Torvik PJ. Biomechanics of anterior cruciate ligament failure: an analysis of strain-rate sensitivity and mechanisms of failure in primates. *J Bone Joint Surg Am.* 1974;56:236-253.)

caused in part by increased strength of the bone component at the fast rate. At the slow rate, failure by tibial avulsion fracture was interpreted as premature failure, indicating a decrease in the specimen's potential strength. The size of the animals was not a factor contributing to the predominant mode of failure. The different types of failure were distributed throughout each strain rate group regardless of the weight of the animal. In addition, juvenile animals were not used, which could have biased the results toward a higher frequency of tibial avulsion fractures.

Analysis of Failure-Mode Mechanisms

Macroscopic Analysis

High-speed films of specimen loadings demonstrated that the mechanism of failure usually involved both the bony and ligamentous components in a progressive manner until complete failure occurred. Sequential failure of ligament fibers commonly occurred first, before major tibial avulsion fractures. In other specimens, minor avulsion fractures were associated with major ligamentous failure (Fig. 4-19).

Microscopic Analysis

Microscopic analyses were conducted after the loading tests to define the mechanisms of specimen failure. Resorption changes at the bone-ligament interface, indicative of premature failure, were not visualized in any of the femoral or tibial insertion sites. Polarized light microscopy demonstrated that the ACL inserted at femoral and tibial sites through four well-defined zones of fibrocartilage (see Fig. 4-19).[19] The



FIG 4-19 Photomicrograph after tibial avulsion mode of failure shows that cleavage occurred through cancellous bone below the more dense cortical bone at the site of ligament insertion. The zonal arrangement at the bone-ligament interface is shown. Ligament, zone 1; fibrocartilage, zone 2; mineralized fibrocartilage, zone 3; and bone, zone 4 (hematoxylin and eosin, ×90). (From Noyes FR, DeLucas JL, Torvik PJ. Biomechanics of anterior cruciate ligament failure: an analysis of strain-rate sensitivity and mechanisms of failure in primates. *J Bone Joint Surg Am.* 1974;56:236-253.)

zonal arrangement at the insertion site represents a change in composition of the surrounding medium as the ligament collagen fibers (zone 1) pass through fibrocartilage (zone 2), across a blue line to mineralized fibrocartilage (zone 3), and into the bone (zone 4).

The specimens in this investigation demonstrated three histologic modes of failure, which were consistent with the macroscopic observations. First, ligamentous failure occurred by an initial tensile failure of collagen fibers, followed by a pulling-apart shear failure of the disrupted fibers (Fig. 4-20). Rupture of collagen fiber bundles was also observed throughout the ligament. The ligament fiber microgeometry under the loading conditions in the experiment determined which fibers were subjected to the greatest deformation, leading to the serial

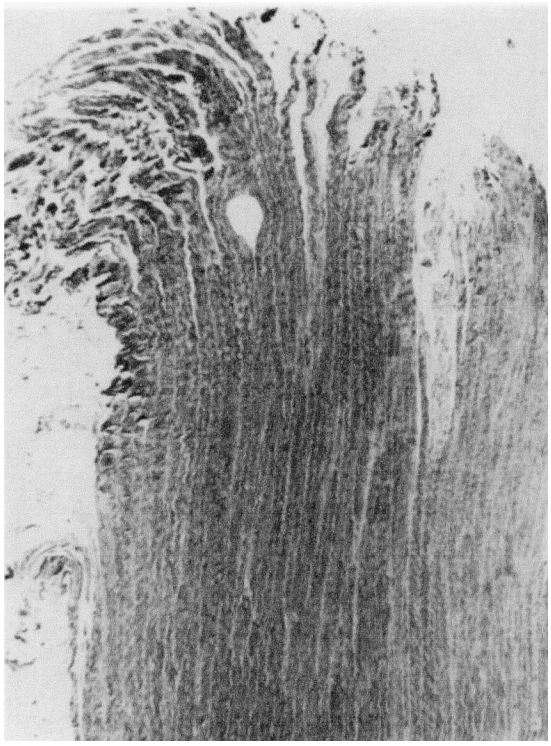


FIG 4-20 Photomicrograph of a portion of the anterior cruciate ligament after failure. The mechanism of failure appeared to be a tensile, pulling-apart type of failure. The collagen fibers are shown to have ruptured at different portions of the ligament, giving an uneven cleavage line corresponding to the common "mop-end" gross appearance (trichrome ×45). (From Noyes FR, DeLucas JL, Torvik PJ. Biomechanics of anterior cruciate ligament failure: an analysis of strain-rate sensitivity and mechanisms of failure in primates. *J Bone Joint Surg Am.* 1974;56:236-253.)

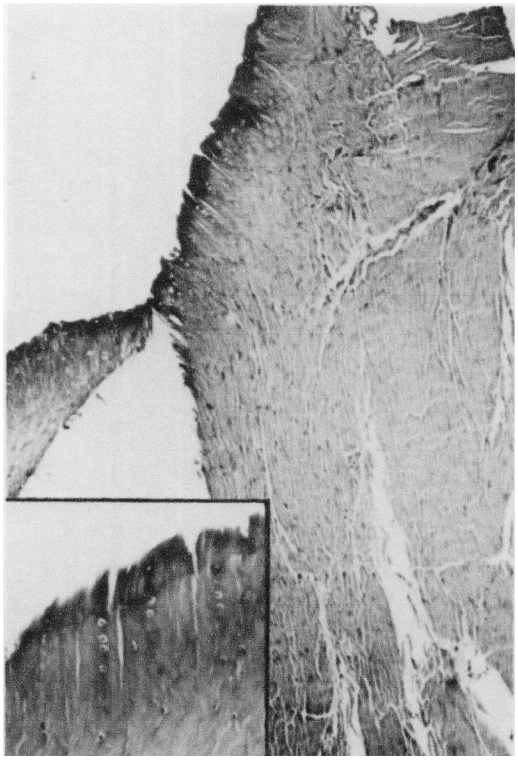


FIG 4-21 Photomicrograph shows predilection for cleavage at the ligament-bone interface to occur through the mineralized fibrocartilage zone. *Inset,* columnar arrangement of chondrocytes (periodic acid–Schiff, ×80). (From Noyes FR, DeLucas JL, Torvik PJ. Biomechanics of anterior cruciate ligament failure: an analysis of strain-rate sensitivity and mechanisms of failure in primates. *J Bone Joint Surg Am.* 1974;56:236-253.)

rupture of fibers and accounted for rupture of fibers in areas adjacent to intact fibers. Although branching among individual collagen fiber bundles was observed, the pulling-apart type of failure suggests that little in the way of cohesive properties exists among the major fiber bundles. A more explicit definition of the mechanism of failure of collagen tissues also involves the ultrastructural changes of fibrils and microfibrils under failure conditions.[63]

Second, avulsion fracture at the attachment site occurred most commonly through the cancellous bone immediately beneath the dense cortical bone (Fig. 4-21). The minute gritty material sometimes just barely palpable on the end of the ligament after failure represented fragments of bone beneath the cartilaginous zone of ligament insertion.[63]

Third, cleavage at the ligament-bone interface showed a predilection for the fracture cleavage line to occur through the zone of mineralized fibrocartilage (zone 3) at or just distal to the blue line. Failure at this interface was the least common mode of failure. It was identified microscopically in 6 of 22 specimens; however, it represented only a minor part of the failure process, the major failure having occurred by either a ligamentous or bone avulsion mode. Failure through the fibrocartilaginous zone was, therefore, never the major mode of specimen failure, but not infrequently accompanied the other two modes of failure.[63]

In summary, it was possible to classify the major mechanism of failure histologically, although minor modes of failure involved to different degrees all portions of the bone-ligament-bone unit. Thus it was not unusual to find microscopic evidence of minor to moderate ligament disruption associated with major bone avulsion failures or vice versa.[63]

This study showed for the first time that an ACL-ligament-bone preparation failed at a higher load and at greater elongation, and absorbed significantly more energy, at a fast rate of deformation rather than at a slow rate. These findings show the time-dependent behavior of bone-ligament-bone preparations and questioned the results of prior ligament failure studies, which often showed premature bone failure at less than expected failure loads. At the slow deformation rate, the bone insertion area of the tibia was the weakest component. At the fast deformation rate, the ligament and tibial osseous component were balanced as to strength properties with an increased frequency of ligamentous failure.[63] The specimen under the fast deformation rate withstood greater loads without premature osseous failure, allowing the ligament to participate in the failure process.[73] Even with expected viscoelastic effects in the ligament as a result of the higher strain rate, the strength of the bone increased faster than did an expected increase in strength of the ligament.[63]

Many cadaveric and experimental animal studies have reported the difficulty of producing ligamentous injuries and have traditionally stated that the bone is the weakest component of the bone-ligament-bone system.[38,57,79,84,85,90,91,100] Other than the difficulty in reproducing in the laboratory the complex loading and displacement conditions that occur in traumatic injuries, the deformation rate of the experimental tests and the effect of disuse-induced bone changes caused by animal caging or aged cadavers are believed to be the major explanation for premature bone avulsion of the ligament-bone unit.[63]

In agreement with these results, Welsh and associates[95] demonstrated that the failure mode of a calcaneal-Achilles tendon unit changed from bone avulsion at low deformation rates to failure at the tendon grip apparatus under high deformation rates. The ultimate load of the specimens in that investigation may not have been obtained because of the difficulty of clamping the tendons; however, the bone insertion site did not fail at the high strain rate despite the specimen reaching a higher load.

In cases of tibial avulsion fracture, the ligament failure component could not be appreciated on gross examination after the test. In view of the demonstrated elongation on the ligament in the region of failure, it is reasonable to expect damage to collagen fibers and blood vessels within the ligament, even though continuity remains. It is well appreciated that the visual determination of continuity of a ligament at surgery provides an inadequate determination of the extent of ligament damage that has actually occurred and its functional capacity. Such factors, among others, may contribute to the occasional unsatisfactory result in cases of partial ligament disruption with continuity and in cases of ligament reinsertion after bone avulsion.[63]

The fibrocartilaginous zone at the ligament insertion site is believed to be advantageous in producing a gradual change in mechanical properties, decreasing the stress-concentration effect of the ligament's insertion into the stiffer bone structure.[19] This zone protects against fatigue and shear failure at the bone-ligament junction, providing a composite structure with the addition of cartilage and mineralized fibrocartilage to the collagen network. The fibrocartilaginous ground substance may provide greater cohesion among fiber bundles and provide a mechanism for diffusion of load over the entire insertion site, avoiding the deleterious effects of stress concentration. Based on the microscopic analysis of specimen failure and the infrequent occurrence of failure through the fibrocartilaginous zone, the zonal insertion arrangement appears to be mechanically advantageous.[63]

EFFECTS OF IMMOBILIZATION AND DISUSE ON LIGAMENT BIOMECHANICAL PROPERTIES

It is well appreciated that immobility may lead to deleterious changes in bone, joint, and soft tissue.[4,18,24,26,28,40,45-47,49,50,82] We conducted a study to determine the effect of altered activity levels on the mechanical properties of ligaments in primates.[67] Although exercise is accepted as beneficial in preventing muscle atrophy and maintaining joint motion, its effect in preventing deterioration or strengthening a bone-ligament-bone unit had not been established. The study simulated certain clinical states of immobility and determined: (1) the effect of immobilization on the mechanical properties of a bone-ligament-bone unit, (2) the effect of an exercise program in preventing changes in these properties, and (3) the extent to which the changes remained after a 20-week reconditioning period. The reader is referred to the publication for the detailed explanation of the study.[67]

The rhesus animals were placed into four groups: (1) group I, control group, 30 knees; (2) group II, nine animals immobilized for 8 weeks in total body plaster casts that included both lower limbs; (3) group III, 11 animals in which one lower limb was immobilized for 8 weeks while the other lower limb was exercised daily; and (4) group IV, 11 animals immobilized as in group II, reconditioned for 5 months in room-sized gang cages that were wide and deep and provided ample room for jumping and other activities.

The animals in the exercise group (group III) performed an active pushing movement against resistance with one free lower extremity in response to a food-reward system. The pushing movement was from 90 degrees of hip and knee flexion to 20 degrees of hip and knee flexion. The foot and ankle were secured by a boot to an exercise apparatus, and with each successful stroke, the animals received a pellet of food. The animals performed the exercise diligently and, on occasion, food had to be restricted. The force required to perform the exercise was minimal initially and then gradually increased over the first 2 weeks so that the animals performed the task at least 600 times daily. The resistance, length of push, and number of repetitions were recorded daily. The animals usually depressed the apparatus 600 to 900 times daily against a resistance of 1.6 to 2.4 kg (about one third body weight).

The average daily work performed by each primate was 11,000 ± 4000 kilogram-force centimeter (kgf-cm) (range, 6600 to 20,200 kgf-cm). The average total work performed by each animal during the 8 weeks of immobilization was $6.19 \times 10^5 \pm 2.4 \times 10^5$ kgf-cm (range, 3.69×10^5 to 1.11×10^6 kgf-cm). There was no significant correlation between the total amount of work each animal performed and the strength of the ligament preparation.

The results showed that 8 weeks of immobilization produced a marked decrease of nearly one half of the maximum failure load ($P < .001$, Table 4-2). No significant differences were found in ultimate failure load between the immobilized or exercised group or between the right and left ligament units from the exercised group. The failure load for the reconditioned animals indicates partial but incomplete recovery at 20 weeks (Fig. 4-22).

The data demonstrate that immobilization leads to significant weakening of a functional ligament unit. The exercise program had little effect in preventing the decline in the strength properties of the ligament unit during immobilization, and only partial recovery in strength properties occurred after 20 weeks of resumed activity. The decrease in strength properties was associated with resorption of haversian bone and weakening of the cortex beneath the ligament's insertion site at both the tibia and femur.

The mechanism of failure of a ligament-bone unit after disuse-induced changes depends on the anatomic characteristics at the ligament-bone insertion site. Most knee ligaments insert into bone through the well-defined zones of fibrocartilage previously described.[19,50,63,74] These zones appear to be protective, because subsynovial and subperiosteal (femoral site) resorption of bone was observed at the peripheral margins of the ligament insertion site but not at the ligament-bone junction. Ultimate failure of the ligament unit occurred through either the underlying cortical bone at the insertion site or through the body of the ligament (or at both of these locations), but not through the ligament-bone junction. This protective effect of the fibrocartilage probably also applies to tendons that have a similar type of attachment[19,74,80] The zone also imposes a barrier to a vascular supply of the ligament from the bone beneath the insertion site.[74] The tibial attachment of the long fibers of the MCL is into the periosteum and Sharpy fibers without a fibrocartilaginous interface. Immobility

CRITICAL POINTS Biomechanical Analysis: Human Ligament Grafts for Reconstruction

We conducted a study on young human cadavers to determine the biomechanical properties of various tissues commonly used to reconstruct knee ligament ruptures.

- Bone-patellar tendon-bone and four-strand semitendinosus-gracilis grafts exceed the percent strength of the ACL.
- Data provide the surgeon with an initial estimate of graft mechanical properties to consider in selection of the appropriate graft for intraarticular and extraarticular ligament reconstructions.

TABLE 4-2 Effect of Immobilization, Exercise, and Reconditioning on Biomechanical Properties of Primate Femur-Anterior Cruciate Ligament-Tibia Preparations*

Parameter	Control ($n = 30$)	Immobilized ($n = 18$)	Exercise Right ($n = 11$)	Exercise Left ($n = 11$)	Reconditioned ($n = 22$)	Statistical Analyses
Linear load (kgf)	78.04 ± 19.35	46.79 ± 15.88	47.66 ± 12.56	55.97 ± 15.87	64.37 ± 23.16	C-I: $P < .001$ C-R: $P < .05$ C-ER: $P < .001$ I-R: $P < .01$ C-EL: $P < .01$ R-ER: $P < .05$
Maximum load (kgf)	87.33 ± 19.40	53.14 ± 12.79	61.71 ± 8.60	61.38 ± 13.04	68.68 ± 18.35	C-I: $P < .001$ C-R: $P < .01$ C-ER: $P < .001$ C-EL: $P < .001$ I-R: $P < .01$
Strain to linear load (%)	39.24 ± 8.52	33.00 ± 9.86	32.04 ± 10.48	36.28 ± 10.66	36.21 ± 9.91	C-I: $P < .05$ C-ER: $P < .05$
Strain to maximum load (%)	46.66 ± 8.63	43.88 ± 9.08	40.86 ± 8.23	41.64 ± 5.66	38.53 ± 7.80	C-R: $P < .01$
Strain to failure (%)	60.47 ± 9.07	66.28 ± 16.72	58.80 ± 8.45	53.89 ± 7.36	58.03 ± 13.26	C-EL: $P < .05$ ER-EL $P < .05$ I-EL: $P < .05$
Energy to failure (kgf-cm)	34.02 ± 10.72	23.16 ± 5.27	23.88 ± 6.31	24.37 ± 5.61	26.53 ± 7.19	C-I: $P < .001$ C-R: $P < .01$ C-ER: $P < .01$ C-EL: $P < .01$

From Noyes FR, Torvik PJ, Hyde WB, DeLucas JL. Biomechanics of ligament failure. II. An analysis of immobilization, exercise, and reconditioning effects in primates. *J Bone Joint Surg Am* 1974;56:1406-1418.

*Mean values and standard deviations for the mechanical test parameters in the control and experimental groups. Statistical comparisons of the mean values among groups are listed for those parameters significantly different from zero on *t* test analysis at $P < .05$ (two-tailed test). Group comparisons not listed are not statistically significant.

C, Control; *I,* immobilized; *ER,* exercise right; *EL,* exercise left (nonexercised limb in exercise group); *R,* reconditioned.

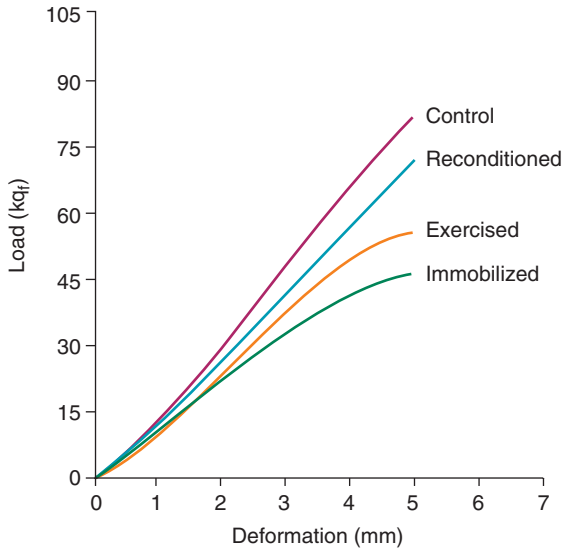


FIG 4-22 Calculated load-deformation curves show ligament behavior under loading for all specimens in each of the animal groups. A significant decrease in stiffness (slope of the load-deformation curve) of the ligament preparation is seen in specimens from the exercised and immobilized group. Partial recovery occurred at 20 weeks. (From Noyes FR, Torvik PJ, Hyde WB, DeLucas JL. Biomechanics of ligament failure. II: An analysis of immobilization, exercise, and reconditioning effects in primates. *J Bone Joint Surg Am.* 1974;56:1406-1418.)

has a pronounced effect in producing subperiosteal bone reabsorption that decreases the tibial MCL attachment site strength, resulting in premature failure before involving the ligament in the failure process.[45,47,50] Because of the premature attachment failure, the use of a MCL bone-ligament unit is not ideal and disuse-induced cage confinement of experimental animals induces this as a variable, affecting the results. We agree with Laros and coworkers[50] that the reported increase in ligament strength above control values, resulting from increased activity in animals, may represent the prevention or reduction of the disuse effect of caging.

The effect of immobility on the ligament itself is of importance to its mechanical function. The change in the relationship between force and ligament elongation (stiffness) after immobilization correlated with the inactivity of the primates. The exercised ligament units were somewhat less affected than the fully immobilized specimens. Both groups were significantly different compared with the control group. The stiffness of the ligament unit in the reconditioned specimens had nearly returned to normal at 20 weeks, although the recovery in strength was incomplete. Other studies have shown a similar correlation between the general level of activity during confinement and the strength of a ligament unit.[1,50,84,86,91,100]

The clinical relevance of this study relates to the suggestion that following immobility, an extended period of time may be required before the functional capacity of a ligament unit returns to normal. Disuse-induced changes after fracture or ligament reconstruction may extend well into the time period after which normal activity has been resumed by the patient.

BIOMECHANICAL ANALYSIS: HUMAN LIGAMENT GRAFTS FOR RECONSTRUCTION

A biomechanical analysis was performed in our laboratory[62] to determine the mechanical properties in human tissues from young donors. Young adult cadaveric tissues were used to exclude age and disuse effects. The overall results of this study are shown in Tables 4-3 and 4-4. The bone-patellar tendon-bone (B-PT-B) grafts exceeded the percent strength of the ACL. However, the specimens used in this study had an increased width of 4 to 5 mm and to apply these results to clinical cases, the conversion of 208 N/mm is provided in Table 4-4. This indicates a 10-mm-wide graft would have a converted value of approximately 2008 N, which still exceeds the approximate strength of a young adult ACL. A single semitendinosus or gracilis tendon has 70% and 49%, respectively, the strength of the ACL, indicating that a four-strand graft would exceed by many times the native ACL strength. In comparison, the distal iliotibial tract has a reduced strength that requires a 45-mm width of fascia to achieve an approximate value equal to the ACL.

Obviously, these maximum load values represent time-zero mechanical properties. Graft fixation and biologic remodeling factors combine to determine the final stabilizing effect of human ligament grafts, as discussed in other sections of this book. Further, the data compare the tissue grafts to human ACL mechanical properties only for uniaxial loading tests. The ACL has a complex fiber microgeometry that none of the graft tissues simulate. Therefore, the data provide the surgeon with an initial estimate of graft mechanical properties to consider in selection of the appropriate graft for intraarticular and extraarticular ligament reconstructions. There is a hypothetical loading curve for the ACL shown in Figure 4-23 that provides a perspective of in vivo ligament function. Although never actually measured, there are safety zones in which the ACL functions for most activities well below its ultimate strength, and the generalization is shown for approximately 454 N (100 lb) for most activities. This represents an approximate built-in safety margin of 4:5:1 ratio of the ultimate in vivo failure strength. Figure 4-23 also shows the slope of the loading curve representing the stiffness (elongation of the ligament per unit load) that determines the stabilizing effect of the ligament in resisting anterior tibial translation that is an equally important property.

CRITICAL POINTS Strength of the ACL: Age-Related and Species-Related Changes

We conducted a study in which the mechanical properties of ACL specimens from humans and rhesus monkeys were determined in tension to failure under high strain rate conditions. The purposes of the study were to determine whether discrepancies in strength and mechanisms of ligament failure between human and animal specimens were caused by size differences, variables in the human specimens such as age or disuse atrophy, or certain experimental testing variables.

- The ligament lengths and areas of the animals were approximately one half and one fourth those in the human donors, respectively.
- Significant differences were found between the older and the younger human specimens in stiffness, strength, and mechanical properties. Preparations from the younger humans failed at a maximum force that was an average of 2.4 times that of the specimens from the older humans.
- Ligaments from the rhesus animals failed at normalized force values (to body mass) over three times higher than those of the younger human specimens.
- The specimens from older humans showed a decrease in cortical thickness and trabecular bone at the insertion of the ligaments. Failure occurred by fracture through the cortical and underlying trabecular bone, owing to both age-related and probably disuse-induced changes.

STRENGTH OF THE ACL: AGE-RELATED AND SPECIES-RELATED CHANGES

Important changes occur in the functional properties of bone-ligament units with age and differences from one animal species to another. We conducted a study in which the mechanical properties of ACL specimens from humans and rhesus monkeys were determined in tension to failure under high strain rate conditions.[64] The age of the cadaver specimens ranged from 16 to 86 years. One of the purposes of the study was to determine whether discrepancies in strength and mechanisms of ligament failure between human and animal specimens were because of size differences, variables in the human specimens such as age or disuse atrophy, or certain experimental testing variables. In addition, human data were required to define the strength properties required for ACL graft replacements.

Comparison of Size Parameters

The mass of the rhesus animals was small compared with that of the human donors (Table 4-5). The ligament lengths and areas of the animals were approximately one half and one fourth those in the human donors, respectively.

TABLE 4-3 Tissue Dimensions

Tissue	No. Specimens	Length (mm)*	Area (mm^2)	Width (mm)
Anterior cruciate ligament	6	26.9 ± 1.1	44.4 ± 4.0	NA
Bone-patellar tendon-bone				
Central	7	48.7 ± 3.8	50.5 ± 2.8	13.8 ± 1.4
Medial	7	48.8 ± 2.8	49.9 ± 3.8	14.9 ± 1.1
Semitendinosus	11	36.6 ± 3.1	14.0 ± 0.5	NA
Fascia lata	18	46.7 ± 2.7	8.2 ± 0.4	15.6 ± 0.8
Gracilis	17	41.9 ± 2.2	7.6 ± 0.2	NA
Distal iliotibial tract	10	39.1 ± 2.5	37.3 ± 3.5	18.0 ± 1.6
Quadriceps tendon-patellar retinaculum-patellar tendon				
Medial	7	30.7 ± 4.0	28.5 ± 4.7	14.4 ± 1.9
Central	6	30.4 ± 4.2	17.4 ± 5.3	16.3 ± 3.5
Lateral	7	30.6 ± 2.3	28.6 ± 5.7	13.7 ± 1.8

From Noyes FR, Butler DL, Grood ES, et al: Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg Am.* 1984;66:344-352.
Data are given as mean and standard error of the mean.
*This is a mean overall length, representing an average of the longest and shortest fiber bundles, and should not be construed as the length of the longest bundles.
NA, Not available; width measurements were not made because these represent whole tissues.

TABLE 4-4 Maximum Loads for the Human Anterior Cruciate Ligament and Its Replacements

	Maximum Load (N)	% of Anterior Cruciate	Maximum Load/Unit Width (N/mm)	Maximum Stress (MPa)
Measured Values				
Anterior cruciate ligament-bone ($n = 6$)	1725 ± 269	100	NA	37.8 ± 3.8
Bone-patellar tendon-bone				
Central third ($n = 7$)	2900 ± 260†	168	208 ± 24	58.3 ± 6.1†
Medial third ($n = 7$)	2734 ± 298†	159	162 ± 13	56.7 ± 4.4†
Semitendinosus ($n = 11$)	1216 ± 50	70	NA	88.5 ± 4.0¶
Gracilis ($n = 17$)	838 ± 30‡	49	NA	111.5 ± 4.0¶
Distal iliotibial tract (18-mm width, $n = 10$)	769 ± 99‡	44	44 ± 6	19.1 ± 2.9§
Fascia lata (16-mm width, $n = 18$)	628 ± 35§	36	39 ± 2	78.7 ± 4.6¶
Quadriceps-patellar retinaculum-patellar tendon				
Medial ($n = 7$)	371 ± 46¶	21	24 ± 4	15.4 ± 3.4§
Central ($n = 6$)	266 ± 74¶	15	17 ± 3	16.1 ± 1.8¶
Lateral ($n = 7$)	249 ± 54¶	14	19 ± 4	9.7 ± 1.5¶
Calculated Values*				
Distal iliotibial tract 25-mm width	1068	62		
Plus adjacent 10 mm of fascia	1468	85		
Plus adjacent 20 mm of fascia	1868	108		
Fascia lata (45-mm width)	1800	104		

From Noyes FR, Butler DL, Grood ES, et al. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg Am.* 1984;66:344-352.
Data are given as mean ± standard error of the mean.
*Calculated by adjusting test values to new specimen widths.
†Statistically different from the maximum value for the anterior cruciate ligament; $P < .05$.
‡$P < .01$.
§$P < .005$.
¶$P < .001$.
NA, Not available; width measurements were not made.

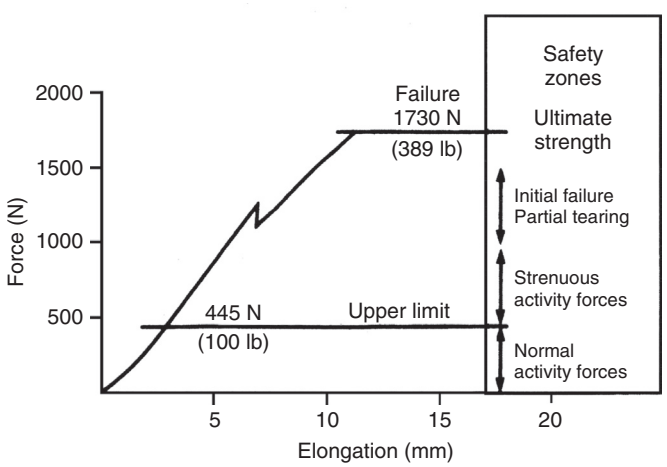


FIG 4-23 A hypothetical load-elongation curve for the anterior cruciate ligament-bone unit is shown along with the idealized safety zones to be considered in evaluating a ligament replacement. The goal is to achieve the highest force zone possible. Some grafts of lesser strength may function as long as lower levels of force are maintained. The cruciate ligament curve does not represent any single failure test that was performed. (From Noyes FR, Butler DL, Grood ES, et al. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg Am.* 1984;66:344-352.)

CRITICAL POINTS Effect of Intraarticular Corticosteroids on Ligament Properties

The effect of slightly soluble corticosteroid (methylprednisolone acetate) was investigated on the mechanical properties of a rhesus ACL ligament unit.

- A direct steroid injection into the ligament resulted in statistically significant decreases in maximum load and energy to failure in both the large-dose and small-dose groups.
- The clinical implications are that a single direct injection of a slightly soluble steroid preparation has a marked effect on decreasing ligament functional properties that remained up to 1 year.
- Intraarticular injections resulted in alterations in ligament behavior that were dependent on the dose of the drug and the time that had elapsed after injection.
- In the high-dose group, the maximum failure load of the ligament unit decreased by 11% after 6 weeks and 20% after 15 weeks. In the low-dose group, the maximum failure load of the ligament unit decreased by 9%.
- In the high-dose group, a significant decline in the stiffness of the ligament unit had occurred at 15 weeks. No such decline was detected in the low-dose group.
- The clinical implications suggest that intraarticular, slightly soluble corticosteroids in high and frequent doses have the potential to alter ligament strength and function. The risk associated with such alterations may be minimal if infrequent, low-dose injections are administered.

TABLE 4-5 Anterior Cruciate Ligament Strength: Comparison of Size

	Specimens (*N*)	Donor Mass (kg)	Length (mm)	Area (mm^2)	Volume (mL)
Older human (48-86 yr)	20	72.1 ± 24.6	27.5 ± 2.8	57.5 ± 16.2	1.60 ± 0.53
Younger human (16-26 yr)	6	52.6 ± 0.52	26.9 ± 1.5	44.4 ± 9.7	1.21 ± 0.31
Rhesus monkey	25	7.0 ± 0.6	12.3	12.7 ± 1.71	0.156

From Noyes FR, Grood ES. The strength of the anterior cruciate ligament in humans and rhesus monkeys. Age-related and species-related changes. *J Bone Joint Surg Am.* 1976;58:1074-1082.

Comparison of Structural Parameters

A typical force/elongation curve for one young and one older adult human specimen is shown in Figure 4-24. The mean values for the stiffness and strength parameters of the human and rhesus ligament specimens are shown in Table 4-6. A significant difference was found between the older and younger human specimens. The preparations from the younger humans failed at a maximum force that was an average of 2.4 times that of the specimens from the older humans. The ligaments from the animals failed at force values higher than those of the older human specimens, despite an approximate fivefold difference in the respective cross-sectional area of the ligaments.

Comparison of Material Properties

The data shown in Table 4-7 represent measurements of the mechanical properties of the ligament collagen as a material. They are normalizations of the structural parameters, adjusted for variations in the cross-sectional areas and lengths of the specimens. There were large differences in all parameters shown between ligaments from younger and older humans. The mean value for the elastic modulus of the ligaments from young adult humans was 1.7 times that of the ligaments from the older humans, but was significantly lower than the mean value for the ligaments from the animals.

The maximum stress and the strain energy to failure in the specimens from younger humans were 2.8 and 3.3 times the respective values for the older human group. The maximum stress and the strain energy to failure in the ligaments from the animals were 1.8 and 1.9 times the respective values for the specimens from younger humans.

Age-Related Changes

Statistically significant decreases were found with age in the elastic modulus, maximum stress, and the strain energy for the specimens that failed by a ligamentous mode, in which prior antemortem effects were excluded, but not for the specimens from older humans that failed by premature bone-avulsion fracture, in which significant antemortem effects were suspected.

The regression equation (y) and correlation coefficient (r) for the specimens that failed by a ligamentous mode are shown in Figure 4-25. Maximum stress showed the highest correlation with age ($r = 0.863$, $P < .005$). A low correction was found with strain energy to failure (0.75) and elastic modulus (0.712), but all correlations were statistically significant.

Histologic Findings

The change in mechanism of specimen failure with age from a ligamentous mode to bone-avulsion fracture correlated with histologic findings. The specimens from older humans showed a decrease in cortical thickness and trabecular bone at the insertion of the ligaments. Failure occurred by fracture through the cortical and underlying trabecular bone. The fibrocartilage junctional zone remained intact with normal straining characteristics and only rarely did the fracture plane extend through it.

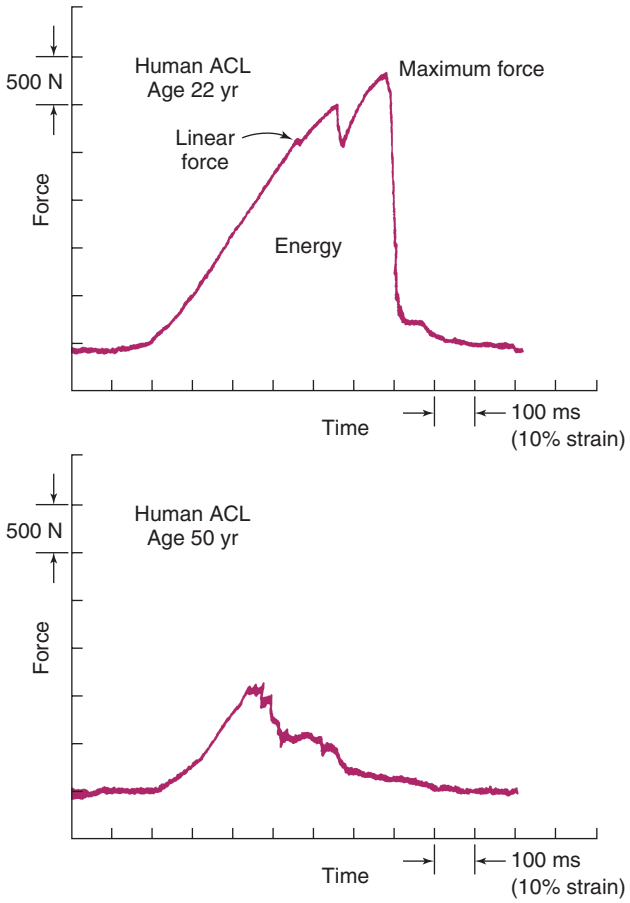


FIG 4-24 Typical oscillograph force versus time records for a younger and an older human specimen show behavior of the anterior cruciate ligament (ACL) preparation in the mechanical test. The specimen from the older human demonstrates a decrease in stiffness (slope of the curve) and failure at lower force and strain values. Failure in the specimen from the older human occurred by femoral avulsion fracture just beneath the ligament attachment site in contrast to the ligamentous mode of failure in the preparation from the younger human. (From Noyes FR, Grood ES. The strength of the anterior cruciate ligament in humans and rhesus monkeys. Age-related and species-related changes. *J Bone Joint Surg Am.* 1976;58:1074-1082.)

The histologic findings frequently included other minor modes of failure involving all other portions of the ACL unit, as previously described.[63,67]

Comparison of Ligament Structural Properties

Alm and colleagues[2] conducted a study on the tensile strength of the canine cruciate ligament in which the data were normalized by calculating the ratio between ligament separation force and animal mass.

TABLE 4-6 Anterior Cruciate Ligament Strength: Comparison of Structural Properties

	Specimens (n)	Stiffness (kN/m)	Linear Force (kN)	Maximum Force (k/N)	Energy to Failure (N-m)
Older human (48-86 yr)	20	129 ± 39	0.622 ± 0.283	0.734 ± 0.266	4.89 ± 2.36
Younger human (16-26 yr)	6	182 ± 56	1.17 ± 0.75	1.73 ± 0.66	12.8 ± 5.5
Rhesus monkey	25	194 ± 28	0.71 ± 0.12	0.83 ± 0.11	3.0 ± 0.6

From Noyes FR; Grood ES. The strength of the anterior cruciate ligament in humans and rhesus monkeys. Age-related and species-related changes. *J Bone Joint Surg Am.* 1976;*9*58:1074-1082.

TABLE 4-7 Anterior Cruciate Ligament Strength: Comparison of Material Properties

	Specimens (n)	Elastic Modulus (MPa)	Linear Stress (MPa)	Maximum Stress (MPa)	Strain Energy to Failure (N-m/mL)
Older human (48- 86 yr)	20	65.3 ± 24.0*	11.3 ± 5.1	13.3 ± 5.0†	3.1 ± 1.5‡
Younger human (16-26 yr)	6	111 ± 26‡	25.5 ± 14.0†	37.8 ± 9.3‡	10.3 ± 3.1‡
Rhesus monkey	25	186 ± 26	56.2 ± 7.6	66.1 ± 8.4	19.4 ± 3.8

From Noyes FR; Grood ES. The strength of the anterior cruciate ligament in humans and rhesus monkeys. Age-related and species-related changes. *J Bone Joint Surg Am.* 1976;58:1074-1082.
Statistical comparison of the Welch modification of the Student *t* test (two-tailed) of each value on each line compared with that on the line below it is indicated as follows: **P* > .01, †*P* > .005, ‡*P* > .001.

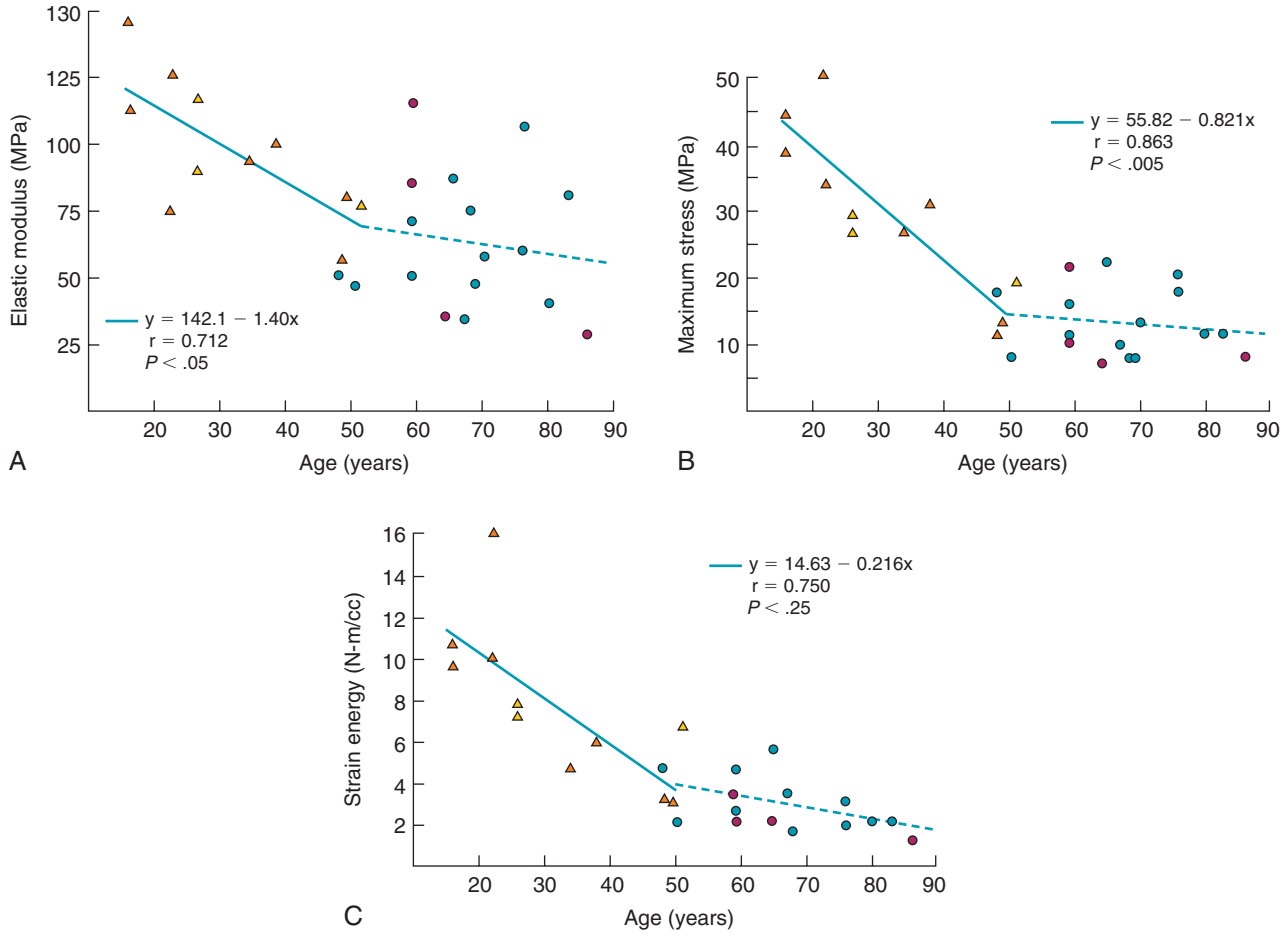


FIG 4-25 Correlation of ligament strength with age. The *solid line* represents the statistically significant correlation with age found in the trauma specimens (*orange triangles*) and younger cadaver preparations (*yellow triangles*), all of which failed through the body of the ligament. The *dashed line* represents the correlation (not statistically significant) found in the amputation (*blue circles*) and older cadaver (*red circles*) preparations, which failed by avulsion fracture of the bone underneath the ligament insertion site. (From Noyes FR, Grood ES. The strength of the anterior cruciate ligament in humans and rhesus monkeys. Age-related and species-related changes. *J Bone Joint Surg Am.* 1976;58:1074-1082.)

Ratios were reported ranging from 80 to 95 N/kg of body mass. Similar ratios ranging from 80 to 118 N/kg of body mass may be calculated from data reported by Viidik[90,91] in the rabbit model. Smith[79] reported a ratio that ranged from 40 to 80 N/kg of body mass in rabbits. A ratio of 119 N/kg of body mass was found in the rhesus monkey preparations in our study,[64] and the specimens from older and younger humans had ratios of 10 and 33 N/kg of body mass, respectively. The human maximum force ratios were markedly low in comparison with those of the rhesus animals as well as other animal models.

It may be invalid, however, to conduct such comparisons based on body mass. The functional demands placed on ligaments vary according to the mode of locomotion, and one cannot compare the stresses of the bipedal gait of humans with the gaits of rabbits, monkeys, or dogs. In addition, the normalization of ligament strength as a function of body mass does not show parallel findings with respect to the variations in size of the ligaments, regardless of which scaling rule is applied. Differences in experimental protocol and testing procedures, such as strain rates, angles of knee flexion, and methods used in gripping the specimens, also make comparisons among studies difficult.

Age-Related Changes

Although it is reasonable to expect an alteration in ligament strength properties with age, our data found greater than expected declines in strength from the younger human specimens compared with the older human preparations (ultimate failure means, 1730 N and 734 N, respectively). The mean body mass of the younger donors was 53 kg; even higher values would be expected for individuals of greater body mass. In the failed specimens from the older humans, there was a decrease in thickness of the cortical and trabecular bone beneath the fibrocartilaginous ligament-bone attachment site. The underlying trabecular bone had wider spaces between trabeculae, and the individual trabeculae appeared thinner than in the specimens from the younger humans. Failure of the ligament-bone unit occurred by an osseous failure owing to both age-related and probably disuse-induced changes.

Kennedy and colleagues[48] reported an ultimate tensile strength of 626 N for human specimens obtained from donors with a mean age of 62 years. Trent and coworkers[87] reported a range of 285 to 1718 N in five cadaver specimens with a donor age of 29 to 55 years. Woo and associates[97] evaluated the structural properties of 27 pairs of human cadaver knees to determine effects of specimen age on the tensile properties of the FATC. Tensile tests of the bone-ligament unit were performed at 30 degrees of knee flexion with the ACL aligned vertically along the direction of applied tension load. One knee from each pair was oriented anatomically, and the second knee was oriented with the tibial aligned vertically. Specimen age did not affect anteroposterior (AP) displacement tests in intact knees at 30 and 90 degrees of flexion. Structural properties of linear stiffness, ultimate load, and energy absorbed significantly decreased with specimen age (Fig. 4-26). Specimen orientation affected these properties because higher values were found in specimens tested in the anatomic orientation (Table 4-8).

It is well known that humans begin to lose bone mass beginning in the fourth decade of life. This phenomenon has important implications in the strength of the osseous components of ligament units for individuals in whom the process is advanced or when it occurs in association with other disuse or disease states in the presence of osteopenia.

Other studies of age-related changes in the mechanical properties of collagenous soft tissues have shown increases in tensile strength and stiffness and decreases in elongation properties with aging.[92,93] However, these studies involved young animals, and the results reflect a maturation process rather than aging, which were probably related to changes in insoluble collagen, increased intermolecular and intramolecular cross-linking, and increases in the collagen/glycosaminoglycan and collagen/water ratios.[79] The physiochemical and mechanical changes that occur in collagen after completion of maturation, which can be ascribed to an aging process in the absence of adverse environmental or disease factors, have not been defined.

Murray and colleagues,[60] in an experimental healing model of ACL in Yucatan minipigs, concluded that the level of skeletal maturity of the animal affected healing properties because immature animals showed higher maximum loads to failure compared with mature animals after suture repair with a collagen platelet composite. However, the data also showed that the immature healing ACL was only an approximate one third of normal ACL load values.

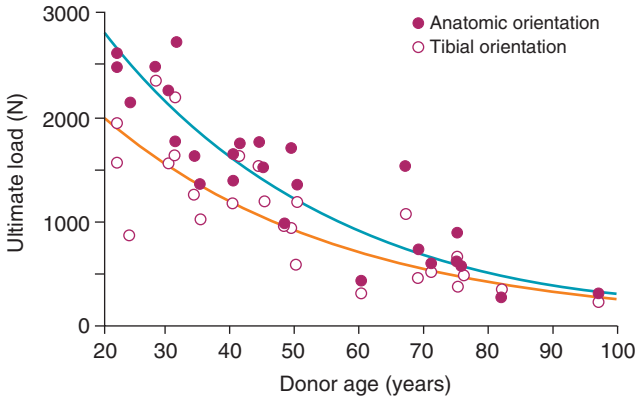


FIG 4-26 The effect of specimen age on femur-anterior cruciate ligament-tibia complex (FATC) ultimate load. Data on ultimate load as a function of specimen age and orientation using a least squares curve fit demonstrated that the strength of FATC decreases in an exponential manner. (From Woo SL-Y, Hollis JM, Adams DJ, et al. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med.* 1991;19:217-225.)

TABLE 4-8 Effects of Specimen Age and Orientation on the Structural Properties of the Femur-Anterior Cruciate Ligament-Tibia Complex

Age (yr)	Specimen Orientation	Stiffness* (N/mm)	Ultimate load* (N)	Energy Absorbed* (N-m)
Younger (22-35)	Anatomic	242 ± 28	2160 ± 157	11.6 ± 1.7
	Tibial	218 ± 27	1602 ± 167	8.3 ± 2.0
Middle (40-60)	Anatomic	220 ± 24	1503 ± 83	6.1 ± 0.5
	Tibial	192 ± 17	1160 ± 104	4.3 ± 0.5
Older (60-97)	Anatomic	180 ± 25	658 ± 129	1.8 ± 0.5
	Tibial	124 ± 16	495 ± 85	1.4 ± 0.3

From Woo SL-Y, Hollis JM, Adams DJ, et al. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med* 1991;19:217-225. Values are mean ± standard error of the mean.
*Younger specimens had significantly higher values than older specimens ($P < .001$).

Gender-Related Anterior Cruciate Ligament Tensile Properties

Chandrashekar and associates[15] determined the tensile properties of the human ACL in 10 male and 10 female unpaired cadaveric knees. The comparison of ACL anthropometry indicated a significant decrease in the female specimens compared with the male specimens in minimum area (72.91 and 57.32 mm^2, respectively; $P = .04$) and volume (2722 and 1996 mm^3, respectively; $P = .04$). The maximum load to failure of the female ACL specimens was 1266 ± 627 N compared with the male value of 1818 ± 699 N ($P = .04$). Similar decreases in stiffness, stress at failure, and modulus of elasticity were also reported. Pairwise correlations between male and female specimens provided a strong relationship among body mass index, ACL volume, and minimum area. The authors suggested the need for further research to explain the difference in ACL mechanical properties, ultrastructural differences, and the impact these differences may have on higher ACL failure rates in women.

EFFECT OF INTRAARTICULAR CORTICOSTEROIDS ON LIGAMENT PROPERTIES

The effect of an intraarticular, slightly soluble corticosteroid (methylprednisolone acetate) was investigated on the mechanical properties of a ligament unit.[65,66] ACL preparations from wild rhesus animals were used to determine the effect of corticosteroid dosage and time duration after administration.

Direct Steroid Injection Into Ligament

In the first study, animals were divided into a control group, a sham control group (saline injection), a 20-mg large-dosage group, and a 4-mg small-dosage group (methylprednisolone acetate).[13,65] The large-dosage group was studied at 6 and 15 weeks after injection, and the small-dosage group was studied at 15 and 52 weeks after injection. The FATC specimens were tested in tension to failure using a procedure previously described.[63]

Statistically significant decreases occurred in maximum load in the large-dosage (21% and 39% declines at 6 and 15 weeks, respectively) and the small-dosage groups (27% at 15 weeks, which remained comparable at 52 weeks). In the large-dosage group, minimal decreases in energy to failure were found at 6 weeks, but significant declines (43%) were present at 15 weeks. In the small-dosage group, decreases occurred in energy to failure of 27% at both time intervals.

Haraldsson and associates[31] showed that corticosteroid administration significantly reduced tensile yield strength by 16% and Young's modulus by 14% compared with controls in a rat tail tendon model. Mikolyzk and colleagues,[56] in a rat rotator cuff tendon model, reported that a single corticosteroid dose produced significant short-term biomechanical effects (decreased maximum load, maximum stress, and stiffness) in injured and uninjured tendons. However, these biomechanical properties returned to control levels by 3 weeks.

Intraarticular Steroid Injection

In our second investigation, two animal groups were studied.[59] The first group (high corticosteroid dosage) comprised 10 animals that received a total of three intraarticular injections of methylprednisolone acetate (6.0 mg/kg) into one knee. The injections were spaced 1 week apart. A sham procedure was performed on the opposite knee that consisted of an intraarticular saline injection in equal volume to that of the drug. These animals were sacrificed 6 weeks after the first injection. The second group (low corticosteroid dosage) consisted of 12 animals that received two injections of a dosage one tenth of that used in the other animal group (methylprednisolone acetate 0.6 mg/kg). The two injections were given 2 weeks apart, with a sham saline injection administered into the opposite knee. The animals were sacrificed 15 weeks after the first injection.

A load-versus-time record from a typical right and left specimen pair in an animal from the high corticosteroid dosage group is shown in Figure 4-27. The strain parameters are approximated because of inherent errors in measuring ligament length and in using the tibiafemur separation distance as a measure of ligament elongation during testing.

The histologic analysis of the failed ligament units showed no detectable corticosteroid effect in that the fibrocartilage zones at the ligament insertion sites were intact. There were no bone resorptive changes at the ligament attachment sites. On scanning electron microscopy, no alterations were found in the surface appearance of collagen fibers and fibrils in the ligaments that received the corticosteroid.[66]

The alterations in ligament behavior were dependent on the dosage of the drug and the time that had elapsed after injection. In the higher-dosage group, the maximum failure load of the ligament unit decreased by 11% after 6 weeks and 20% after 15 weeks. The stiffness of the ligament preparation showed a minimal decrease 6 weeks after injection; however, at 15 weeks, a significant decline had occurred. In the lower-dosage group, the maximum failure load of the ligament unit decreased by 9% and the energy absorbed before failure decreased by 8%. The decreases were found when the right-left specimen pairs were compared and were statistically significant. No significant change occurred in the stiffness of the ligament unit. These small changes suggest only slight alterations in the projected functional capacity of the ligament unit.

The specific ultrastructural mechanisms responsible for the alterations in ligament mechanical properties following administration of corticosteroid are unknown. There are known inhibitory effects of corticosteroids on the synthesis of glycosaminoglycans, proteins, and collagen. Whether decreased collagen synthesis occurs owing to the drugs' effect on specific collagen precursors and enzymes or from a general inhibitory effect on overall protein synthesis is unknown. Corticosteroid preparations are known to alter fibroblast proliferation and metabolism. The cellular and subcellular effects are highly complex and beyond the scope of this chapter. The end result of these drugs is generally antianabolic and responsible for the adverse effect on wound and soft tissue healing.

The clinical implications of this study are suggestive that intraarticular, slightly soluble corticosteroids in high and frequent doses have the potential to alter ligament strength and function. The risk associated with such alterations may be minimal if infrequent, low-dose injections are administered. Alternatively, a single direct injection of a slightly soluble steroid preparation has a marked effect on decreasing ligament functional properties, which remained up to 1 year.

Wiggins and colleagues[96] and Walsh and coworkers[94] have reported extensive studies on the effect of a steroid injection in human equivalent doses on the healing of a rabbit MCL model. Their data show statistically significant reductions in maximum failure loads and alteration in histologic properties compared with appropriate controls. The authors concluded that a single steroid injection at the site of a healing ligament would decrease or retard healing properties; however, they suggested that the effect was probably reversible. The authors reviewed a number of mechanisms for the deleterious effects. It should be noted that the studies were performed on a rabbit model that exhibits a known hypersensitivity to steroids that is more pronounced than that expected in other animals and humans.

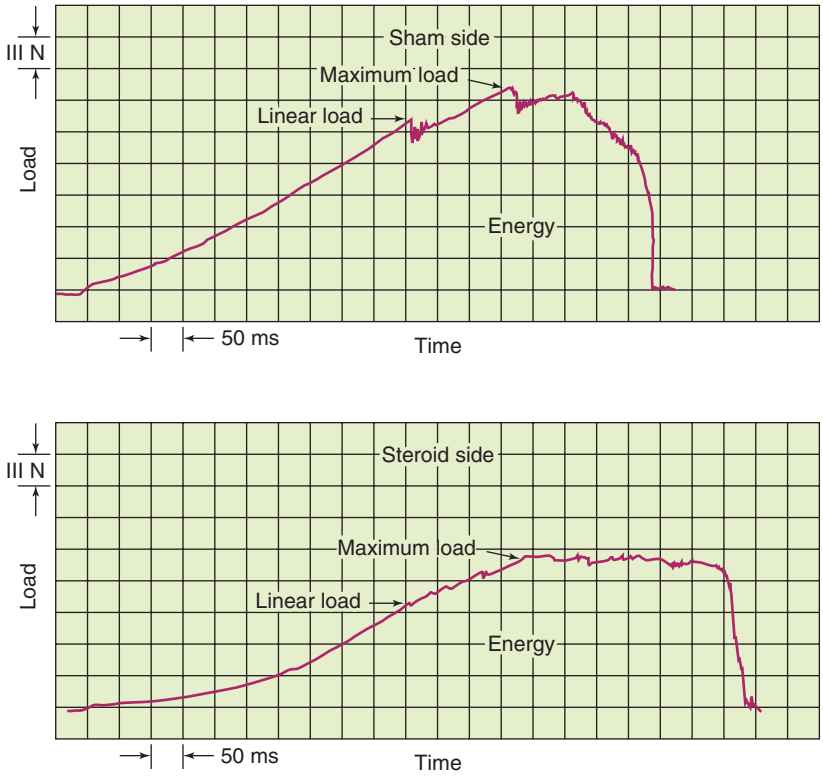


FIG 4-27 Typical load-versus-time records for a right-left pair of specimens. The sham specimen demonstrates normal behavior under loading. The steroid side demonstrates a decrease in stiffness (initial slope of the curve), failure at lower loads, and an increase in ligament elongation at complete failure. (From Noyes FR, Grood ES, Nussbaum NS, Cooper SM. Effect of intra-articular corticosteroids on ligament properties. A biomechanical and histological study in rhesus knees. *Clin Orthop.* 1977;23:197-209.)

EFFECT OF VASCULARIZED AND NONVASCULARIZED ACL GRAFTS ON BIOMECHANICAL PROPERTIES

After ACL graft reconstruction, there is a marked cellular invasion that removes necrotic collagenous tissues with replacement collagenous fibers that are a ligament in a parallel fashion, but do not resemble the native microgeometry of the ACL. The question that has been posed is whether maintaining a vascular supply (and any concomitant neural innervation) of an ACL graft would limit the so-called necrotic phase of ligament remodeling and retain more normal ligament functional properties. An investigation was conducted to measure the mechanical properties of patellar tendon autografts used to replace the ACL in the cynomolgus monkey at four time periods up to 1 year.[12] The ACL was replaced with the medial half of the patellar tendon as a vascularized graft in one knee and as a nonvascularized (or free) graft in the contralateral knee. The 5-mm–wide medial patellar tendon free grafts were prepared through a standard medial parapatellar exposure. The vascularized grafts were prepared in a similar manner, except the medial retinacular vascular supply and a portion of the fat pad were preserved. The tibial attachment sites were prepared by producing a thin bony trough in the anteromedial aspect of the tibia to the site of the ACL attachment, and the ACL grafts with the vascularized pedicle were transposed into a bony trough. An identical tibial and femoral placement was used for the free grafts. Standard graft fixation methods were used. The knees were immobilized for 4 weeks at 30 degrees of flexion followed by unrestricted activity in large cages.

CRITICAL POINTS Effect of Vascularized and Nonvascularized ACL Grafts on Biomechanical Properties

An investigation was conducted to determine whether maintaining a vascular supply (and any concomitant neural innervation) of an ACL graft would limit the so-called necrotic phase of ligament remodeling and retain more normal ligament functional properties.

- The ACL was replaced with the medial half of the patellar tendon as a vascularized graft in one knee and as a nonvascularized (or free) graft in the contralateral knee in cynomolgus monkeys.
- Both the vascularized and nonvascularized grafts underwent significant reductions in structural mechanical and material properties as early as 7 weeks after surgery.
- Retention of a portion of the blood supply to the ligament is not sufficient to avoid a major reduction in ligament mechanical properties that occur in vivo following implantation.

Both the vascularized and nonvascularized grafts underwent significant reductions in structural mechanical and material properties as early as 7 weeks after surgery. Stiffness values were as low as 24% to 28% of control ACL and medial patellar tendon values. Maximum force at 7 weeks was 16% of control ACL values, increasing to 39% of control maximum force by 1 year (Fig. 4-28, *A*). Modulus and maximum stress showed even greater reductions and were only 34% and 26%, respectively, of control ACL values at 1 year (Fig. 4-28, *B*). The rate of return was slow up to 1 year for all variables studied. The

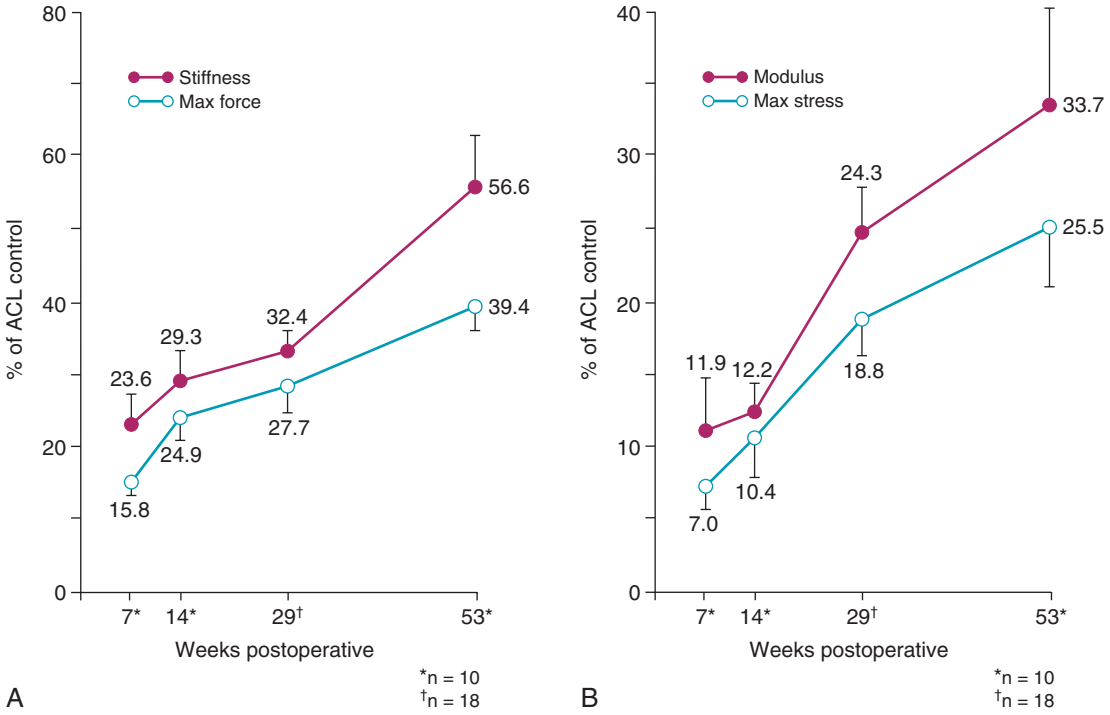


FIG 4-28 **A,** Normalized graft stiffness and maximum force (standard error of the mean) are plotted against weeks postoperative. Note the more rapid increase in the stiffness values over time. By 1 year, stiffness and maximum force were 57% and 39% of control, respectively. **B,** Normalized graft modulus and maximum stress are plotted against weeks postoperative. No significant differences are present among the parameters at any time period. Modulus and maximum stress are lower than corresponding stiffness and maximum force in **A,** suggesting that the collagen material is both very compliant and weak. (From Butler DL, Grood ES, Noyes FR, et al. Mechanical properties of primate vascularized vs. nonvascularized patellar tendon grafts: changes over time. *J Orthop Res.* 1989;7:68-79.)

changes in maximum force over time were generally consistent with other studies that used free grafts, showing on a mechanical basis that an extended period of time is required for ACL graft remodeling and partial return of strength. The study concluded that retention of a portion of the blood supply to the ligament is not sufficient to avoid a major reduction in ligament mechanical properties that occur in vivo following implantation.

EFFECT OF CELLULAR NECROSIS AND STRESS-SHIELDING ON ACL HEALING AND RETENTION OF NATIVE ACL FIBER MICROARCHITECTURE

Jackson and associates[41-43] performed a series of landmark studies in a goat model in which the ACL was frozen in situ, producing cellular necrosis while retaining the normal fiber microarchitecture. Mechanical loading tests of the ACL bone-ligament-bone preparation at 6 months showed no difference in the maximum failure load, stiffness, or AP translation compared with those in untreated controls. The authors theorized that the large decreases in ACL mechanical properties and strength in experimental animals after ACL reconstruction could not be explained by cell death and devascularization.

To provide additional experimental information, a study was conducted in our laboratory in which the previously described devitalized frozen model in the goat ACL was used and two conditions were added.[11] In one group of knees, the ACL tibial attachment was elevated by osteotomy and then replaced in its normal anatomic position. In a second group of knees, the ACL tibial attachment was osteotomized and replaced on the tibia 5 mm posterior to its normal attachment to study the effects of an altered loading state (stress-shielding) on ligament remodeling properties. The results of the ACL mechanical failure tests are summarized in Table 4-9. The stiffness, maximum force, and stress and modulus were greater in the anatomic placement group than in the posterior ACL placement group; however, they were still less than historic controls. Increased failures were noted at the tibial attachment site in the posterior ACL placement group.

CRITICAL POINTS Effect of Cellular Necrosis and Stress-Shielding on ACL Healing and Retention of Native ACL Fiber Microarchitecture

- Based on a series of studies,[41-43] Jackson and associates concluded that large decreases in ACL mechanical properties and strength in experimental animals after ACL reconstruction could not be explained by cell death and devascularization.
- Other experimental studies strongly suggest that the use of ACL ligament grafts, which have no similarity to the native ACL fiber organization and in vivo microstrains, results in replacement of the ACL graft with a scarlike disorganized collagen framework with marked loss of mechanical strength and stiffness.
- Clinically, ACL grafts are limited in their ability to truly restore native ACL fiber microgeometry and therefore never function similar to a normal ligament. The grafts function to provide a gross checkrein to abnormal knee displacements.

The results of all of the studies[12,14,16,17,37,43,52,53,61,77,83,88,99] are summarized in Figure 4-29, which compares historic maximum failure loads in experimental animals with the frozen devitalized specimens in Jackson and associates' study[42] and the anatomic- and posterior-placed ACL preparations.[11] Although the anatomic-placed ACL (after tibial osteotomy) had a reduction in strength compared with the native frozen ACL, the strength was still greater than ACL graft reconstructions. The presumed loss of the normal stress and fiber loading in the posterior-placed ACL, in addition to tibial healing effects, produced marked reductions in all mechanical properties.

The results of these experimental studies strongly suggest that retaining the complex native microgeometry of the ACL provides a necessary stimulus for ligament remodeling. In addition, the use of ACL ligament grafts, which have no similarity to the native ACL fiber organization and in vivo microstrains, results in replacement of the ACL graft with a scarlike disorganized collagen framework with marked loss of mechanical strength and stiffness. Insofar as the results apply to clinical ACL reconstructions, the suggestion is that ACL grafts are limited in their ability to truly restore native ACL fiber microgeometry and, therefore, never function similar to a normal ligament. The authors hypothesized that ACL grafts function to provide a gross checkrein to abnormal knee displacements in contrast to the so-called fine-tuning of joint motions by a ligament fiber guiding microarchitecture mechanism. It is probable that even two-bundle graft constructs behave in a similar manner, replacing the collagen fiber mass of the ligament at tibial and femoral attachments. However, with remodeling, even two-bundle constructs have altered mechanical properties and function that does not approximate native ligament function.

TABLE 4-9 Mean Geometric, Structural, and Material Properties

	Anatomic Placement	Posterior Placement	SEM	Historic Controls
Length (mm)	20.4	21.5	0.7	18.2 ± 0.3
Area (mm^2)	31.2	23.0	3.3	17.7 ± 1.2
Stiffness (N/mm)	473.9*	315.8*	11.4	548.0 ± 31.0
Maximum force (N)	1625.0†	895.0†	246.8	2603.0 ± 213.0
Maximum stress (MPa)	59.4	35.9	22.9	155.0 ± 13.0
Modulus (MPa)	338.4	297.5	45.9	578.0 ± 51.0

From Bush-Joseph CA, Cummings JF, Buseck M, et al. Effect of tibial attachment location on the healing of the anterior cruciate ligament freeze model. *J Orthop Res.* 1996;14:534-541.
*Significant difference ($P < .0005$) between anatomic and posterior placements.
†Significant difference ($P < .05$) between anatomic and posterior placements.
SEM, Standard error of the mean.

ALLOGRAFTS AND AUTOGRAFTS: BIOMECHANICAL PROPERTIES AFTER IMPLANTATION AND EFFECT OF IRRADIATION

Multiple studies have been published on the biomechanical properties of autografts and allografts in experimental animal models.[3,11,22,41-44,76,77,83,89] The majority demonstrate that allografts have inferior results compared with those of autografts (and contralateral controls) in regard to mechanical strength properties. In 1989, Thorson and colleagues[83] studied the 4-month postoperative mechanical properties of adult canines that received either bone-tendon-bone allografts or autografts. The allograft group showed a mean load to failure of only 17% of the contralateral control ligament, compared with 41% in the autograft group. Shino and coworkers,[76,77] in two studies using the canine model, reported that allografts had a mean maximum tensile load of approximately 30% that of contralateral controls 1 year postimplantation. Jackson and associates[43] reported in 1993, in a goat model, that the strength of fresh frozen patellar tendon allografts was only 27% of controls at 6 months postimplantation. In contrast, the strength of patellar tendon autografts was 62% of control ACLs. The

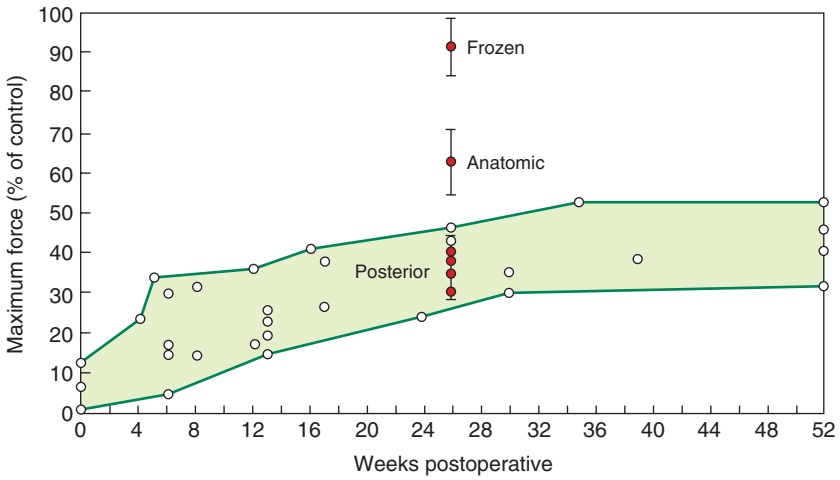


FIG 4-29 Maximum load to failure versus postoperative time. The range (*shaded region*) of means for allograft reconstructions (*open circles*) are from previously published studies. The mean (± standard error of the mean) for frozen ligaments and their tibial insertion moved 5 mm posterior lie within this range. Ligaments frozen and replaced in the anatomic position have greater maximum loads but still less than for in situ freezing alone as reported by Jackson et al.[42] (From Bush-Joseph CA, Cummings JF, Buseck M., et al. Effect of tibial attachment location on the healing of the anterior cruciate ligament freeze model. *J Orthop Res.* 1996;14:534-554.)

authors concluded that allograft remodeling is much slower than autograft and suggested that patients who receive allografts should probably be protected against maximum activities for a longer period of time than those who receive autografts.

In another study in which freeze-dried bone-ACL-bone allografts were implanted, Jackson and associates[41] reported that the maximum load of the allografts was only 25% of the contralateral ACL controls at 1 year postimplantation. Figure 4-30 summarizes a number of allograft ACL reconstruction studies and demonstrates that all had mechanical properties in low ranges from 4 to 52 weeks postoperative. The healing effects of autografts and allografts are covered in greater detail in Chapter 5.

Our laboratory[27,70,72] has studied the effects of gamma irradiation on the mechanical and material properties of allografts in the goat model and in human cadavers. In the first study, Gibbons and colleagues[27] reported on the effects of 2 and 3 mrad of gamma irradiation on goat ACL B-PT-B in vitro properties. The study reported that the maximum stress, maximum strain, and strain energy were significantly reduced after 3 mrad; however, there were no significant reductions after 2 mrad of irradiation (Table 4-10).

In a second study, the effects of a higher level of irradiation (4 mrad) were studied on human cadaver donor (aged 18 to 59 years) frozen patellar tendon-bone allografts and were compared with a frozen control graft (0 mrad).[70] Irradiation produced a small, but significant, decrease in graft length (0.6 mm, $P < .01$; Table 4-11). The irradiated grafts showed significant reductions in stiffness ($P < .025$) and maximum force ($P < .001$).

In a third study, Salehpour and associates[72] studied the effects of 4, 6, and 8 mrad (40,000, 60,000, or 80,000 Gy) of gamma irradiation on the in vitro properties of a B-PT-B allograft unit retrieved from mature female goats. On average, stiffness decreased by 18%, 40%, and 42% at 4, 6, and 8 mrad, respectively ($P < .05$ for all comparisons). The data

CRITICAL POINTS Allografts and Autografts: Biomechanical Properties After Implantation and Effect of Irradiation

The majority of experimental studies demonstrate that allografts have inferior results compared with autografts (and contralateral controls) in regard to mechanical strength properties. The effects of gamma irradiation on the mechanical and material properties of allografts have been studied in the goat model and human cadavers for many years.

- Effects of 2 and 3 mrad of gamma irradiation on goat ACL bone-patellar tendon-bone in vitro properties showed maximum stress, maximum strain, and strain energy were significantly reduced following 3 mrad; however, there were no significant reductions following 2 mrad of irradiation.
- Effects of 0 versus 4 mrad of gamma irradiation on human cadavers: irradiation produced a small, but significant, decrease in graft length (0.6 mm). Irradiated grafts showed significant reductions in stiffness and maximum force.
- Effects of 4, 6, and 8 mrad on goat ACL bone-patellar tendon-bone units: data showed the overall dose-dependent effects of irradiation on ligament mechanical properties; doses less than 2 mrad had minimal effects.
- In vivo effect of 4 mrad of gamma irradiation on bone-patellar tendon-bone units in goats at time 0 and 6 months postimplantation: irradiation significantly altered structural but not material properties.

At present, there are no experimental data to show that the low-dose irradiation as used to secondarily sterilize allografts has a deleterious effect on graft mechanical properties.

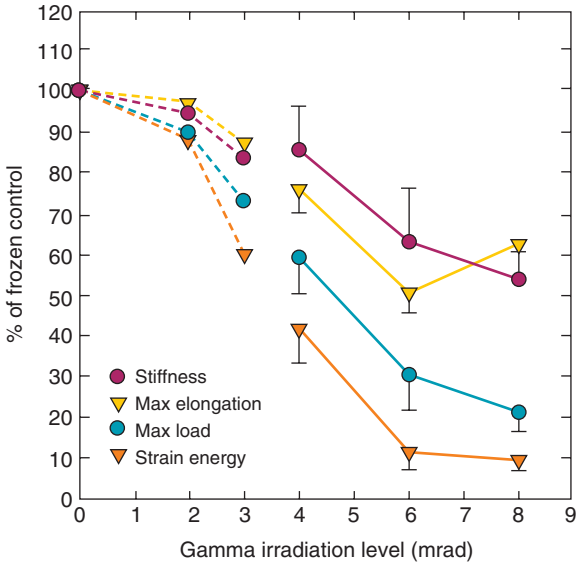


FIG 4-30 Average dose-dependent response curves for all four mechanical properties (*solid lines*), expressed as percentages of values for contralateral frozen controls. Normalized data for 2 and 3 mrad (*dashed lines*) from earlier studies are also shown. Those studies used different testing conditions. Note the nearly linear declines in all curves between 2 and 6 mrad. (From Salehpour A. Butler DL. Proch FS, et al. Dose-dependent response of gamma irradiation on mechanical properties and related biochemical composition of goat bone-patellar tendon-bone allografts. *J Orthop Res.* 1995;13:898-906.)

TABLE 4-10 Dose-Dependent Effects of Gamma Irradiation on Composite Unit Structural Mechanical Properties

Composite Unit	*n*	Stiffness (N/mm)*	Max Force (N)*	Max Elongation (mm)*	Strain Energy (N-m)*
Frozen control	24	189.9 ± 33.6	1406.1 ± 363.8	10.2 ± 1.5	8.2 ± 3.2
2 mrad	12	179.3 ± 23.9	1261.8 ± 252.1	9.9 ± 1.8	7.2 ± 3.0
3 mrad	12	158.2 ± 14.3†	1206.2 ± 101.2‡§	8.9 ± 1.3¶	4.9 ± 1.1†‡

Data are presented as means ± standard deviation.
*$P < .05$ compared with control (based on one-sided Dunnett multiple comparison of irradiated to control).
†$P < .005$ compared with control (based on contrasts for individual variables).
‡$P < .05$ compared with control (based on analysis of variance for all variables).
§$P < .0005$ compared with control (based on contrasts for individual variables).
¶$P < .05$ compared with control (based on contrasts for individual variables).
From Gibbons MJ, Butler DL, Grood ES, et al. Effects of gamma irradiation on the initial mechanical and material properties of goat bone-patellar tendon-bone allografts. *J Orthop Res.* 1991;9:209-218.

TABLE 4-11 Effects of 4 mrad Irradiation on Human Patellar Tendon-Bone Allograft Length and Mechanical Properties

	Allograft Length Before Irradiation (mm)	Allograft Length After Irradiation (mm)	Static Creep* (mm)	Peak Cyclic Creep† (mm)	Stiffness (kN/m)	Maximum Load (N)
Control	58.0 ± 6	—	0.4 ± 0.3	0.4 ± 0.2	311 ± 51	2549 ± 434
Irradiated	57.6 ± 6	57.0 ± 6	0.5 ± 0.3	0.5 ± 0.3	275 ± 52	1884 ± 330
Number of pairs	18	18	20	20	20	16
Significance (*P*)	—	.01‡	—	—	.025	.001

From Rasmussen TJ, Feder SM, Butler DL, Noyes FR. The effects of 4 mrad of gamma irradiation on the initial mechanical properties of bone-patellar tendon-bone grafts. *Arthroscopy*. 1994;10:188-197.
*Measured at 90-N force after 10 min.
†Measured at 200-N force after 3600 cycles at 1 cycle/sec.
‡Preirradiation to postirradiation.

TABLE 4-12 Structural Properties of Anterior Cruciate Ligament Allografts 6 Months Postimplantation in Caprine Model

	Linear Stiffness (KN/m)	Maximum Force (N)	Elongation to Failure (mm)	Energy to Maximum Force (N-m)
0 mrad	123.2 (45.4)*	496.6 (144.6)*	8.2 (2.7)	1.6 (0.8)
4 mrad	86.3 (32.5)*	392.0 (165.2)*	7.6 (1.3)	0.9 (0.3)
0 mrad as a percentage of normal ACL†	16.8 (732)	19.8 (2506)	172.1 (4.8)	29.8 (5.3)
4 mrad as a percentage of normal ACL†	11.8	15.6	158.9	17.9

From Schwartz HE, Matava MJ, Proch FS, et al. The effect of gamma irradiation on anterior cruciate ligament allograft biomechanical and biochemical properties in the caprine model at time zero and at 6 months after surgery. *Am J Sports Med*. 2006;34:1747-1755.
Values are mean (standard deviation), n = 12.
*$P < .05$ between 0-mrad and 4-mrad groups.
†Mean values for normal ACL based on prior published literature.

as a whole showed the overall dose-dependent effects of irradiation on ligament mechanical properties. Doses less than 2 mrad have minimal effects. Schwartz and coworkers[75] examined the in vivo effect of 4 mrad of gamma irradiation on B-PT-B units in adult goats at time 0 and 6 months postimplantation. The irradiation significantly altered structural but not material properties. Stiffness was reduced by 30% and maximum force by 21%, resulting in these parameters averaging 12% to 20% of normal ACL values (Table 4-12).

We concluded that 4 mrad of gamma irradiation affect ACL allograft subfailure viscoelastic and structural properties but not material or biochemical properties over time.[70,72,75] The ACL allografts of the 0 mrad failed at 497 N (see Table 4-9), which in comparison with the first study of Gibbons and associates[27] showed a control graft of 1400-N maximum force. This suggests that the effects of the remodeling process, resulting in a weakened graft with altered mechanical properties as previously described, produced even more profound deleterious effects than the irradiation treatment.

Bhatia and colleagues[8] reported that maximal load and stiffness in a rabbit ACL model, using tendon allografts and autografts, were unaltered by low-dose (1.2 mrad) gamma irradiation. They concluded that low-dose gamma irradiation was safe for sterilization of soft tissue ACL allografts. Yanke and colleagues[98] studied cyclic and failure properties of human B-PT-B allografts treated with 1.0 to 1.2 mrad compared with paired untreated specimens and found no significant difference in biomechanical properties except for decreased in graft stiffness of 20%. They concluded that low-dose irradiation was not deleterious to preimplantation mechanical properties. Recent interest in electron-beam irradiation, rather than gamma irradiation, is noted in Hoburg and associates' investigation.[36] This sterilization process demonstrated a minimal effect on B-PT-B ACL allograft strain, cyclic elongation, stiffness, and failure and may provide a higher level of safety.

The published results of studies showing the delayed healing of allografts and low ultimate strength properties even at 1 year in the animal model are consistent with clinical observation in humans of the higher failure rate of ACL allografts, and we recommend to use autograft tissues whenever possible in ACL surgery. These concepts are further discussed in Chapters 7 and 8. We prefer to obtain allografts for patients from tissue banks that use secondary chemical sterilization for bacterial contamination.

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Video Content

Video 3-1

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5

Biology of Anterior Cruciate Ligament Graft Healing

Brian M. Grawe, Fumitaka Sugiguchi, Asheesh Bedi, Scott A. Rodeo

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INTRODUCTION

Traumatic rupture of the anterior cruciate ligament (ACL) can be a common source of knee instability and dysfunction in athletes. Reconstruction of a torn ACL, to restore function and limit injury to the menisci, has become a common orthopedic procedure. Despite advances in surgical techniques and the ability to implant an isometric graft that restores knee stability, ACL reconstruction is not always a universally efficacious procedure. Rates of recurrent laxity, 1 year postoperatively, have been reported to be as high as 17%.[101]

Graft integration failure and inadequate tendon-to-bone healing may be an important cause of recurrent knee instability following ACL reconstruction. The healing of tendon to bone is the basic requirement for successful long-term survival of the graft.[17,32] Whether an autograft or allograft tendon is used, biomechanical testing has shown that the initial strength of the graft material is superior to the intact ACL.[17,32] Therefore, the weakest link after reconstruction is not the graft itself, but rather the fixation points until graft osteointegration occurs. The intraarticular portion of the graft must ultimately undergo remodeling and the process of *ligamentization* to form an organized structure that resembles a native ligament.[5,6,41,47,49]

Current techniques of ACL reconstruction require tendon-to-bone healing in a surgically created bone tunnel. No native human tendons pass through an osseous tunnel; therefore, this type of healing environment is inherently unusual. When a bone-tendon-bone graft is used for ACL reconstruction, graft fixation initially depends on bone-to-bone healing. However, tendon-to-bone healing still remains critical regardless of whether an all soft-tissue graft or a graft with a bony plug is selected. The length of the tendinous portion of the bone-tendon-bone graft is greater than the intraarticular length of the native ACL, resulting in a substantial amount of tendon within the bony tunnel. Aperture healing to minimize graft micromotion and tunnel widening requires tendon-to-bone healing with any graft.[49]

Because all grafts depend on tendon-to-bone healing, this chapter focuses on graft osteointegration and the process by which structural and functional continuity between the tendinous portion of the graft and bone is achieved. Both the biologic milieu and the biomechanical environment occurring at the bone tunnel result in formation of an attachment site that differs from the native ligament-bone insertion. The biology of this healing remains incompletely understood and is exposed to a number of biomechanical and physiologic influences. The current understanding of the biology of graft reconstruction is reviewed and potential strategies to enhance early graft integration are discussed.

NATIVE TENDON-BONE INSERTION

The ACL is an intraarticular, extrasynovial structure that acts to control anterior translation and rotational movements of the femur on a fixed tibia. It is composed of multiple fascicular collagen bundles enveloped in a sheath that contains vascular and neural elements.[2] The ACL inserts to bone via a direct type of insertion, similar to the transition seen from tendon to bone. Microscopic examination of the sites of bony attachment shows interdigitation of the collagen fibers with bone though four distinct transition zones: tendon, unmineralized fibrocartilage, mineralized fibrocartilage, and bone (Fig. 5-1).[2,24,75,92] This graduated change in stiffness allows for transmission of complex mechanical loads from soft tissue to bone while minimizing peak stresses at any single point along the ligament. Cartilage-specific collagens including types II, IX, X, and XI are found in the fibrocartilage insertion site. Collagen X plays a key role in maintaining the interface between the mineralized and unmineralized zones.[2,24,75,92] Recently, it was noted that both the femoral origin and tibial insertion of the ACL contain discrete regions of both direct and indirect ligamentous insertions.[37,94] The theoretical biomechanical advantages of recreating the direct fibers have been explored; however, few clinical data support targeted surgical reconstruction of these discrete tissue attachments.[86]

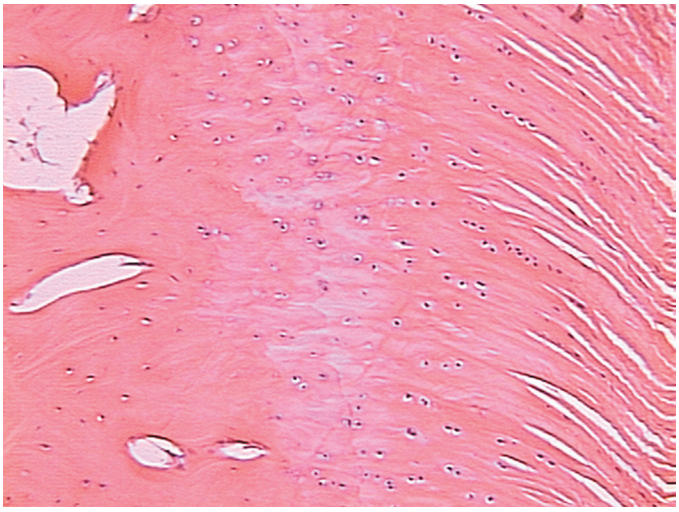


FIG 5-1 Histology of native anterior cruciate ligament insertion to bone. Examination shows interdigitation of the collagen fibers with bone through four distinct transition zones: tendon, unmineralized fibrocartilage, mineralized fibrocartilage, and bone.

CRITICAL POINTS Native ACL Insertion

- The native ACL inserts via a direct type of insertion to bone, with distinct transition zones of ligament, unmineralized fibrocartilage, mineralized fibrocartilage, and bone.
- Insertion site provides gradual transition in material properties, thereby minimizing stress concentration at the interface.
- All ACL reconstruction procedures require tendon-to-bone healing in a surgically created bone tunnel, to which there is no analogous situation in the native human body.
- Regardless of ACL graft choice, some degree of tendon-bone healing must take place for successful ligament reconstruction.

TENDON-BONE INSERTION AFTER ACL RECONSTRUCTION

The overall structure, composition, and organization of the native ACL attachments sites are not reproduced after surgical reconstruction of the ACL. This disparity reflects an inability to recapitulate the events that occur during embryonic development with current surgical strategies. Rather than regenerating the four organized zones of direct insertion, the graft heals with an interposed zone of vascular, highly cellular granulation tissue between the graft and tunnel wall (Fig. 5-2).[28,29,87] The healing process of a tendon graft in a bone tunnel has been defined in rabbit and dog models.[45,87] In the initial postoperative period, the graft-tunnel interface is filled with vascular granulation tissue containing an abundance of type III collagen. Vascular endothelial growth factor (VEGF) and fibroblast growth factor (FGF) are expressed, stimulating an influx of macrophages and enlarged fibroblasts. Chondroid cells accumulate along the walls of the bone tunnel and deposit type II collagen as part of the endochondral process of new bone formation. After 3 to 4 weeks, this interface tissue undergoes a maturation process until its matrix consists of oriented Sharpey-like collagen fibers that bridge the bone to the graft (Fig. 5-3). The chondroid cells are gradually replaced with lamellar bone in a process similar to endochondral ossification.[45] The Sharpey-like fibers are composed of type III collagen and extend into the surrounding bone to resist shear stresses. The number and size of these collagen fibers positively correlate with the pull-out strength of the graft (Fig. 5-4). The time interval for this process to occur has been variably reported in the literature, ranging from 8 to 30 weeks.[45] Graft attachment strength further improves as bone grows into the interface tissue and outer portion of the graft.[28,29,87]

CRITICAL POINTS Tendon-Bone Insertion After ACL Reconstruction

- A native ACL insertion is not reproduced after ACL reconstruction and reflects an inability to recapitulate the events of embryonic development.
- Graft-to-bone healing occurs via an interposed zone of vascular granulation tissue between the graft and tunnel wall that matures with time.
- Attachment strength is proportional to the magnitude of bony ingrowth into the interface tissue and anchoring Sharpey-like collagen fibers that bridge the tendon to bone.

CHALLENGES OF TENDON-BONE HEALING AFTER ACL RECONSTRUCTION

The biologic cascade of healing between a grafted tendon and bone tunnel remains incompletely understood. The biologic and biomechanic environments result in the formation of an inferior attachment site that is different from the organized, direct-type ACL insertion. Current work suggests a number of fundamental challenges responsible for the suboptimal healing response between tendon and bone instead of regeneration of the insertion site.[31] These factors include:

1. The presence of inflammatory cells at the graft-tunnel interface that precipitates scar formation.
2. Slow and limited bony ingrowth into the graft from the tunnel walls, resulting in a biomechanically weaker attachment.
3. Insufficient number of undifferentiated stem cells at the healing tendon-bone interface.
4. Graft-tunnel micromotion that precludes the formation of a firm attachment at the tunnel aperture.
5. Lack of a coordinated gene-signaling cascade that directs healing toward regeneration rather than scar tissue formation in the postnatal organism.

Strategies to promote tendon-to-bone healing in ACL reconstruction focus on overcoming these challenges through modification of the biologic and biomechanical environment.

MODULATION OF TENDON-BONE HEALING

Technical Factors

Adjustments can be made in the surgical technique of reconstruction to optimize tendon-to-bone healing. The fundamental principle is to maximize the surface area of the tendon-bone interface. Animal studies have shown that increasing the length of the bone tunnel positively correlates with the quality and strength of the reconstruction.[105] Minimizing graft tunnel mismatch by effectively achieving a press fit of the graft into the bony tunnel improves healing.[30] Additionally, maximizing circumferential contact area of the graft and tunnel (i.e., avoiding use of an interference screw) may improve healing.[96] However, this final factor must be ultimately balanced with the increased stiffness from decreased fixation-to-fixation construct length that aperture fixation provides to the healing graft environment.

Mechanical Factors

Relative graft-tunnel micromotion may preclude the formation of a firm attachment to the tunnel wall. Yu and Paessler[108] compared

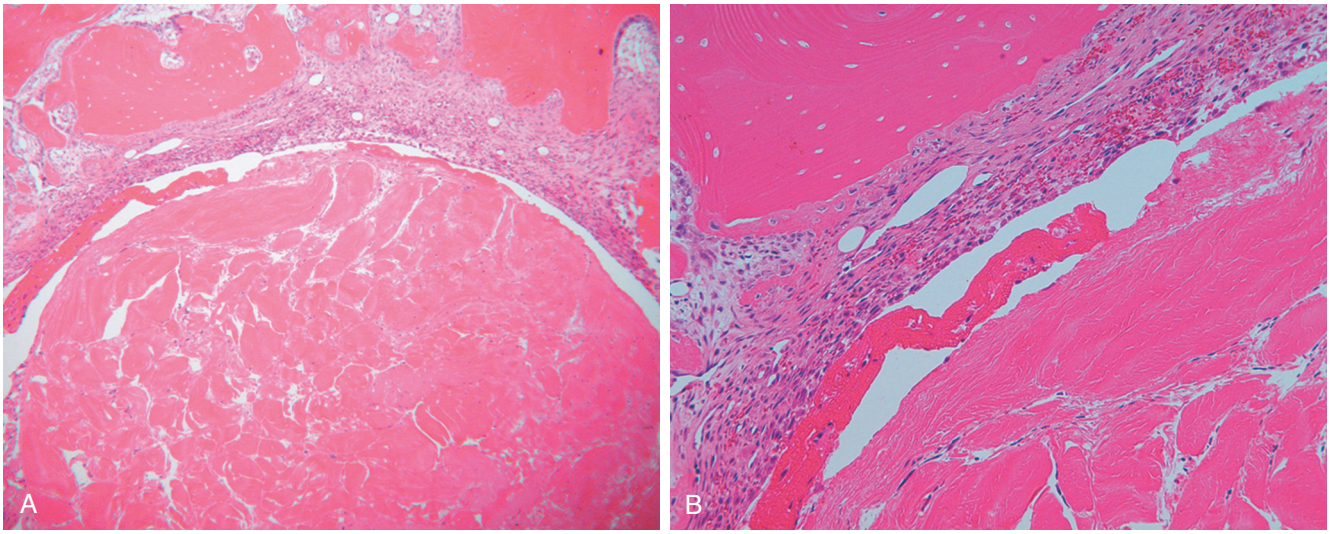


FIG 5-2 Insertion site histology 1 to 2 weeks after anterior cruciate ligament reconstruction. Shown are low-power **(A)** and high-power magnification **(B)**. Vascular, highly cellular granulation tissue is interposed as a layer between the graft and tunnel wall.

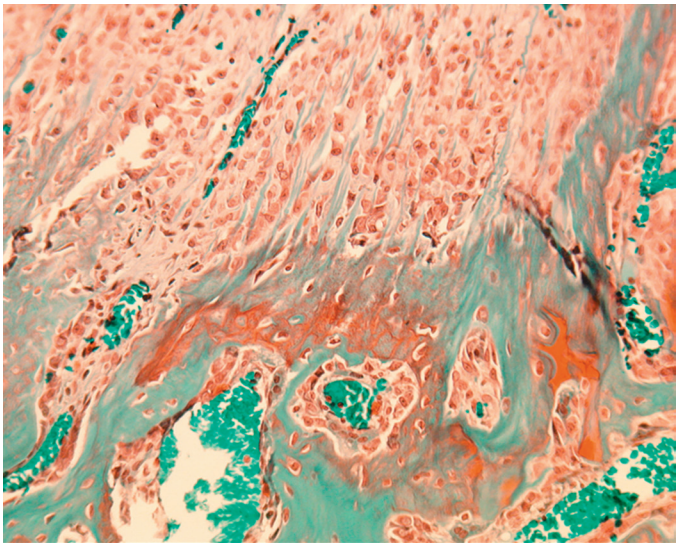


FIG 5-3 Insertion site histology 3 to 4 weeks after anterior cruciate ligament reconstruction. The interposed tissue has matured with oriented, Sharpey-like collagen fibers bridging the tendon to bone.

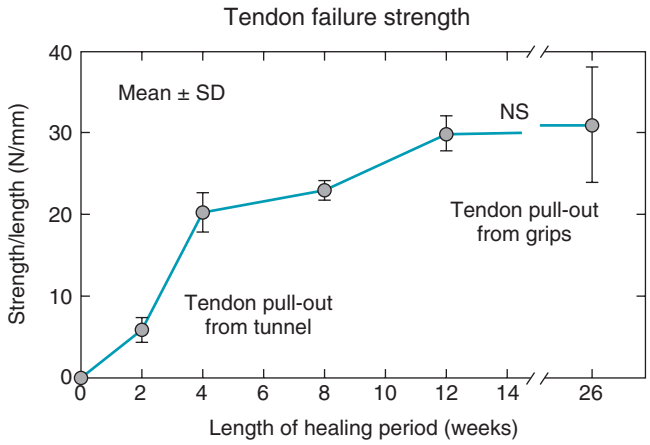


FIG 5-4 Pull-out strength of graft correlates with the number and size of bridging, Sharpey-like collagen fibers. *NS,* Not significant. (From Rodeo SA, Arnoczky SP; Torzilli PA, et al. Tendon-healing in a bone tunnel. A biomechanical and histological study in the dog. *J Bone Joint Surg Am.* 1993;75:1795-1803.)

"aggressive" versus "conservative" rehabilitation protocols in patients after ACL reconstruction with quadrupled hamstring grafts. Significantly greater tunnel widening was reported in the aggressive rehabilitation group, supporting the view that graft-tunnel micromotion is a cause of tunnel widening and that the mechanical environment in the bone tunnel influences tendon-bone healing.

Animal studies have corroborated these clinical observations. Sakai and associates[93] compared immediate motion with varying periods of immobilization for up to 6 weeks after ACL reconstruction in a rabbit model. Biomechanical analysis demonstrated a greater load to failure of the graft in immobilized animals, and histologic studies demonstrated closer tendon-bone apposition with less fibrovascular interface scar tissue. Rodeo and colleagues[88] evaluated the effect of graft-tunnel motion on tendon-to-bone healing in a rabbit ACL reconstruction model. ACL reconstruction was performed in five cadaveric rabbit limbs with aluminum beads fixed to the tendon and bone tunnel. Three-dimensional graft-tunnel motion was quantified using micro-computed tomography (microCT) analysis. Motion was observed to be greatest at the tunnel apertures and least at the tunnel exits, adjacent to the graft fixation at the tunnel exit (Fig. 5-5). Histomorphometric analysis demonstrated healing to be slowest at the apertures, with a wider fibrovascular interface tissue present between tendon and bone. An inverse relationship between graft-tunnel motion and healing in the femoral tunnel was demonstrated. In addition, osteoclasts were preferentially observed at the tunnel aperture, supporting the hypothesis that graft-tunnel motion may stimulate osteoclast-mediated bone resorption and secondary tunnel widening.[88]

These findings have been further investigated in rodent models. We developed a rat ACL reconstruction model that permits application of controlled cyclic axial loading postsurgery. We found that low-magnitude cyclic axial loading of the ACL graft for a short period of time each day, postoperatively, was associated with greater

CRITICAL POINTS Modulation of Tendon-Bone Healing

- Maximizing the surface area of the tendon-bone interface by minimizing graft tunnel mismatch and using long bone tunnels can help to improve the chances of secure graft-bone healing.
- ACL graft-tunnel micromotion, often seen with suspensory fixation techniques, can preclude the formation of a secure attachment to the tunnel wall and is associated with osteoclast-mediated bone resorption and tunnel widening.
- The rapid inflammatory response after ACL reconstruction is highly complex and may trigger a cascade of events that favors fibrosis and scar formation over tissue regeneration, resulting in an inferior tendon-bone attachment site.
- Ingrowth of bone from the surrounding tunnel wall into the interface zone and graft is ultimately responsible for the improved biomechanical properties of the attachment site after healing is complete.
- Use of undifferentiated stem cells and/or cytokines at the tendon-bone interface may have a future role in promoting tissue regeneration and the restoration of native insertion site morphology after ACL reconstruction.

inflammation and less bone formation in the tunnel when compared with animals that underwent continuous immobilization; however, this loading regimen was not detrimental to the strength of the healing tendon-bone interface.[13] Delayed application of cyclic axial load after ACL reconstruction in the same model resulted in improved mechanical and biologic parameters of tendon-to-bone healing compared with those associated with immediate loading or prolonged postoperative immobilization of the knee.[9] Higher strain levels applied to the healing ACL graft in this model had deleterious effects during the early time periods of graft healing.[83] However, stress deprivation to the graft can also have negative consequences on the biomechanical properties of the healing graft.[25]

Modulation of the mechanical environment may have profound effects on the cellular and molecular events at the tendon-bone interface. An improved understanding of these mechanisms may help to develop a postoperative rehabilitation program that provides an optimal environment for tissue regeneration and tendon-bone healing. The delicate balance that must be achieved will need to be explored with larger animal models, along with well-designed clinical trials to improve our understanding of the mechanobiology of healing.

Biologic Factors

Modulation of the Inflammatory Response

The normal response to surgery involves an acute inflammatory response marked by influx of neutrophils, macrophages, and mesenchymal cells. Important insights about the effect of this inflammatory response on tissue healing can be learned from the study of fetal wound healing. Wounds in the embryo and early fetus heal by tissue regeneration and result in "scarless healing." These healing events are characterized by the absence of an acute inflammatory response. Inflammation after trauma, although essential for healing in adults, is also responsible for healing by scar rather than regeneration of native tissue. The rapid inflammatory response that ensues after ACL reconstruction may trigger a cascade of events that ultimately leads to fibrosis rather than tissue regeneration and restoration of the native tendon-to-bone insertion.[27,51,95]

The fibrin clot that forms after surgery allows for a controlled release of cytokines that drive the early response. Transforming growth

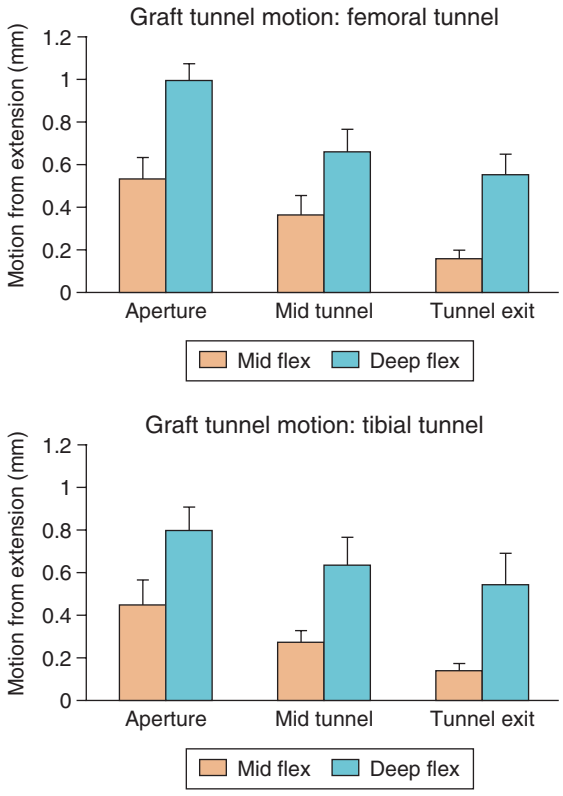


FIG 5-5 Relative motion between the tendon and bone tunnel in the femoral and tibial tunnels. Anterior cruciate ligament reconstruction was performed in five cadaveric rabbit limbs, and graft tunnel motion was measured by microcomputed tomography. Graft tunnel motion was greatest at the tunnel apertures and least at the tunnel exit in cadaveric testing. Healing of the graft was slowest at the tunnel apertures. (From Rodeo SA, Kawamura S, Kim HJ, et al. Tendon healing in a bone tunnel differs at the tunnel entrance versus the tunnel exit: an effect of graft-tunnel motion? *Am J Sports Med.* 2006;34:1790-1800.)

factor-β (TGF-β) and platelet-derived growth factor (PDGF) act together to modulate tissue healing and matrix deposition by recruiting neutrophils and macrophages to the local tissue.[27,51,95] Neutrophil influx peaks at about 2 days after the operation and is followed by an influx of macrophages. These monocytes are essential to the early formation of granulation tissue from the clot, initiating the process of soft tissue adherence to bone.[46] They also drive the angiogenic phase, providing nutrients and oxygen for the prolonged period of matrix synthesis and remodeling that ensues over the next several weeks. TGF-β secreted by macrophages recruits and stimulates fibroblasts to degrade matrix through matrix metalloproteinases (MMPs). Simultaneously, these fibroblasts synthesize new matrix proteins to replace the early granulation tissue with scar tissue. Tissue inhibitors of MMPs (TIMPs) inhibit MMPs and provide a check-and-balance regulation to this complex process of matrix degradation, synthesis, and remodeling.[26]

The accumulation of macrophages around the tendon graft in bone has been further characterized in a rat ACL reconstruction model.[46] Two distinct subpopulations of macrophages were identified at the tendon-bone interface. ED1+ macrophages derived from the circulation act in a proinflammatory fashion in the early response with neutrophils to migrate into the tissues and remove debris after surgery. This is followed by the accumulation of proregenerative ED2+ macrophages from the local tissues, which promote anabolic tissue healing and scar formation by fibroblasts via TGF-β secretion (Fig. 5-6).[46]

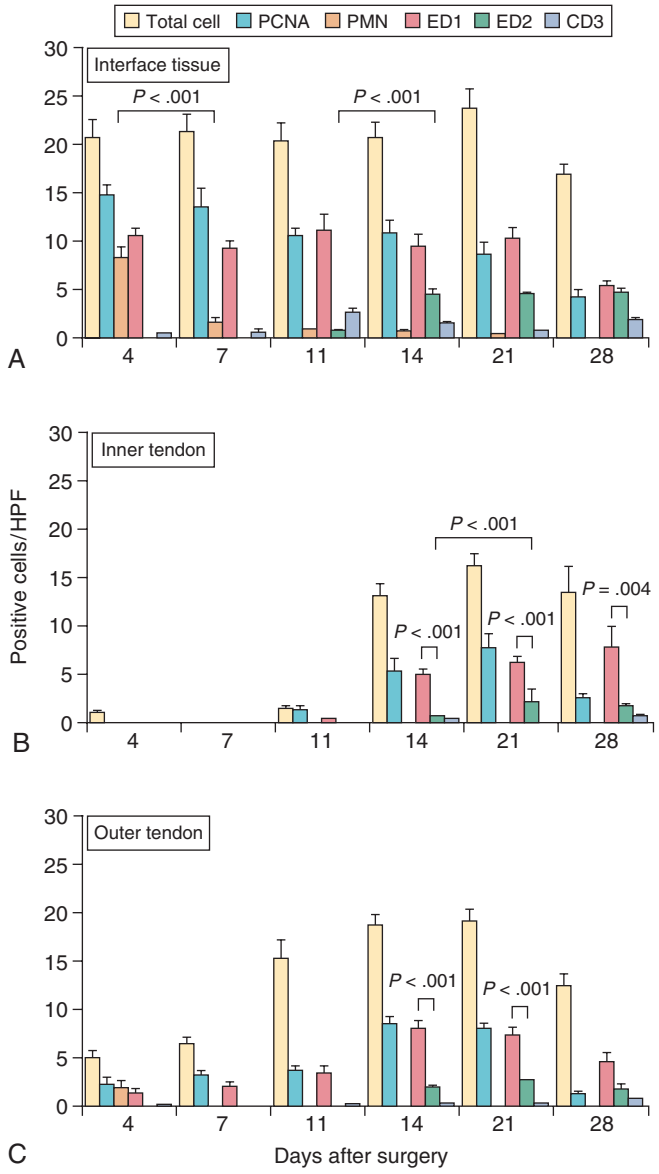


FIG 5-6 Time course of inflammatory cell accumulation in the tendon-bone interface **(A)**, inner tendon **(B)**, and outer tendon **(C)**. The number of positively stained cells for PCNA, PMN, ED1, ED2, and T-lymphocytes were counted in 15 randomly chosen high-power fields 50 µm × 50 µm at ×400 for each area. **A,** There was a significant decrease in the number of neutrophils between 4 and 7 days ($P < .001$). ED2+ macrophages were not present until 11 days after surgery, with a significant increase in positive staining by 14 days after surgery ($P < .001$). **B,** There were significantly more ED1+ macrophages than PCNA+ cells at 28 days after surgery ($P = .014$). There were significantly more ED1+ macrophages than ED2+ macrophages at 14 days and 21 days after surgery ($P < .001$) and at 28 days after surgery ($P = .004$). There were significantly more ED2+ macrophages 21 days compared with 14 days after surgery ($P < .001$). There were no significant differences in the number of CD3-positive cells at all time points. *HPF,* High-power field; *PCNA,* proliferating cell nuclear antigen; *PMN,* polymorphonuclear cells. (Modified from Kawamura S, Ying L, Kim HJ, et al. Macrophages accumulate in the early phase of tendon-bone healing. *J Orthop Res.* 2005;23:1425-1432.)

Given the critical role of macrophages in scar tissue formation, animal studies have investigated the role of macrophage depletion on tendon-bone healing to test the hypothesis that macrophage depletion could promote a "scarless" regenerative healing process at the healing insertion site. Hays and colleagues[34] demonstrated less scar tissue formation, improved collagen organization, and superior biomechanical strength in a rat ACL reconstruction model when macrophages were depleted by administration of liposomal clodronate, a selective inducer of macrophage apoptosis. Other studies have identified gastric pentadecapeptide BPC 157, a novel antiinflammatory used in the treatment of inflammatory bowel disease, to improve Achilles tendon-to-surface bone healing and tissue regeneration in a rat Achilles tendon model.[48]

The impact of inflammatory response suppression, however, has not been uniformly favorable for tendon-bone healing. Cohen and associates[16] evaluated the effect of antiinflammatory medications indomethacin and celecoxib, selective cyclooxygenase 2 (COX-2) inhibitors, on tendon-bone healing in a rat rotator cuff model. The treated group was found to have histologic and biomechanically inferior tendon-bone interfaces at both 4 and 8 weeks relative to controls (Fig. 5-7).

These studies indicate that the acute inflammatory response that ensues after ACL reconstruction is highly complex and remains to be further defined. Selective reduction in inflammatory mediator expression, improved angiogenesis, and improved tissue regeneration may promote formation of a native tendon-bone insertion over scar tissue formation. However, a dichotomy exists because other elements of the inflammatory response are necessary in the postnatal organism to initiate the tissue healing response and allow for an efficient graft interface remodeling process.

Modulation of Bone Ingrowth

Bone ingrowth plays a critical role in the later stages of tendon-bone healing after ACL reconstruction and is ultimately responsible for the improved biomechanical properties after healing is complete. Animal studies have provided strong evidence to support that increased bone ingrowth positively correlates with graft-bone fixation strength.[89] The primary strategies that have been employed include use of osteoinductive agents, osteoconductive agents, and modulation of osteoclast activity.

Osteoinductive agents, particularly from the bone morphogenic protein (BMP) family, have been shown to promote ingrowth of bone from the tunnel into the soft tissue graft. Rodeo and coworkers[89] delivered recombinant human BMP-2 (rh-BMP-2) on an absorbable type I collagen sponge in a canine tendon-bone model. At all time points, the rh-BMP–2 treated limbs healed with increased bone formation around the tendon. Biomechanical testing demonstrated higher tendon pull-out strength in the treated limbs relative to controls at 2 weeks. Ma and colleagues[53] delivered rh-BMP-2 in an injectable calcium phosphate matrix to the bone tunnel in a rabbit ACL reconstruction model. Histologic analysis revealed a dose-dependent increase in bone formation at the tendon-bone interface and significantly narrower tunnel diameters (15% to 45%) relative to the control group. Increased construct stiffness was also seen in the treatment group at 8 weeks postoperatively.[53] Martinek and associates[56] transected semitendinosus grafts in vitro with adenovirus-BMP-2 (Ad-BMP-2) and compared them with untreated controls in a rabbit ACL reconstruction model. These investigators demonstrated the formation of a fibrocartilaginous interface at the tendon-bone junction in the experimental group that was absent in the controls. Both stiffness and load-to-failure parameters were superior in the treatment group at 8 weeks. BMP-7 has also been shown to improve bone formation at the tendon-bone interface

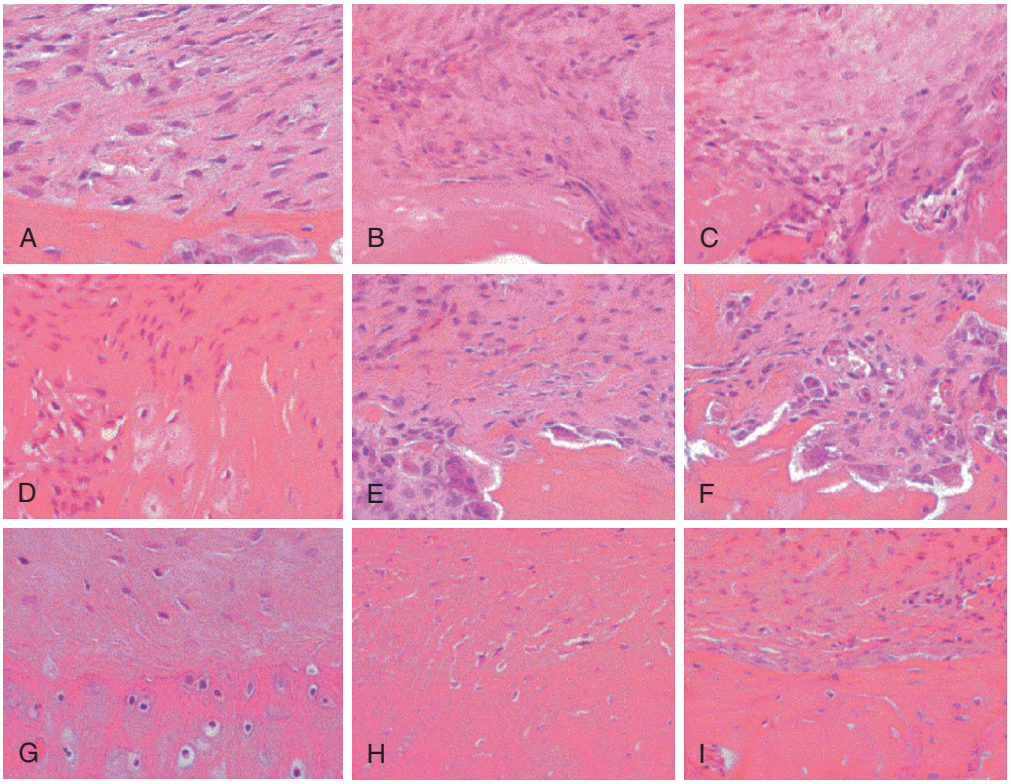


FIG 5-7 Photomicrograph demonstrating tendon-bone insertion site at 2 weeks (**A,** control group; **B,** celecoxib group; **C,** indomethacin group), 4 weeks (**D,** control group; **E,** celecoxib group; **F,** indomethacin group), and 8 weeks (**G,** control group; **H,** celecoxib group; **I,** indomethacin group) after surgery (hematoxylin-eosin, ×320). (From Cohen DB, Kawamura S, Ehteshami JR, Rodeo SA. Indomethacin and celecoxib impair rotator cuff tendon-to-bone healing. *Am J Sports Med.* 2006;34:362-369.)

and load-to-failure at both 3 and 6 weeks postoperatively in an ovine reconstruction model.[1,61]

Further support for the role of BMPs in bone ingrowth around tendon graft comes from studies of BMP inhibition. Ma and colleagues[53] delivered noggin, a potent inhibitor of all BMP activity, to the healing tendon-bone interface using an injectable calcium phosphate matrix in a rabbit ACL reconstruction model. Noggin significantly inhibited new bone formation at the tendon-bone interface. Furthermore, a significant increase in the width of the fibrous tissue interface between tendon and bone was found in the noggin-treated animals (Fig. 5-8).

The favorable effect of osteoinductive agents on tendon-bone healing in a tunnel is further supported by studies that have used tendons wrapped in periosteum. Transplantation of a long digital extensor tendon wrapped in periosteum into a tunnel in the proximal tibia were compared with controls in a rabbit model.[14,80] Improved biomechanical strength, along with bone and fibrocartilage formation at the tendon-bone interface, was ultimately demonstrated in the treated animals at 8 and 12 weeks. Ohtera and colleagues[80] completed further studies comparing fresh and frozen periosteum and demonstrated better histologic and biomechanical outcomes using fresh periosteal wraps. These findings support the hypothesis that the viable osteoinductive factors in the periosteum may contribute to the improved outcomes.

Osteoconductive agents have also produced favorable outcomes in animal models. Calcium-phosphate (CaP)-hybridized grafts used in a rabbit ACL reconstruction model demonstrated improved fibrocartilage and bone formation relative to animals treated with unhybridized

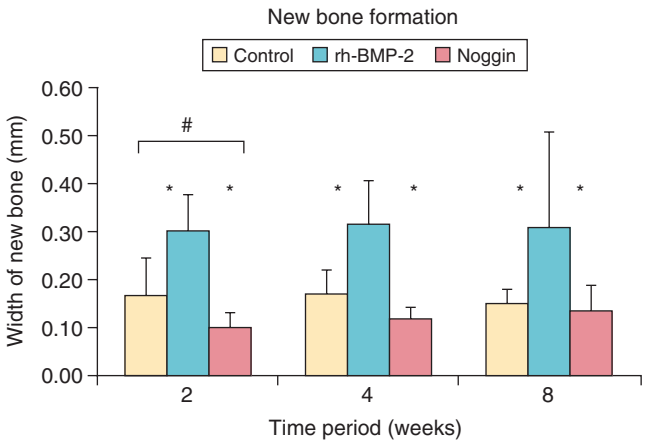


FIG 5-8 The width of new bone formation (mm ± standard deviation) at the tunnel-graft interface after anterior cruciate ligament reconstruction in a rabbit model. *Asterisks* represent significant differences compared with the rh-BMP-2 group ($P < .05$). #Represents significant differences compared with the control group ($P < .05$). For each dosage of rh-BMP-2 and noggin test, 4 rabbit limbs were used for histomorphometric analysis. (Modified from Ma C, Kawamura S, Deng X, et al. BMP-signaling plays a role in tendon-to-bone healing: A study of rhBMP-2 and noggin. *Am J Sports Med.* 2007;35:597-604.)

grafts at 3 weeks postoperatively.[73] Furthermore, Tien and coworkers[99] used injectable CaP cement in the femoral tunnel of a rabbit ACL reconstruction model and reported improved bone formation and biomechanical strengths relative to controls at 1 and 2 weeks postoperatively.

Modulation of osteoclast activity in the bone tunnel is another technique of promoting bone formation at the tendon-bone interface. Furthermore, inhibition of osteoclast-mediated bone resorption offers a potential means by which to limit the bone tunnel expansion commonly seen after ACL reconstruction. One study demonstrated that increased knee laxity correlated with radiographic tunnel widening after ACL reconstruction using hamstring tendon.[33] The role of osteoclastic bone resorption on tendon-bone healing has been evaluated in a rabbit ACL reconstruction model.[20] Osteoprotegerin (OPG), a potent inhibitor of osteoclast activity, or receptor activator of nuclear factor κB ligand (RANKL), a potent stimulant of osteoclast formation, were delivered to the bone tunnels around a tendon graft using a CaP carrier matrix. A significantly greater amount of bone surrounding the tendon at the interface was seen in the OPG-treated limbs relative to controls and RANKL-treated limbs at all time points (Fig. 5-9).[20] Furthermore, biomechanical testing at 8 weeks demonstrated significantly increased stiffness of the femur-graft-tibia complex in the OPG-treated limbs compared with the RANKL-treated limbs.

Stem Cells

Undifferentiated, pluripotent mesenchymal cells (MSC), also termed *stem cells,* may be critical to stimulate tissue regeneration rather than scar formation at the tendon-bone interface. These cells retain the capacity to differentiate into various specialized cell types based on biologic signals in the local environment. Therapeutic use of these cells has been investigated for numerous clinical conditions in the field of orthopedics, and cell lines can be derived from various sources (bone marrow, adipose tissue, synovium, etc.). Animal studies have tested the effects of local stem cell delivery on tendon-bone healing. Rabbit bone marrow stromal cells placed in a fibrin glue carrier were delivered to the tendon-bone interface of the hallucis longus tendon in a calcaneal tunnel.[82] Histologic analysis revealed improved healing with fibrocartilaginous attachment between tendon and bone in the experimental group. Lim and associates[52] performed bilateral ACL reconstructions in a rabbit model and evaluated the role of mesenchymal stem cells on the tendon-bone interface. The grafts coated with MSC demonstrated cartilage at the tendon-bone interface, whereas only fibrous tissue was observed at the interface in the contralateral control limbs. The interface stained positively for type II collagen in the MSC-treated grafts, and was similar in organization to a native, direct ligament insertion. Furthermore, biomechanical testing at 8 weeks demonstrated higher loads to failure and stiffness relative to controls. More recent studies have demonstrated improved efficiency in collagen organization with the use of MSCs, and have even demonstrated the presence of pluripotent-like ($CD34^+$) cells in the substance of the ruptured ligament.[44,60]

Further work is required to determine the mechanism by which pluripotent stem cells enhance tendon-bone healing. It is unknown whether these cells differentiate into fibrochondrocytes (i.e., the ultimate fate of these cells) or if they produce cytokines that improve insertion site organization and tissue regeneration. It is likely that optimal use of cellular therapy will require concomitant delivery of growth factors to produce a regenerative healing response at the tendon-bone interface.

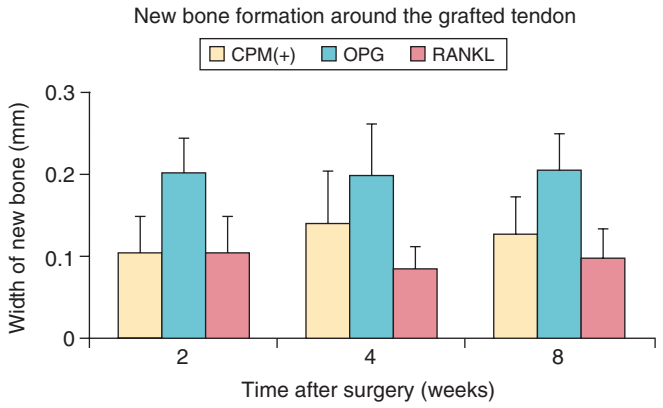


FIG 5-9 Fifteen New Zealand white rabbits underwent unilateral anterior cruciate ligament reconstruction using an autologous semitendinosus tendon graft. Animals treated with 100 μg osteoprotegerin (OPG) had a significant ($P = .007$) increase in newly formed bone around the graft compared with the control group (0.16 ± 0.01 mm^2 vs. 0.06 ± 0.02 mm^2). *CPM,* Calcium phosphate matrix; *RANKL,* receptor activator of nuclear factor κB ligand. (Modified from Rodeo SA, Kawamura S, Ma CB, et al. The effect of osteoclastic activity on tendon-to-bone healing: an experimental study in rabbits. *J Bone Joint Surg Am* 2007;89: 2250-2259.)

Modulation of Vascularity

Whereas vascularity is critical for the efficient delivery of oxygen and nutrients to support tissue healing, the precise role of local vascularity at the tendon-bone interface remains to be defined. Krivic and colleagues[48] demonstrated improved vascularity at the healing Achilles tendon-bone interface after treatment with gastric pentadecapeptide BPC 157 in a rat model. This improved vascularity correlated with favorable histologic and biomechanical properties of the tendon-bone interface. In contrast, a recent study examined the effect of VEGF on graft healing in an ovine ACL reconstruction model.[107] Although vascularity and cellularity were increased in the VEGF-soaked grafts relative to controls, the stiffness of the femur-graft-tibia complex was significantly inferior to controls at 3 months. Even though only a single concentration of VEGF was used, the results suggest the possibility that excessive vascularity may adversely affect healing and the biomechanical properties of the tendon-bone interface.[107]

Modulation of Matrix Metalloproteinases

The MMPs are a family of zinc-dependent endoproteinases that play a critical role in tissue degradation, healing, and normal remodeling. They function in both an extracellular environment and through transmembrane and intracytoplasmic domains.[19] Inflammatory cytokines such as interleukin-1 (IL-1) and tumor necrosis factor (TNF) initiate the transcription and activation of MMPs from their zymogen form. Their catabolic, destructive activity is balanced, however, by tissue inhibitors of TIMPs. TIMPs provide a check-and-balance mechanism to control the activity of these degradative enzymes and thereby maintain homeostasis of extracellular matrix formation and degradation that occurs with tissue remodeling.[26]

Synovial fluid tracking between the graft and tunnel walls after ACL reconstruction is known to contain large amounts of collagenase and stromelysin. It has been theorized that MMPs may have adverse effects on the tendon-bone interface, perhaps by limiting the formation of Sharpey-like collagen fibers. Demirag and coworkers[19] used α_2-macroglobulin (A2 M), an endogenous inhibitor of matrix metalloproteinases, to study this hypothesis in a rabbit ACL reconstruction model. Each rabbit underwent bilateral ACL reconstruction with hamstring autograft. A2 M was injected into one knee postoperatively and was compared with the contralateral control limb. The interface tissue

in treated specimens was more mature with significantly greater Sharpey-like fibers. Biomechanical studies demonstrated greater load to failure compared with controls at 2 and 5 weeks (Fig. 5-10).[19] This work was further substantiated by Bedi and colleagues,[10] who demonstrated A2 M improved fibrocartilage formation at the site of healing tendon. The answer is likely somewhere in the middle ground as the importance of MMP-2 mediation has been recently elucidated as a reason for in vitro cell migration in the ruptured ACL.[103] Further studies are necessary to characterize the precise mechanism of action of MMPs at the tendon-bone interface. Nonetheless, this work provides preliminary evidence that modulation of MMP activity may improve graft-bone healing in a bone tunnel.

Modulation of Nitric Oxide

Nitric oxide is a free radical agent synthesized by nitric oxide synthase from L-arginine. It acts as a regulatory molecule both in cells and in the extracellular matrix. Studies have shown that it is induced during tendon healing in vitro, with a dose-dependent effect on fibroblast collagen production.[71,72] ACL ligament fibroblasts are uniquely able to produce more nitric oxide compared with other local fibroblasts, including those derived from the medial collateral ligament (MCL).[62] Limited research exists defining the exact role behind the potential beneficial effects of nitric oxide. Therapeutic delivery of nitric oxide has demonstrated improved collagen organization in the healing tendon, with improved biomechanical properties compared with controls, and likely works via improving blood flow to the healing site.[12] The influence of nitric oxide levels, specifically in regard to tendon-bone healing after ACL reconstruction, remains to be defined.

Effect of Hyperbaric Oxygen

Yeh and associates[106] studied the influence of hyperbaric oxygen (HBO) therapy on the graft-bone tunnel interface in a rabbit model. The HBO group was exposed to 100% oxygen at 2.5-atm pressure for 2 hours daily, 5 consecutive days a week. The control group was exposed to normal air. The HBO group demonstrated increased neovascularization and an increased number of Sharpey fibers relative to controls. Furthermore, the HBO group achieved higher maximal pull-out strengths at 12 and 18 weeks relative to control specimens.[106] Although the mechanism of action is unclear, these preliminary results suggest that HBO therapy may improve tendon-bone healing after ACL reconstruction.

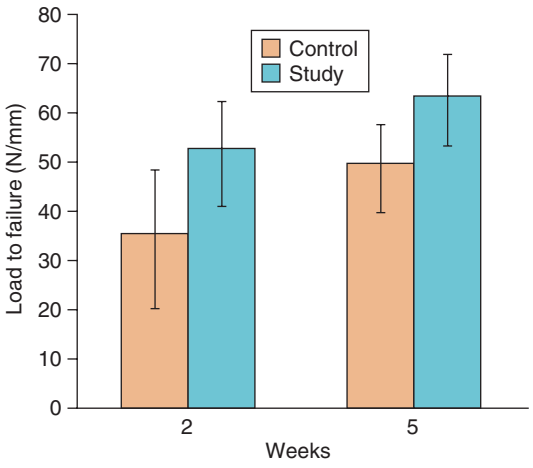


FIG 5-10 The ultimate load to failure was significantly greater in the α_2-macroglobulin–treated specimens than in the untreated control specimens at both 2 and 5 weeks ($P = .007$ and $P = .006$, respectively). (Modified from Demirag B, Sarisozen B, Durak K, et al. The effect of alpha-2 macroglobulin on the healing of ruptured anterior cruciate ligament in rabbits. *Connect Tissue Res.* 2004;45[1]:23-27.)

Modulation of Other Biologic Mediators

Future techniques to enhance tendon-bone healing after ACL reconstruction will be directed by an improved understanding of the biology of this healing process. Use of cytokines to provide important signals for tissue formation and differentiation, gene therapy techniques to provide sustained cytokine delivery, the use of stem cells, or transcription factors to modulate endogenous gene expression represent some of these possibilities. *Scleraxis*, a transcription factor expressed in mesenchymal tendon progenitor cells, Indian hedgehog, a factor involved in growth plate and limb development, and *Sox-9*, a transcription factor that is critical for chondrogenesis, are examples of proteins that may play key roles in native tendon insertion site formation.

BONE-TO-BONE HEALING IN ACL AUTOGRAFT RECONSTRUCTION

Healing of a bone plug to the osseous tunnel walls after autograft ACL reconstruction is unique and unlike anywhere else in the body. The biomechanic and biologic environment in the graft tunnels present significant challenges to union.

The sequence of bone-tendon-bone autograft incorporation has been defined in animal models. Tomita and colleagues[100] compared healing of a soft tissue graft to a bone-patellar tendon-bone (B-PT-B) autograft in a canine model. The bone plug undergoes osteonecrosis and is gradually replaced by a process of creeping substitution (Fig. 5-11). Newly formed bone surrounding the plug is seen at 3 weeks. These investigators found pull-out strength of the B-PT-B graft to be superior to the soft tissue graft at 3 weeks, but not significantly different at 6 weeks. At 6 weeks, a change in the point of failure was noted from the graft-tunnel interface to the tendon-bone plug interface. Papageorgiou and coworkers[85] directly compared tendon-bone to bone-bone healing in a goat model. Bone-patellar tendon autografts were harvested; the soft tissue graft was placed in the tibial tunnel while the bone plug was secured in the femoral tunnel. Biomechanical testing at 3 weeks demonstrated universal failure of the tendon-bone interface with pull-out from the tibial tunnel. At 6 weeks, however, approximately 20% of cases demonstrated mid substance failures. The remaining cases continued to be tibial tunnel graft pull-out. Histologic evaluation at 3 weeks confirmed creeping substitution with a necrotic bone plug surrounded by granulation tissue. Evaluation at 6 weeks revealed complete plug incorporation with bridging cancellous bone.[85]

Synovial fluid flows from the joint into the tunnels and can interfere with healing at the tendon-bone interface. The high quantities of MMPs and other proteolytic enzymes in synovial fluid can slow bone tendon-bone and bone-bone healing. Berg and associates[11] evaluated

CRITICAL POINTS Bone-to-Bone Healing After ACL Autograft Reconstruction

- The process of bone plug incorporation after ACL reconstruction is complex and is characterized by osteonecrosis followed by creeping substitution and new host bone formation.
- Synovial fluid flow into the bone tunnels may interfere with healing at the tendon-bone interface.
- Regardless of whether a soft tissue or bone-tendon-bone graft is used, the critical healing at the intraarticular aperture that must occur to minimize graft micromotion usually requires tendon-bone healing.

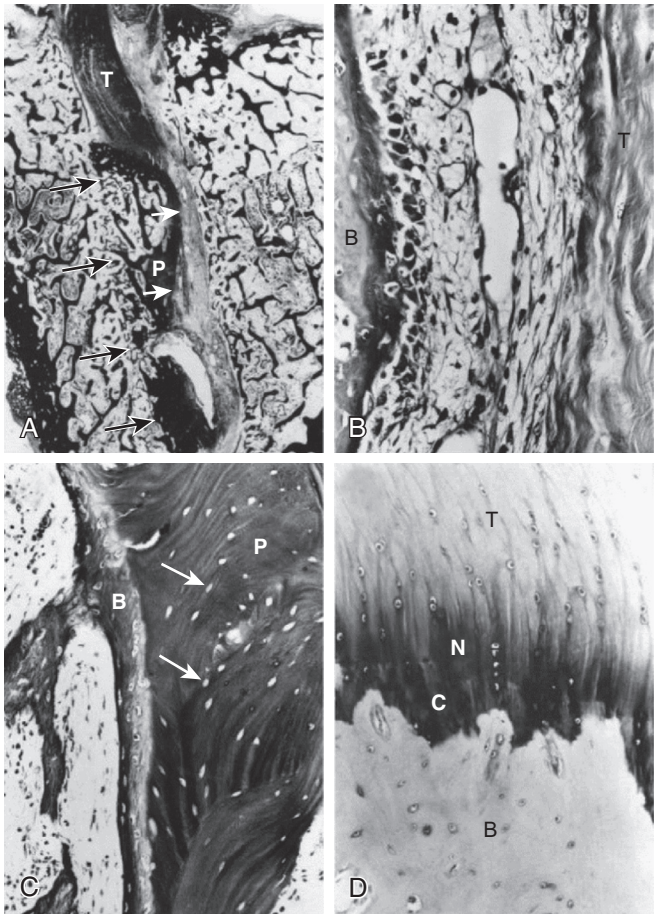


FIG 5-11 Healing of a bone-patellar tendon-bone (B-PT-B) autograft in a canine model. The bone plug undergoes osteonecrosis and is gradually replaced by a process of creeping substitution. In the bone plug of the B-PT-B graft, a number of empty lacunae (*white arrows*) indicate bone necrosis, except at the superficial portion of the plug. *B,* Bone wall; *C,* calcified fibrocartilage; *N,* noncalcified fibrocartilage; *P,* bone plug of the B-PT-B graft; *T,* patellar tendon. (From Tomita F, Yasuda K, Mikami S, et al. Comparisons of intraosseous graft healing between the doubled flexor tendon graft and the bone-patellar tendon-bone graft in anterior cruciate ligament reconstruction. *Arthroscopy.* 2001;17: 461-476.)

the role of synovial fluid by drilling femoral and tibial tunnels and leaving them empty in a rabbit ACL model. These authors found that healing occurred most rapidly at points farthest away from the joint, whereas the slowest and most incomplete regions of healing were at the tunnel apertures. These findings are suggestive of a possible inhibitory effect of synovial fluid on healing in the tunnel.

It is critical to remember that regardless of whether a soft tissue or bone-tendon-bone graft is used, the critical aperture fixation will usually require tendon-bone healing. The tendon length of a B-PT-B graft exceeds the native ACL length, such that a substantial portion of the tunnel, including the aperture zone, will contain tendon. Tendon-bone healing at the aperture, regardless of graft choice, is essential to minimize graft micromotion and subsequent risk of tunnel widening.

INTRAARTICULAR GRAFT HEALING IN ACL AUTOGRAFT RECONSTRUCTION

Ligamentization refers to the complex process of biologic incorporation and remodeling of the tendon graft that occurs after ACL

CRITICAL POINTS Intraarticular Graft Healing in ACL Autograft Reconstruction

- Intraarticular graft healing occurs by a process of remodeling that is dependent on revascularization and cellular repopulation from the host synovium.
- The incorporated graft does not achieve the organization or vascularity of the native ACL.

reconstruction. Animal studies have attempted to define the phases of intraarticular graft healing that occur postoperatively. The graft goes through an initial phase of avascular necrosis. At 2 weeks, the graft demonstrates patches of necrosis, although the collagen architecture and scaffold remain intact.[3,5,47,84] By 4 weeks, the graft is almost entirely avascular and acellular. This phase, however, is followed by cellular repopulation from the host synovial cells. Biopsy at 3 months reveals extensive vascular proliferation and cellular repopulation. By 9 months, the graft histologically resembles the native ligament.[3,5,47,84]

However, it should be noted that our understanding of the process of revascularization and graft incorporation is based on animal models, which have distinct limitations. For various reasons, it is very difficult to stabilize the animal knee with ACL reconstruction. Consequently, most animal models of ACL reconstruction have graft laxity, which may affect graft biology. It is known that stress deprivation in fibrous connective tissue (which would occur in a lax, unstressed graft) leads to upregulation of MMPs, which adversely affect the matrix. It is clear that further studies are required to fully elucidate the process of graft revascularization, incorporation, and remodeling.

Intraarticular healing has been studied in other animal models. Oaks and colleagues[79] demonstrated remodeling occurred from the periphery toward the graft center. This was associated with a change from large-diameter to small-diameter collagen fibrils. This pattern of remodeling supports the hypothesis that healing is dependent on gradual revascularization and cellular repopulation from the host synovium. Arnoczky and coworkers[5] evaluated patellar tendon graft revascularization in a canine model. Initially the grafts were avascular, but by 6 weeks they were completely ensheathed in a vascular synovial envelope. The soft tissues of the infrapatellar fat pad, the tibial remnant of the ACL, and the posterior synovial tissues contributed to this synovial vasculature. Intrinsic revascularization of the patellar tendon graft progressed from the proximal and distal portions of the graft centrally.[5] The tibial attachment of the patellar tendon graft did not contribute any vessels to the revascularization process. The contribution of the soft tissues of the knee to the revascularization process of the graft emphasized the importance of their preservation in maintaining the graft's viability. Recent advanced imaging studies in humans have confirmed that graft revascularization occurs in a gradual fashion. Ntoulia and coworkers[78] demonstrated with contrast-enhanced magnetic resonance imaging that the intraarticular portion of the graft successfully revascularized before the attachment sites, which was still displaying uptake at the 12-month postoperative mark.

Although animal models have provided insight into the process of ligamentization, the process has not been fully characterized in humans. Jackson and associates[41] concluded that an incorporated graft never replicates the native ACL, but rather functions like a checkrein of organized scar tissue. Delay and colleagues[18] described a case report of a B-PT-B autograft with avascular, acellular regions in the deep, distal graft, 18 months after reconstruction. Rougraff and Shelbourne[91] performed patellar tendon graft biopsies on nine subjects 3 to 8 weeks after autogenous ACL reconstruction. Graft vascularity was present at 3 weeks and increased over the 8-week interval.

PRIMARY ACL HEALING AND REPAIR

Primary repair of the ACL after traumatic rupture was historically considered to be a viable surgical option. Outcome studies, however, reported unacceptable rates of failure after primary surgical repair.[21] In their classic study, Feagin and Curl[21] reported a 94% rate of instability in patients at 5-year follow-up after primary suture and drill hole ACL repair. Marshall and coworkers[55] reported a 20% to 40% failure rate despite repair using a sophisticated, multiple-depth suture technique. Zysk and Refior[110] also reported modest outcomes in a study of middle-aged patients who underwent primary ACL repair and recommended that open primary repair be abandoned in favor of autogenous tissue reconstruction or augmentation. These results were further corroborated by a Norwegian study that assessed long-term outcomes in a large series of patients who underwent primary ACL repair.[98] An open procedure using the original Palmer technique with nonabsorbable Bunnell sutures was performed in all cases. At 15 to 23 years postoperatively, 57% had greater than 3 mm of anterior translation on KT-1000 testing. The estimated rate of total failure was 27%. These results are in sharp contradistinction to the MCL, in which failure to primarily heal is the exception rather than the rule.

The poor rate of primary healing that is observed after ACL rupture is believed to be multifactorial in nature. One of the most salient factors is the intraarticular environment and synovial fluid that surrounds the ACL.[63,65-70,97] Studies by Murray and associates[63,65-70,97] demonstrated the differences in intraarticular (i.e., ACL) versus extraarticular (i.e., MCL) healing in a canine, central ACL wound model. An empty wound persists at the defect of an intraarticular ligament wound, whereas these wounds are rapidly filled with a fibrin-platelet scaffold in an extraarticular injury. This scaffold is critical to allow subsequent cellular repopulation, revascularization, and ligament remodeling into mature scar tissue. The presence of fibrinolysates in the joint prevents the formation of a stable fibrin clot that could serve as a provisional scaffold. The lack of a scaffold in the intraarticular ligament wounds was associated with decreased inflammatory cytokines needed for the healing response, including fibrinogen, PDGF, TGF-β, and FGF.[63,65-70,97] Studies by Murray and associates[63,65-70,97] demonstrated that replacement of the central intraarticular ligament void with a collagen-platelet-rich plasma scaffold resulted in increased filling of the wound with repair tissue that had similar profiles of protein expression to matched, extraarticular ligament wounds. Biomechanical studies of suture ACL repair augmented with a collagen-platelet–rich scaffold in a porcine model have shown significant improvement in load to failure and linear stiffness at 4 weeks compared with unaugmented, control repairs.[63,65-70,97] These studies support the concept of a bioenhanced repair, and a recent large animal model randomized trial demonstrated equivalent functional results in pigs treated with repair versus reconstruction. Importantly, 80% of those knees treated with reconstruction developed posttraumatic osteoarthritis, whereas none of the knees in the bioenhanced repair group developed osteoarthritis in the same time period.[102]

Other factors implicated in the poor ACL healing response included alterations in cellular metabolism after injury, cellular loss within the tissues after injury, and intrinsic differences in ACL fibroblasts compared with fibroblasts in extraarticular ligaments. Murray and associates[63,65-70,97] defined the histologic changes that occur after ACL rupture. The human ACL undergoes four histologic phases, consisting of inflammation, epiligamentous regeneration, proliferation, and remodeling (Fig. 5-12). Although similar to the response to injury in other dense connective tissues, major exceptions include (1) formation of an α-smooth muscle actin–expressing synovial cell layer on the surface of the ruptured ends, (2) the lack of any tissue bridging the rupture site, and (3) the presence of an epiligamentous reparative phase that lasts 8 to 12 weeks.[63,65-70,97] The biology involved in intraarticular ligament healing will need to be further defined to overcome the obstacles to long-term success with primary ACL repair.

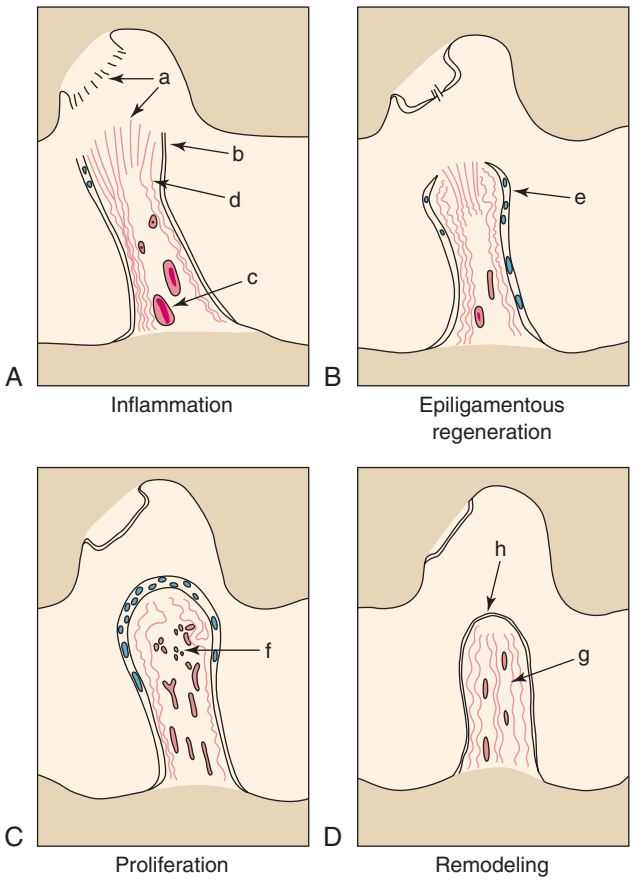


FIG 5-12 Schematic of the gross and histologic appearance of the four phases of the healing response in the human anterior cruciate ligament. **A,** The inflammatory phase, showing mop ends of the remnants *(a)*, disruption of the epiligament and synovial covering of the ligament *(b)*, intimal hyperplasia of the vessels *(c)*, and loss of the regular crimp structure near the site of injury *(d)*. **B,** The epiligamentous regeneration phase, involving a gradual recovery of the ligament remnant by vascularized, epiligamentous tissue and synovial tissue *(e)*. **C,** The proliferative phase, with revascularization of the remnant with groups of capillaries *(f)*. **D,** The remodeling and maturation phase, characterized by a decrease in cell number density and blood vessel density *(g)* and by retraction of the ligament remnant *(h)*. (Modified from Murray MM, Martin SD, Martin TL, Spector M. Histological changes in the human anterior cruciate ligament after rupture. *J Bone Joint Surg Am.* 2000;82-A:1387-1397.)

CRITICAL POINTS Primary ACL Healing and Repair

- Clinical outcomes studies have shown unacceptable rates of failure after primary ACL repair.
- The poor healing rate is believed to be multifactorial in nature, including an unfavorable, intraarticular biologic environment and altered cellular metabolism and function after injury.
- Augmentation with a collagen-platelet-rich plasma scaffold may offer future promise to improve healing after primary ligament repair.

ALLOGRAFT HEALING IN ACL RECONSTRUCTION

An increasing desire to avoid the morbidity of graft harvest and to reduce operative times has led to a dramatic increase in the use of allografts as an alternative graft source in primary ACL reconstruction.[7] Allografts are also frequently used in revision procedures or multiligament reconstruction procedures. Good clinical outcomes have been reported with allograft reconstructions at 2- to 5-year follow-up, and multiple studies have found no significant subjective or objective difference in knee function after allograft versus autograft ACL reconstructions.[8] However, other studies have reported less favorable results after allograft reconstruction, particularly in the setting of chronic or revision knee surgery,[76,77] and larger multicenter cohorts have echoed these observations.[35] A recent systematic review of overlapping metaanalyses reviewed eight studies with a total of 15,819 patients.[57] Approximately one half of the metaanalyses found no differences in patient outcomes between autograft and allograft, whereas the other half concluded autografts produced better outcomes. Because the first half included studies with higher level of evidence, the authors concluded that the current evidence shows no differences in rupture rate and clinical outcomes between autograft and allograft.[57] Important considerations regarding allograft preparation and processing are germane for the surgeon, as nonirradiated, nonchemically treated allografts have shown equivocal outcomes to autografts in regards to stability and function.[50] See also Chapters 7 and 8 for further discussion on clinical outcomes of ACL allograft and autograft reconstructions.

Despite compatible clinical outcomes, animal studies have shown that allografts have a slower rate of incorporation, prolonged inflammatory response, and greater initial decrease in biomechanical properties compared with autografts.[2-6,38-40,42,43,109] The phases of healing, although delayed, resemble those of the autograft. The tendon-bone interface develops a fibrovascular granulation tissue interface that eventually undergoes bone ingrowth and develops Sharpey-like anchoring fibers.[2-6,38,43,109] The intraarticular graft undergoes ligamentization with a phase of avascular necrosis followed by cellular repopulation and vascular proliferation from host synovium. Donor DNA was entirely replaced by host DNA within 4 weeks in a goat reconstruction model. Revascularization starts at 3 weeks and progresses gradually over the next several weeks. Jackson and colleagues compared healing of patellar tendon autografts with fresh allografts in a goat ACL reconstruction model.[2-6,38,43,109] Although graft structural properties were similar at time 0, the allografts healed at a much slower rate. At 6 months, the autografts demonstrated a superior load to failure, larger increase in graft cross-sectional area, and better restraint to anteroposterior displacement. The allografts demonstrated a significantly greater decrease in their preimplantation structural properties.

Human studies have supported these findings of slower allograft incorporation. At 2 years postoperatively, biopsy studies have shown that the central portion of allografts can be acellular.[36] Cellular repopulation of the entire graft was often seen only after 3 years or more after allograft reconstruction.[54]

Because of the relatively hypocellularity of tendon allografts and current sterilization techniques, the host immune response is relatively limited. Major histocompatibility complex antigens that incite a potent immune response are largely depleted. Matrix antigens, however, persist and can elicit an immune response that may contribute to the delayed incorporation and the pronounced alteration in structural properties after surgery.[90,104] The specific influences of such an immune response on the biology of ACL graft healing remains to be defined.

CRITICAL POINTS Allograft Healing in ACL Reconstruction

- Allografts demonstrate a slower rate of host incorporation, prolonged inflammatory response, and greater decrease in initial biomechanical properties than those of autograft in ACL reconstruction.
- Allografts have greater variability in clinical outcomes compared with autograft ACL reconstruction.
- Allografts have a higher failure rate when used for revision ACL reconstruction.

PLATELET-RICH PLASMA AS AN ADJUNCT TO IMPROVED HEALING

Platelet-rich plasma (PRP) has been evaluated as an adjunct to improve healing after primary repair of the ACL and after ACL graft reconstruction. Growth factors present in PRP have been found to stimulate proliferation and migration of ACL fibroblasts.[59] PRP alone does not improve healing of the ACL after primary repair, likely because of rapid degradation of fibrin in the PRP from the presence of plasmin in the joint. However, the combination of PRP with collagen to form a scaffold is resistant to degradation by plasmin, and the use of a composite collagen-platelet concentrate has been reported to improve healing after primary repair of the ACL in a porcine model.[64] In this model, Murray and associates[64] performed primary ACL repair that was augmented with whole blood containing a physiologic concentration of platelets in a collagen-based scaffold. There was no significant difference in mechanical properties when the "bioenhanced" ACL repair was compared with ACL reconstruction using an allograft tendon at 3 months and 1 year after surgery. A notable finding was less cartilage degeneration at 1 year in the animals that underwent enhanced repair compared with animals that underwent ACL graft reconstruction. Further study is required to determine the optimal PRP formulation to stimulate primary healing of the ACL. In vitro and in vivo data currently suggest that the use of concentrations of platelets greater than 1X within extracellular matrix scaffolds may not be as effective at stimulating ACL healing at physiologic concentrations.[58] However, the inclusion of plasma with platelets has been found to improve ACL fibroblast collagen gene expression.[15]

PRP has also been evaluated for augmentation of ACL graft healing in animal models. Treatment of an ACL graft with a collagen-platelet composite resulted in improvement in graft tensile properties and reduced laxity in a porcine model.[23] Several studies have evaluated the use of PRP in ACL reconstruction in humans, using magnetic resonance imaging (MRI) to directly evaluate the ACL graft. In general, these clinical studies show that platelet concentrates may improve the rate at which grafts achieve low signal intensity on MRI or an improved ligament maturity index on histology[81]; however, no study showed an improvement in clinical or patient-oriented outcome at 2 years[74] or significantly improved bone-tendon healing.[22] Further study is necessary to determine the optimal platelet preparation and method of delivery in an effort to further explore the potential of PRP and blood products to improve ACL graft healing, revascularization, and incorporation.

CONCLUSION

This chapter presents the basic principles of the biology behind ACL reconstruction and reviews several potential techniques to improve graft healing. A sound understanding of the complex mechanism of tendon-to-bone healing offers new and exciting ways to manipulate

the chemical and molecular mediators of the inflammatory response and to ultimately improve on the quality of surgical and postoperative interventions.

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6

Human Movement and Anterior Cruciate Ligament Function: Anterior Cruciate Ligament Injury and Gait Mechanics

Sean F. Scanlan, Thomas P. Andriacchi

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INTRODUCTION

The anterior cruciate ligament (ACL) plays an important role in stability of the knee primarily through its passive constraint to anterior tibial translation and tibial rotation. In addition, the ACL influences the dynamic function of the knee. For example, ambulatory changes have been associated with functional adaptations after loss of ACL function and after ACL reconstruction. The nature of these functional adaptations may be considered a potential functional marker for the ability to return to vigorous activities,[3,36,37] as well as for secondary degenerative cartilage changes after ACL injury.[7]

CRITICAL POINTS Introduction

The purpose of this chapter is:

- To develop some fundamental gait analysis principles.
- To illustrate the application of gait analysis to the issues related to the evaluation and treatment of ACL injury.
- To describe the cause and implications of a change in muscle-generated moments after ACL injury.
- To describe kinematic changes at the knee during walking and the association of kinematics changes with emergence of premature osteoarthritis after ACL injury.
- To describe the influence of the adduction moment on the progression of knee OA and its implication for ACL-deficient patients with concomitant varus knee alignment and lateral ligament laxity.

Differences in the manner in which patients adapt their gait characteristics to the loss of the ACL provide a possible explanation for the variable outcome after this injury. It is likely that some patients can dynamically adapt to the loss of an ACL, whereas others will not. The large variation in treatment selection and outcome[9,10] suggests a need for better methods of assessing the clinical and functional status of the patient after ACL rupture. Diagnostic methods for identifying a torn ACL have improved substantially; however, prognostic methods for assessing the probability of successful treatment are not yet available. Even quantitative laxity measurements obtained from devices such as the KT-1000 (MEDmetric) have not been predictive of clinical outcome.[51] Thus variability in dynamic adaptations achieved through alteration in the patterns of muscle firing[1,26,48] during a particular activity provides a possible explanation for the differences in outcome of patients after ACL injury.

The variable natural history in the progression of degenerative joint disease suggests that some patients make appropriate functional adaptations for the loss of the ACL. The nature of these functional adaptations can differ substantially among patients who present with the same clinical status. Thus, the ability to identify and understand the nature and cause of changes in ambulatory function, or specifically gait characteristics, is an important consideration in the evaluation and treatment of ACL injury.

This chapter discusses fundamental gait analysis principles and illustrates the application of gait analysis to the issues related to the evaluation and treatment of ACL injury. Specific examples are provided on the interaction between the passive function of the ACL and the change in muscle-generated moments, kinematics, and

the relationship between kinematic changes and the emergence of premature osteoarthritis (OA). In addition, the influence of specific characteristics of gait in ACL-deficient patients with concomitant varus lower limb malalignment and lateral and posterolateral ligament deficiency are described.

JOINT KINETICS DURING GAIT AND THE ACL-DEFICIENT KNEE

An analysis of the kinetics (forces and moments) that act at the knee during walking provides useful insight into the functional changes associated with the ACL-deficient knee. In particular, the moments that act at the knee suggest the cause and potential effect of gait changes after ACL injury. For example, a reduction in the intersegmental moment tending to flex the knee (balanced by net quadriceps contraction) during walking was among the first changes in walking mechanics reported in the ACL-deficient knee.[11] The reduction of the net internal quadriceps moment is consistent with quadriceps muscle atrophy, which is frequently reported after ACL injury[22] and helps to explain why it is difficult to restore quadriceps strength in these knees. Thus it is useful to examine the physical meaning and relevance of the intersegmental moment at the knee during walking. This section provides a summary of the methods used to determine the joint moments, an example of how to interpret the magnitude and pattern of the flexion-extension moment at the knee in context of the function of the knee flexors and extensors during ambulation, and an example of how an analysis of the flexion-extension moment during walking can provide insight into the functional role of the ACL.

When interpreting the findings presented in this chapter, it is important to first discuss the limitations of joint kinetic and kinematic measures made with marker-based optoelectronic gait analysis. All skin-based marker systems suffer from the fact that bony landmarks are typically identified via manual palpation; ultimately what is being measured is the motion of the skin and soft tissue overlying the bone rather than the bones themselves. Errors in palpation of anatomic landmarks propagate into incorrectly defined anatomic coordinate systems and can consequently cause substantial errors in the reported kinetic and kinematic measures. Further, motion of the skin relative to the bones during movement can also result in substantial errors; therefore strategies are often employed such as the use of redundant cluster marker sets and computational postprocessing techniques to minimize error caused by skin motion artifact.[15] Other techniques that can image the bones directly, such as fluoroscopy and high-speed radiography,[52] have the potential to be more accurate at examining tibiofemoral motion, but currently cannot capture the full gait cycle during overground walking and can encumber natural motion. Because studying tibiofemoral motion and loading during unencumbered walking is critical for understanding the function of the knee joint,[6] the error associated with skin markers has been considered an acceptable compromise for many applications.[4,6,7,41] The validity of using skin markers with robust correction techniques[15] is supported by studies that show associations between gait kinematics and other physical characteristics of the joint.[4,7,42]

CRITICAL POINTS Joint Kinetics During Gait and the ACL-Injured Knee

- The magnitude and phasing of the intersegmental flexion-extension moment during walking can be used to characterize normal gait.
- The intersegmental flexion moment is balanced by a net quadriceps muscle–generated moment.
- A reduction in the maximum external flexion moment during walking is common to patients after ACL injury and has been interpreted as a tendency to reduce the net internal quadriceps moment during walking.
- A reduction in the maximum quadriceps moment during walking is consistent with quadriceps muscle atrophy after ACL injury.
- Reduction in quadriceps contraction during walking can reduce the anterior force on the tibia generated by muscle contraction because the anterior angulation of the patellar ligament insertion angle (PLIA) causes an anterior force to be applied to the tibia when the quadriceps contracts.
- The anterior component of force produced by quadriceps muscle contraction during running and stair climbing is lower than during walking because the high quadriceps forces occur at higher knee flexion angles than those occurring during walking.
- Anatomic differences in the angle of insertion of the patellar ligament with the knee at full extension can explain individual differences in the magnitude of the reduction in the net quadriceps moment during walking after ACL injury.
- A reduction in the maximum external flexion moment during walking persists after ACL reconstruction and has been associated with a more vertical orientation of the ACL graft.

Definition of Intersegmental Moment

A *moment* is a vector quantity that can be considered a rotational force (lever arm × force) in the sense that it tends to produce a rotation about a specific point. Although moments can be calculated at any point, it is useful to use the joints between adjacent limb segments to define the moments that act on the body during walking. For example, the moment acting at the knee would be the intersegmental moment between the thigh and the shank. The external moment tending to flex or extend the joint is illustrated in Figure 6-1. The intersegmental moments are typically calculated from measurement of the foot-ground reaction forces (using a force platform) and the motion of markers placed on the limbs using an optoelectronic system for motion capture. The weight and inertial forces are often approximated by modeling the leg as a collection of rigid segments representing the

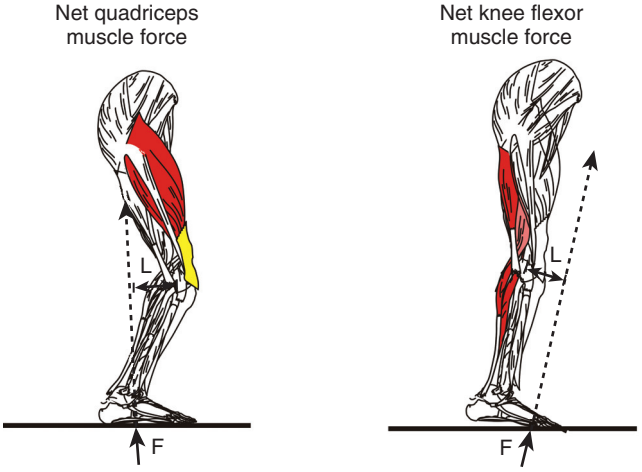


FIG 6-1 The intersegmental flexion-extension moment can be visualized by considering a ground reaction force vector that passes posterior to the knee will produce an external flexion moment that is balanced by a net internal quadriceps moment. When the vector passes anterior to the knee, an external extension moment is produced that must be balanced by a net internal flexor muscle moment. *F,* Ground reaction force; *L,* lever arm.

thigh, shank, and foot. The reader should be aware of the assumptions used in performing these calculations.[5] Finally, the units of a moment are force and length. Therefore, it is useful when comparing different-sized subjects to express the intersegmental moments in nondimensional units by dividing the moment by the subject's height (Ht) and body weight (BW). Thus moments measured during gait are often expressed in units of percentage of the product of the body weight and height (% BW × Ht), so that moments can be compared among subjects of different heights and weights.

Interpretation of Intersegmental Moment

The moment can be visualized in the context of the direction of the ground reaction vector relative to the position of the knee joint center (see Fig. 6-1). If the vector passes anterior to the knee, the moment will tend to extend the knee, whereas if the vector passes posterior to the knee, the moment will tend to flex the knee. As noted previously, the direction of the moment can be used to infer the net muscular moment. Thus an external moment tending to flex the knee will be balanced by a net quadriceps moment. Previous studies have demonstrated that the external moments measured can be interpreted in terms of the loads on muscles, passive soft tissue, and joint surfaces.[44] In addition, the joint moments have been shown to be sensitive indicators of differences between normal and abnormal function.[3,11,40]

It is useful to examine the assumptions used as the basis for the interpretation of the joint moments during function. Mechanical equilibrium dictates that external forces and moments must be balanced by internal forces and moments. Internal forces generated by muscle, passive soft tissue, and joint contact force create these internal moments. If muscles act only synergistically when balancing the external moments, one could directly infer the internal muscle force in synergistic muscle groups. For example, the total force in the quadriceps needed to balance an external moment tending to flex the knee joint could be determined.[44] However, if antagonistic muscle activity is present, the external moment reflects the net balance between agonist and antagonist muscles. The force in the synergistic muscle group would be greater under these conditions. The external moment can, however, be used to obtain a conservative estimate or lower bound on the synergist muscle force. Throughout this chapter, external moments are described from the measurements taken in the laboratory and inferences are made in terms of the net muscular moment (see Fig. 6-1).

Flexion-Extension Moment and the ACL-Deficient Knee

The normal temporal pattern of the flexion-extension moment during stance phase of walking can be interpreted in terms of the net quadriceps moment or net knee flexor muscle moment (hamstrings and/or gastrocnemius) during stance phase (Fig. 6-2). Typically, at heel strike, there is an external moment that tends to extend the knee joint, demanding a net knee flexor force. As the knee moves into mid stance, the external moment reverses its direction, demanding a net quadriceps force. As the knee passes midstance, the moment again reverses its direction, demanding net flexor muscle force. Finally, in the preswing phase, the moment tends to flex the knee, demanding a net quadriceps muscle force. As previously noted, a reduction of the net quadriceps moment relative to normal is frequently seen in ACL-deficient subjects during level walking (see Fig. 6-2). Specifically, ACL-deficient subjects walk in a manner that has been interpreted as a tendency to avoid or reduce the demand on the quadriceps muscle.[11] Although the reduction in net quadriceps moment can be interpreted as either a reduction in the quadriceps or an increase in the knee flexor muscle moment, the fact that quadriceps atrophy is a common finding after ACL injury[22] supports the conclusion of a reduction in quadriceps contraction during walking.

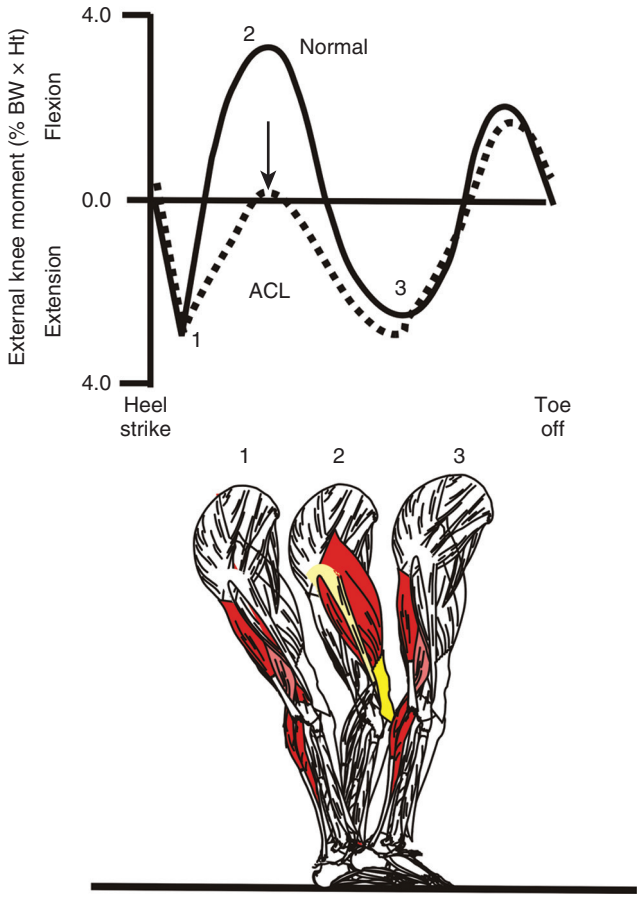


FIG 6-2 The pattern of the external flexion-extension moment during normal walking for anterior cruciate ligament (ACL)-deficient (*dashed line*) and normal (*solid line*) knees. Typically, patients with ACL-deficient knees have a reduced moment, tending to flex the knee (net quadriceps moment) during midstance. The figure of the leg indicates the position of the knee joint and the net muscular activation (*shaded area*) required to balance the external moment shown in the graph. *BW,* Body weight; *Ht,* height.

The mechanics of the knee extensor mechanism suggest a possible cause for the inhibition of quadriceps contraction during walking. As illustrated in Figure 6-3, the anterior angulation of the patellar ligament insertion angle (PLIA) causes an anterior force to be applied to the tibia when the quadriceps contracts. In the absence of the ACL, the tibia moves forward when the quadriceps contracts until the force is balanced by other secondary restraints to anterior tibial displacement, such as the medial collateral ligament, meniscus, or a hamstring contraction. Thus, more anterior tibial translation could occur in ACL-deficient knees than in uninjured knees when the quadriceps contracts. The amount of anterior force is greatest at full extension because the PLIA has the largest anterior angle at full extension and this angle reduces as the knee flexes.[18,32] Thus, walking would produce a substantial component of anterior force owing to quadriceps contraction because the knee remains near full extension throughout stance phase, with maximum flexion angles less than 30 degrees. A reduction in quadriceps contraction could eliminate large anterior tibial translations near full extension and prevent sensations of joint instability by the patient.

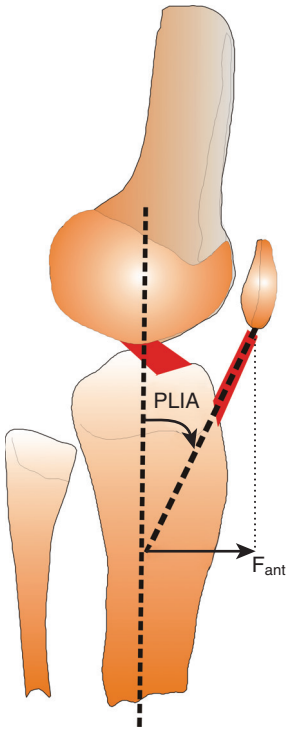


FIG 6-3 The line of action of the patellar ligament running from the posterior pole of the patella to the tibial tuberosity. The patellar ligament insertion angle *(PLIA)* is measured as the angle between the midshaft of the tibia and the line of action of the patellar ligament. With the knee in an extended position as shown, contraction of the quadriceps would transmit a relatively large anterior force *(F_{ant})* to the proximal tibia.

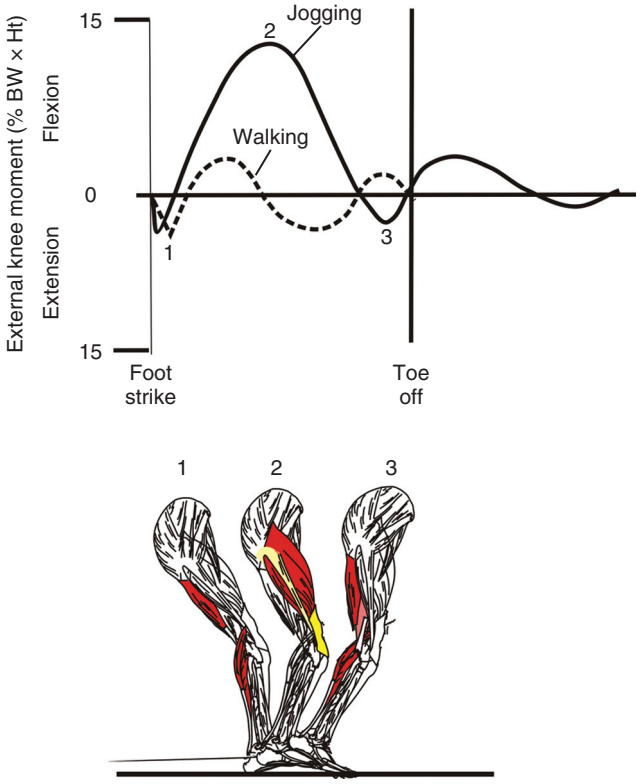


FIG 6-4 A comparison of the flexion-extension moments occurring during normal walking (*dashed line*) and jogging (*solid line*). The magnitude of the moment tending to flex the knee (net quadriceps moment) can be 5 times greater during jogging than during normal walking. *BW,* Body weight; *Ht,* height.

Interestingly, the magnitude of the net quadriceps moment can increase by more than a factor of 5 during jogging as compared with level walking (Fig. 6-4), yet the percentage change in the net quadriceps moment between ACL-deficient and normal subjects is substantially less during jogging than during walking.[11] The fact that the maximum net quadriceps moment during jogging occurs when the knee is at approximately 40 degrees of flexion, as compared with 20 degrees during level walking, might provide an explanation for the fact that patients with an ACL-deficient knee do not show a similar reduction in the net quadriceps moment during jogging compared with walking. Similarly, while ascending stairs, the maximum net quadriceps moment occurs at approximately 60 degrees of flexion and thus the amount of reduction in the net quadriceps moment is small compared with that during level walking. The adaptations during activities of daily living appear to be dependent on the angle of knee flexion when the greatest net quadriceps moment occurs. These observations suggest an interaction between the direction of pull of the patella ligament and the functional role of the ACL (Fig. 6-5). When the knee is near full extension, the patellar ligament places an anterior pull on the tibia. As the knee flexes beyond approximately 45 degrees, the orientation of the patellar ligament reverses direction during the quadriceps contraction and places a posterior pull on the tibia. At deeper flexion angles, the contraction of the quadriceps acts to compensate for an absent ACL.

Thus, during level walking, when the maximum net quadriceps moment occurs between 0 degrees and approximately 20 degrees, there is a greater tendency for the quadriceps contraction to produce an anterior pull on the tibia. The adaptation to avoid quadriceps contraction eliminates this anterior force component when the knee is near full extension (see Fig. 6-3).

Activity	Knee flexion angle	Patellar ligament orientation
	Angle at maximum quadriceps moment	AP component on tibia
Walking	20°	Anterior
Jogging	40°	Anterior
Stair climbing	60°	Posterior

FIG 6-5 The relationship between the knee flexion angle at which the maximum net quadriceps moment occurs during activities of daily living and the orientation of the patellar ligament relative to the tibia. As the knee moves from a relatively extended position (walking) to a more flexed position (stair climbing), the anteroposterior *(AP)* component of the patellar ligament shifts from an anterior orientation to a posterior orientation relative to the tibia.

Anatomy of the Extensor Mechanism and Quadriceps Inhibition

The variation in the amount of reduction in the net quadriceps moment during walking can be explained by anatomic differences in the anatomy of the extensor mechanism as defined by the PLIA (see Fig. 6-3). As noted previously, the PLIA is of particular importance to the knee extensor mechanism because it determines the decomposition of quadriceps force into anterior and superior directions (see Fig. 6-3) while transferring the quadriceps contraction to the tibia. Previous studies confirmed this relationship by showing that the patellar ligament pulls the tibia anteriorly when the knee is near full extension and also that anatomic variations exist between individuals in both PLIA and the moment arm of the patellar ligament.[18] Thus knees with larger PLIAs generate larger anterior forces on the tibia with the same level of quadriceps contraction.

More importantly, it has been shown that the PLIA negatively correlates to the peak knee flexion moment (balanced by net quadriceps moment) during walking in ACL-deficient knees,[49] whereas no correlation exists in uninjured contralateral knees of ACL-deficient patients (Fig. 6-6). The negative correlation between PLIA and the peak external knee flexion moment indicates that ACL-deficient knees with higher PLIAs significantly reduce usage of the quadriceps during walking. These results suggest that the subject-specific anatomy of the knee extensor mechanism provides a possible explanation for the variability[16] previously observed in adaptation of a quadriceps reduction strategy after ACL injury. This mechanism may explain the reduction in the external knee flexion moment, which is balanced by net quadriceps force, among ACL-deficient knees. This mechanism is further supported by the clinical observation of quadriceps atrophy in ACL-deficient subjects,[22] because reduced use of the quadriceps during walking should lead to muscle atrophy. However, the variability between individuals' adaptations to ACL injury suggests that other factors, such as PLIA, may influence which subjects adopt a strategy of quadriceps reduction.[14,36]

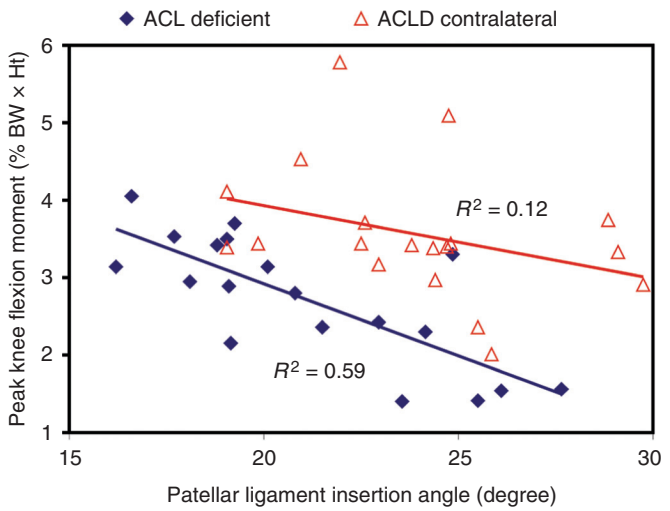


FIG 6-6 Anterior cruciate ligament (ACL)-deficient knees show a significant negative correlation between peak external knee flexion moment (net quadriceps moment) and patellar ligament insertion angle during normal walking. However, uninjured contralateral knees do not show a significant correlation. *ACLD,* Anterior cruciate ligament deficient; *BW,* body weight; *Ht,* height.

Flexion-Extension Moment and the ACL-Reconstructed Knee

Surgical reconstruction of the ACL has become well established as the standard of care for the ACL-injured knee. Given the primary function of the ACL as the passive restraint to anterior tibial translation, ACL reconstruction has been traditionally assessed based on its ability to restore anterior knee stability on static laxity tests and ultimately on its ability to return patients to high-performance activities.[8,47] However, considering the functional changes that commonly occur after ACL injury, it is important to also evaluate the surgical procedure based on its ability to successfully restore the salient features of normal ambulatory knee mechanics. As discussed previously, the knee flexion moment during walking (balanced by an internal quadriceps moment) represents a sensitive measure of joint function as it has been demonstrated to provide important insight into joint anatomy (i.e., PLIA), neuromuscular function, and dynamic tibiofemoral stability after ACL injury.[4,11,31] ACL reconstruction thus presents a unique subject population to reexamine this interaction among ACL anatomy, the knee extensor mechanism, and the adaptation of the net quadriceps moment during walking.

Differing from the ACL-deficient knee, the variation in the amount of reduction in the net quadriceps moment during walking in the ACL reconstructed knee was not related to differences in the anatomy of the extensor mechanism as defined by the PLIA.[50] The lack of relationship indicates that ACL-reconstructed knees with higher PLIAs do not significantly reduce usage of the quadriceps during walking. This finding agrees with the static laxity testing and suggests that the ACL reconstruction has restored the restraint to anterior translation because subjects no longer adapt their gait to reduce quadriceps usage in proportion to the anterior pull of the tibia through the patellar ligament. However, it has been shown that the magnitude of the knee flexion moment still remained significantly reduced in the ACL-reconstructed knees relative to the contralateral, though the reduction was no longer associated with the PLIA.[50] This indicates that there are other factors associated with the ACL reconstructed knee that prevent the full restoration of the quadriceps function during ambulation.

Although the PLIA was no longer directly related to the knee flexion moment, it is important to examine other structural factors in the ACL reconstructed knee that can have a significant influence on knee joint stability. Specifically, in vitro biomechanical investigations have demonstrated that postoperative tibiofemoral stability is sensitive to the 3-dimensional obliquity of the ACL graft.[27,45] Grafts that are placed with more vertical orientation relative to the orientation of the native ACL, particularly in the coronal plane, have reduced ability to resist the complex 3-dimensional loads that occur during dynamic activities such as walking. Thus, when the variability in knee flexion moment during walking after ACL reconstruction was investigated relative to the coronal obliquity of the single-bundle ACL graft in 17 subjects, a statistically significant relationship was observed (Fig. 6-7).[41] The relationship indicated that reconstructed knees with more vertical coronal graft orientation (less anatomic) were associated with a greater reduction in the knee flexion moment (balanced by internal quadriceps moment) during walking (1.0 m/s, $r = -0.866$, $P < .001$; 1.3 m/s, $r = -0.657$, $P = .004$). This finding suggests that as the ACL graft is placed in a more vertical coronal orientation, the capacity of the reconstruction to replicate the function of the native ACL is diminished, and the patient subconsciously adapts his or her gait to avoid joint instability in a manner consistent with complete ACL deficiency. Complete restoration of the 3-dimensional anatomy and function of the ACL during the ACL reconstruction procedure plays a critical role in the

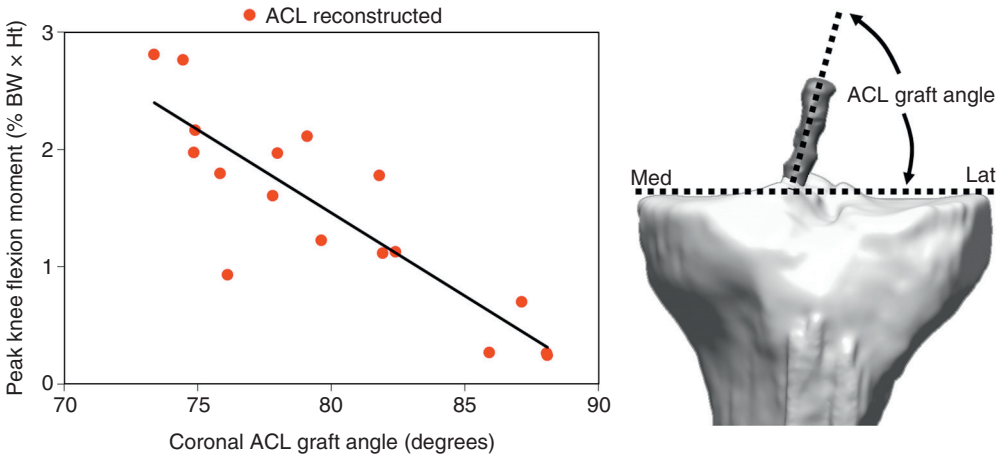


FIG 6-7 Anterior cruciate ligament *(ACL)*-reconstructed knees show a significant negative correlation between peak external knee flexion moment (net quadriceps moment) and coronal ACL graft angle during walking. ACL-reconstructed knees with a more vertical coronal orientation of the graft had a greater reduction in the peak external knee flexion moment. *BW,* Body weight; *Ht,* height.

return of normal ambulatory mechanics in the ACL-reconstructed knee.

KNEE KINEMATICS DURING WALKING AND ACL INJURY

The anatomy of the ACL suggests its potential role in determining the motion (kinematics) of the knee during ambulation. Clearly, passive function of the ACL for guiding motion and stabilizing the knee has been well documented. However, the analysis of the functional role of the ACL during dynamic in vivo ambulatory activities is more complex than for passive movements. The force generated by the ACL during passive stretch is relatively small compared with the magnitude of the muscle forces and extrinsic forces (load bearing) that occur during ambulation. Further, the ability to capture the movement of the knee under conditions that reflect natural movement remains a challenge. The kinematic role of the ACL during functional activities has been described for several weight-bearing activities.[4,17,25,52] The knee kinematics presented in this chapter focus primarily on walking. The kinematics of walking can provide valuable insights into the functional role of the ACL during locomotion.[6] Functional adaptation to the loss of the ACL can be detected during walking, because it has been suggested that patients can adapt patterns of locomotion that compensate for the loss of the ACL. In addition, walking is the most frequent ambulatory activity of daily living, and specific characteristics of this activity have been associated with cartilage thinning.[7,34] ACL rupture, regardless of whether it is reconstructed or not, has been identified as a significant risk factor for premature knee OA. This chapter focuses on the internal-external (IE) rotation and anteroposterior (AP) translation that occur at the knee during walking. These secondary movements (IE, AP) of the knee are directly related to the function of the ACL and have been shown to be altered in patients with ACL-deficient and ACL-reconstructed knees during walking for the reasons described previously.

Methods for Defining and Measuring Knee Kinematics During Walking

The kinematics of human movement during walking is normally described in terms of relative motion between adjacent limb segments (Fig. 6-8). In practice, human gait is most often described in terms of the sagittal plane motion (flexion-extension). This practice has come as a consequence of the much larger motions in this plane, making these motions relatively easy to measure and perhaps most relevant to function. However, the motion at the knee is more complex than other major joints of the lower extremity, involving all six degrees of freedom (three rotations and three translations). The complexity of the kinematic analysis substantially increases when going from a sagittal plane analysis to a complete 3-dimensional analysis. The appropriate interpretation of in vivo kinematic measurements requires a precise and physically meaningful definition of anatomic references. For the

CRITICAL POINTS Knee Kinematics During Walking and ACL Injury

- The motion (kinematics) of the knee is complex, and normal motion requires critical secondary movements of AP and IE rotation.
- The characteristics of the AP translation and IE rotation during walking provide a useful basis for understanding the pathomechanics of kinematic changes associated with the loss of the ACL.
- The swing phase of repetitive activities such as walking can provide useful insight into the functional role of the ACL because the passive force capacity of the ACL can have a substantial influence on the knee motion during non–weight-bearing, whereas extrinsic forces and muscle forces dominate knee motion during the stance phase.
- The tibia translates forward and externally rotates as it extends during the terminal portion of swing phase in preparation for heel-strike positioning the tibia at an anterior position and in external rotation at heel strike.
- The normal external rotation and anterior translation of the tibia that occur as the knee extends during terminal swing is reduced in the absence of the ACL, and the tibia maintains this offset relative to normal throughout the stance phase of the walking cycle.
- Following ACL reconstruction, alterations in rotational motion of the knee remain, with the tibia tending to be more externally rotated throughout the stance phase of the walking cycle.
- The kinematic changes at the knee after ACL injury have been implicated as a factor in the cause of premature OA by shifting joint contact to regions in the cartilage that cannot adapt to the changes in the repetitive loads that occur during walking.

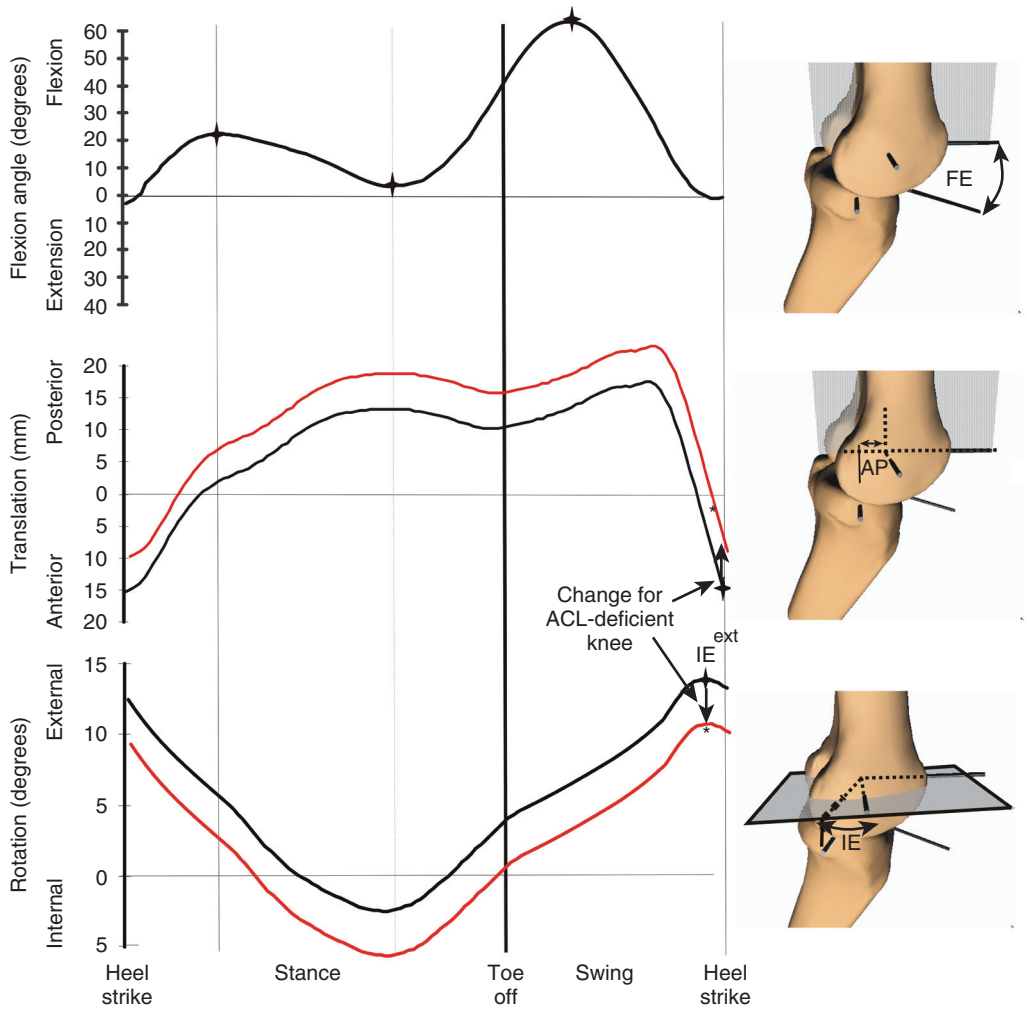


FIG 6-8 The flexion-extension, anterior-posterior, and internal-external motions of the knee that occur during normal walking (expressed as the position of the tibia relative to the femur) for normal (*black line*) and anterior cruciate ligament *(ACL)*-deficient (*red line*) knees. The kinematic changes in the ACL-deficient knee are characterized by a posterior translation offset and an internal rotation offset.

kinematics described in this chapter, the anatomic femoral coordinate system was located at the midpoint of the transepicondylar line of the distal femur, and the anatomic tibial coordinate system was set at the midpoint of a line connecting the medial and the lateral points of the tibial plateau. The AP translation was determined by calculating the displacement between the origins of the tibial coordinate system relative to a femoral coordinate system projected onto the AP axis of the tibia (see Fig. 6-8). IE rotations were measured by projecting the mediolateral femoral axis onto a plane created by the AP and mediolateral axes fixed in the tibia. Additional details of defining the system used in this chapter can be found in Andriacchi and Dyrby,[4] Andriacchi and coworkers,[5] and Dyrby and Andriacchi.[15]

Anterior-Posterior Translation and Internal-External Rotation of the Knee During Normal Walking

The flexion-extension motion of the knee is the primary motion of the joint because this movement is required for most ambulatory activities. However, AP translation and IE rotation are important secondary movements of the knee because these movements can influence the moment-generating capacity of the muscles,[2] as well as the movement of the position of the tibiofemoral contact, all important for normal function. The AP translation and IE rotation of knee have been previously described for normal walking based on the coordinate system.[4,15]

The characteristics of AP translation and IE rotation (see Fig. 6-8) provide a useful basis for understanding the pathomechanics of kinematic changes associated with the loss of the ACL. During normal walking, the tibia is in an anterior position at heel strike that is the result of anterior tibial translation during the terminal portion of swing phase (see Fig. 6-8). During the major portion of stance phase, the tibia translates to a posterior direction. Finally, during the later portion of swing phase, the tibia moves in an anterior direction relative to the femur, reaching a maximum anterior position at or just before heel strike. In addition, at heel strike, the tibia is externally rotated and internally rotates through the major portion of stance phase. The tibia begins to externally rotate during swing phase as the knee extends before heel strike and reaches a maximum external rotation at or just before heel strike. The motion of the tibia during the terminal portion of swing phase reflects the natural screw-home motion[19] of the knee in which the tibia externally rotates as the knee extends. This natural screw-home movement occurs during the non–weight-bearing portion of the gait cycle in which the passive structure and joint surface drive the movement of the knee. As previously noted, during the

weight-bearing stance phase of the walking cycle, the kinematics are driven by the extrinsic forces that act at the knee rather than the internal passive structures such as the ligaments. Thus, the swing phase of repetitive activities such as walking can provide useful insight into the functional role of the ACL because the passive force capacity can have a substantial influence on the knee motion during non–weight-bearing activities.

Kinematic Changes After Anterior Cruciate Ligament Injury

Kinematic changes at the knee during ambulation have been reported for patients with ACL-deficient knees.[4,17] In particular, the normal external rotation and anterior translation of the tibia that occur as the knee extends during terminal swing are reduced in the absence of the ACL. The tibia maintains this offset relative to normal throughout the stance phase of the walking cycle. These observations indicate that the ACL plays a critical role in the positioning of the knee at the end of swing phase[4] in preparation for heel strike during walking (see Fig. 6-8), suggesting a loss of the normal screw-home movement.[19] The loss of the screw-home movement at the end of swing phase produces an offset toward internal rotation in the average position of the tibia relative to the healthy knee that is maintained through stance phase. The reduced anterior displacement of the ACL-deficient knee at heel strike also appears to be related to modified kinematics during terminal swing phase. Thus, the transition between swing phase and stance is an important consideration in evaluating the ACL-deficient knee.[12,30]

ACL injury is associated with premature OA of the knee.[21-23,35] Numerous pathogenic factors have been associated with the initiation of OA in the ACL-injured knee, including meniscectomy, severe bone marrow edema, articular cartilage injury, lower limb malalignment, and associated injuries to other knee ligaments.[24,28,31,38,39] The kinematic changes at the knee after ACL injury have been implicated as a factor in the cause of premature OA in this population.[7] A shift in the rotational alignment near heel strike can shift the load-bearing contact to regions in the cartilage that have not adapted to the high loads occurring at heel strike. Typically, the thickest regions of the femoral and tibial load-bearing articular cartilage are aligned when the knee is at full extension.

The change in the rotational characteristics at the knee could cause specific regions of the cartilage to be loaded that were not loaded before the ACL injury. It has been suggested that the altered contact mechanics in the newly loaded regions could produce local degenerative changes to the articular cartilage.[13,56] As previously reported, cartilage in highly loaded areas is mechanically adapted relative to underused areas where signs of fibrillation can be observed in healthy knees in relatively young subjects.[13,54] Thus a spatial shift in the contact region could place loads on a region of cartilage that may not adapt to the rapidly increased load initiating degenerative changes.[55]

Kinematics of the Anterior Cruciate Ligament-Reconstructed Knee

Kinematic alterations at the knee have also been reported for patients who undergo ACL reconstruction during walking and other dynamic activities.[42,52,53] In particular, the tibia tends to be more externally rotated in the ACL-reconstructed knee, differing from the shift toward internal rotation in the ACL-deficient knee. In the ACL-reconstructed knee, the tibia maintains the external rotation offset (mean, 2.3 degrees; 95% CI, 1.0-3.7 degrees) relative to normal throughout the stance phase of the walking cycle (Fig. 6-9).[42] These observations further support the assertion that the ACL plays a critical role in guiding the secondary motions of the knee and that conventional ACL reconstruction is not effective in replicating the complex anatomy and function of the native ligament. This is consistent with previously reported in vitro biomechanical studies that have demonstrated that conventional ACL reconstruction techniques often place grafts in a nonanatomic orientation that cannot replicate the rotary stability provided by the native ACL.[27,45]

Interestingly, reconstruction of the ACL has not been shown to reduce the increased incidence of premature knee OA following ACL injury.[29,33] Based on the kinematic findings and natural history of the ACL-deficient knee, many researchers have also implicated altered tibiofemoral kinematics as a precipitating factor in the degenerative process in the ACL-reconstructed knee.[6,7,20,42,43] In a similar manner, the shift in the rotational alignment of the ACL-reconstructed knee during walking would also shift the load bearing to regions of the tibiofemoral cartilage that cannot adapt to the high loads experienced during ambulation. Although the shift in contact caused by the change in rotational position may appear to be relatively small at first, it represents a fairly substantial change when considering the overall range of rotational motion that normally occurs during walking (~10 degrees).[42] It is hypothesized that, when combined with the chronic repetitive nature of walking, the cumulative effect over time of even a minor kinematic change could ultimately play an important role in the early onset of OA in this population. Taken together, these studies further support the importance of assessing the success of new ACL reconstruction techniques based on their ability to replicate the normal 3-dimensional joint anatomy, restore ambulatory mechanics, and prevent long-term degenerative changes.

THE ADDUCTION MOMENT AT THE KNEE AND ANTERIOR CRUCIATE LIGAMENT INJURY

The external adduction moment during walking is a result of the line of action of the ground reaction force passing medial to the center of the knee (Fig. 6-10). The offset or lever arm of this force causes a moment that tends to adduct the knee during walking (Fig. 6-11). The adduction moment will influence the relative distribution of load (see Fig. 6-10) between the medial and the lateral compartments of the knee,[44] causing a higher force on the medial compartment relative to the lateral compartment. The adduction moment has become an ambulatory biomechanical marker for risk of progression of medial compartment OA at the knee.[7,34] In general, patients with a higher adduction moment have worse treatment outcome after high tibial osteotomy,[40] more severe disease,[46] and a higher rate of progression of OA.[34]

Adduction Moment and Osteoarthritis at the Knee

The adduction moment during walking can be an important consideration in patients with ACL-deficient knees because OA in this group occurs most frequently in the medial compartment. It has been shown that patients with a varus angulation at the knee and ACL injury introduce additional problems that should be considered when making treatment decisions.[38] Varus angulation in conjunction with clinical indication of medial compartment OA, cartilage damage, or loss of medial meniscus function is a potential indication for high tibial osteotomy. Gait analysis can provide useful insight into those patients who are at greater risk for medial compartment OA.

The adduction moment during walking makes the knee vulnerable to lateral joint opening in the absence of stabilizing muscle forces. As illustrated in Figure 6-12, muscle contraction can dynamically stabilize the knee to resist a varus thrust and can compensate for lateral joint laxity. Therefore, there is a potential interaction between the reduced

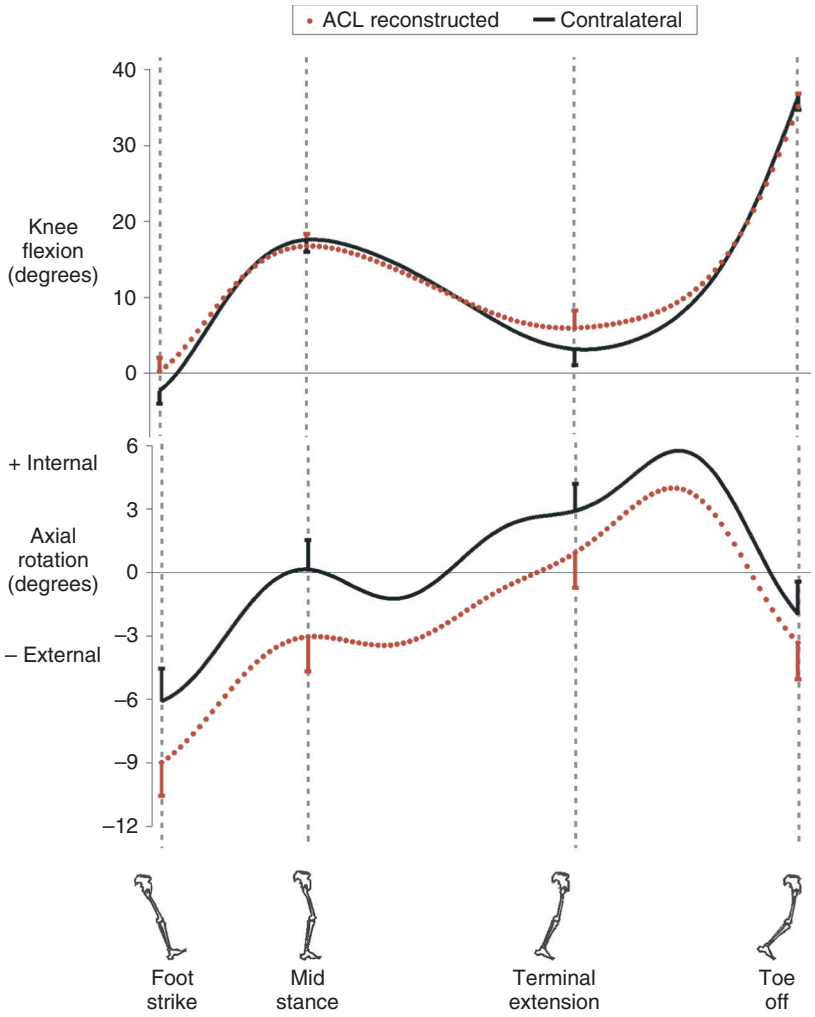


FIG 6-9 The flexion-extension *(FE)* and internal-external *(IE)* motions of the knee that occur during normal walking (expressed as the position of the tibia relative to the femur) for normal (*black line*) and anterior cruciate ligament *(ACL)*-reconstructed (*red line*) knees. The kinematic alterations in the ACL-reconstructed knee are characterized by an internal rotation offset. *AP*, Anterior-posterior.

CRITICAL POINTS **Adduction Moment at the Knee and ACL Injury**

- The external adduction moment during walking causes higher force on the medial compartment relative to the lateral compartment of the knee.
- The adduction moment has become an ambulatory biomechanical marker for risk of progression of medial compartment OA at the knee.
- The adduction moment is an important consideration in patients with ACL-deficient knees because OA in this group occurs most frequently in the medial compartment.
- In ACL-deficient patients with lateral joint laxity, a high adduction moment during walking makes the knee vulnerable to lateral joint opening in the absence of stabilizing muscle forces and can cause the entire force across the knee to be transmitted to the medial compartment.
- Varus angulation in conjunction with clinical indication of medial compartment OA, cartilage damage, or loss of medial meniscus function and a high adduction moment during walking is a potential indication for a high tibial osteotomy in patients with ACL-deficient knees.

quadriceps contraction, a high adduction moment, and lateral laxity[38] because a high adduction moment can produce a tendency to open the joint laterally in the absence of the stabilizing forces of muscle contraction (see Fig. 6-11). Based on the mechanics of walking, lateral laxity presents an additional risk in the presence of a varus malaligned knee, a high adduction moment, and reduced quadriceps activity because this combination of conditions can cause the entire force across the knee to be transmitted to the medial compartment. This combination of conditions places the medial compartment of the joint at greater risk for breakdown and should be considered in the overall clinical evaluation of patients with ACL injury.

SUMMARY

The ambulatory characteristics of patients after ACL injury provide unique insight into the functional role of the ACL and provide information that can be helpful in treatment evaluation and planning. The nature and cause of the reduction of quadriceps muscle strength after ACL injury can be explained in part by the reduction of the moment sustained by the quadriceps during walking. The anatomy of the PLIA and the fact that quadriceps contraction creates the greatest anterior pull on the tibia when the knee is near full extension (as during

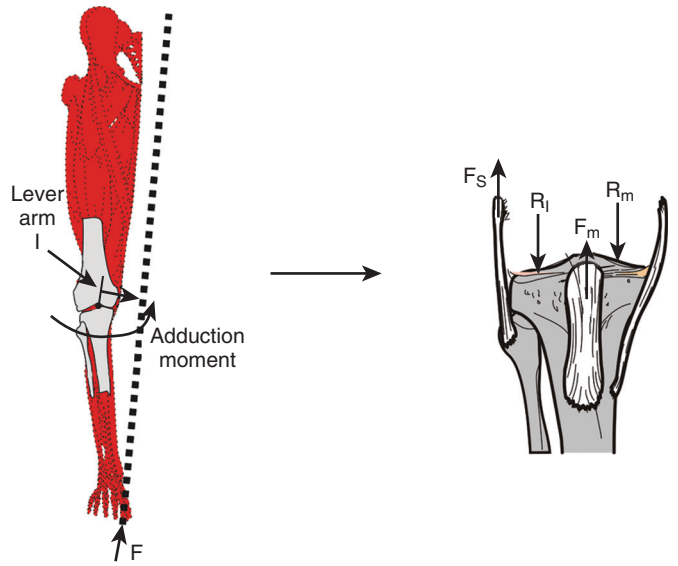
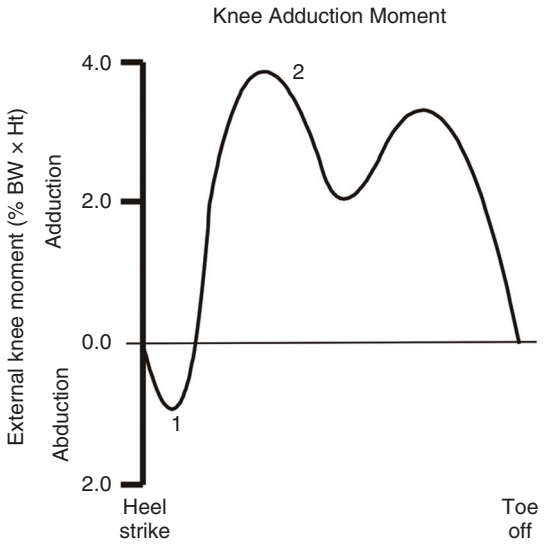


FIG 6-10 An external knee adduction moment occurs during walking when the ground reaction force vector passes medial to the knee joint center in the frontal plane. The adduction moment will influence the relative distribution of load between the medial and the lateral compartments of the knee, with a high adduction moment resulting in a greater compressive load passing through the medial compartment relative to the lateral compartment. *F,* Ground reaction force; F_s, force in lateral soft tissues; F_m, muscles (quadriceps) force; R_l, lateral joint reaction force; R_m, medial joint reaction force.

CRITICAL POINTS Summary

- Gait characteristics of patients after ACL injury provide unique insight into the functional role of the ACL and provide information that can be helpful in treatment evaluation and planning.
- The reduction of quadriceps muscle strength after ACL injury can be explained in part by the reduction of the moment sustained by the quadriceps during walking.
- The anatomy of the patellar insertion angle provides a functional explanation for quadriceps reduction during level walking.
- Kinematic changes have been implicated in the premature OA frequently reported in patients after ACL injury.
- Gait mechanics can provide insight into the treatment of the varus-aligned knee with ACL injury.



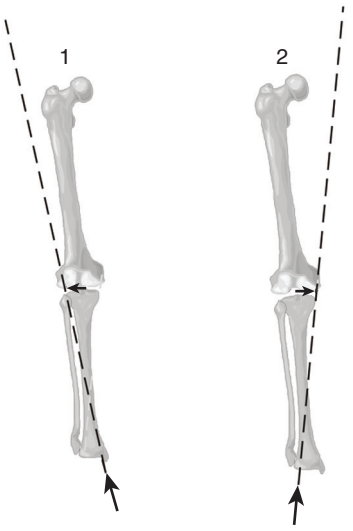


FIG 6-11 The pattern of the external adduction-abduction moment during normal walking. Typically, an abduction moment occurs just after heel strike, and then an adduction moment is maintained throughout the rest of stance phase. The figure of the legs indicates the line of action of the ground reaction force vector relative to the frontal plane position of the knee joint. An external abduction moment is produced when the ground reaction force vector passes lateral to the knee joint center, and an adduction moment is produced when the vector passes medial to the knee joint center. *1,* Peak abduction moment (just after heel strike); *2,* peak adduction moment (mid stance).

walking) provide a functional explanation for quadriceps reduction during level walking. Because the knee is more flexed during activities such as stair climbing or jogging, the PLIA has less anterior pull and there is a reduced need to adapt a pattern of movement to reduce quadriceps contraction unless there is secondary quadriceps weakness and the adaptation is to a weak quadriceps.

The kinematic changes at the knee during walking after ACL injury suggest that the ACL provides an important role in positioning the knee during the swing phase of walking. In particular, patients with ACL injury or ACL reconstruction demonstrate a rotational offset in the position of the tibia that is maintained during the stance phase of walking. It is hypothesized that this rotational offset could play a role in the premature OA frequently reported in patients after ACL injury. The rotational offset can cause a shift in the position of the articular cartilage contact between the femur and the tibia, and it has been suggested that the cartilage cannot adapt to this change in the local mechanical environment, causing the initiation of a degenerative process leading to OA.

Gait mechanics can also provide insight into the treatment of the varus malaligned knee with ACL injury. A high adduction moment during walking in patients with ACL deficiency and varus malaligned knees has been suggested as a consideration for high tibial osteotomy when symptoms of cartilage degradation are present.

Finally, this chapter has discussed how an analysis of ambulatory mechanics can provide insight into the pathomechanics of knee OA after ACL injury that cannot be obtained from other methods. Restoration of function and prevention of long-term comorbidities, such as OA and meniscus degeneration, are among the primary goals of

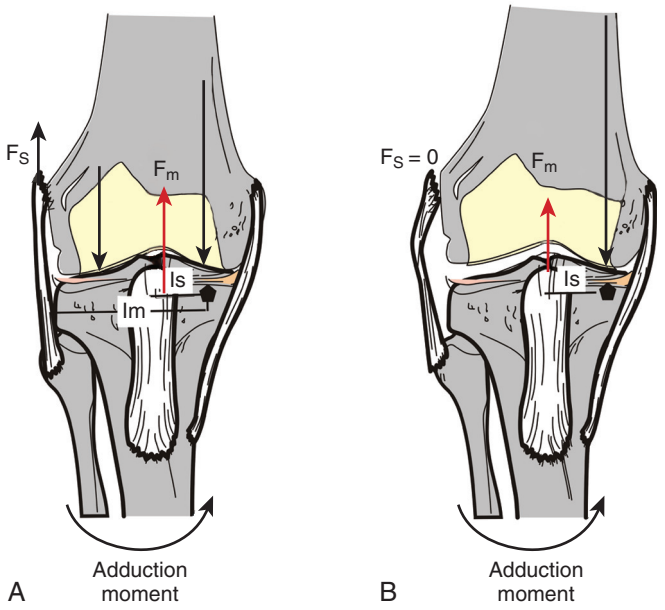


FIG 6-12 **A,** Muscle contraction (F_m) acting through the lever arm (lm) and competent lateral soft tissue structures (F_s) acting through the lever arm (ls) are capable of dynamically stabilizing the knee joint in the presence of a large moment, tending to adduct the knee (such as occurs during walking in the varus malaligned knee). **B,** However, the combination of weak extensor muscles and lateral joint laxity (Fs = 0) in the anterior cruciate ligament–deficient knee can be potentially insufficient to resist a large adduction moment, resulting in opening of the lateral compartment and a concentration of the load across the medial compartment of the knee.

treatment. Thus quantitative analysis of function should be considered in the evaluation of new treatment modalities.

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7

Anterior Cruciate Ligament Primary Reconstruction: Diagnosis, Operative Techniques, and Clinical Outcomes

Frank R. Noyes, Sue D. Barber-Westin

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CRITICAL POINTS Indications

- Complete ACL rupture: >5 mm of increased anterior tibial translation, positive pivot shift test.
- Profile patient for desired future activity level.
- High-risk activities (pivoting, cutting, twisting, and turning): reconstruct.
- Acute ACL rupture and concomitant displaced bucket-handle meniscus tear: surgery within 2 to 3 weeks to repair meniscus, usually concurrent ACL reconstruction.
- Low-risk activities, willing to avoid strenuous activities that place the knee at increased risk for giving-way episodes: conservative treatment.
- Successful ACL reconstruction reduces risk of subsequent injuries.
- Partial ACL tears: <50% fibers torn: conservative treatment; >50% torn in athlete: consider graft augmentation.

INDICATIONS

Patients presenting with acute complete ruptures of the anterior cruciate ligament (ACL) (>5 mm of increased anterior tibial translation and positive pivot shift test) are treated with rehabilitation until pain and swelling subside and joint motion and muscle function are restored. This delay markedly reduces the incidence of postoperative complications of knee motion limitations and muscle weakness. All patients with acute ruptures are profiled with regard to their desired future activity level to determine whether ACL reconstruction is warranted.[212] Those who are highly motivated to return to high-risk activities, including strenuous athletics or occupations involving pivoting, cutting, twisting, and turning, are considered for reconstruction.[64] In patients with acute ACL ruptures and a concomitant displaced bucket-handle meniscus tear, surgery within 7 to 10 days is required to reduce the meniscus to a normal location and repair the tear. The ACL reconstruction may be performed at the same setting; however, knees with excessive swelling and pain undergo a staged meniscus repair first. After an appropriate period of rehabilitation, ACL reconstruction is then performed.

Patients involved in low-risk activities or who are willing to avoid strenuous athletic and occupational activities that place the knee at increased risk for giving-way episodes may not require ACL reconstruction. These patients are placed into a conservative treatment program that includes rehabilitation to regain muscle strength and neuromuscular function and counseling on the risk of future giving-way reinjuries and potential damage to the joint. Even with surgical reconstruction, patients are informed that an ACL rupture is a serious injury and it is unlikely that they will ever have a truly normal knee joint. The injury may also involve a bone bruise and chondral damage, with sequelae for future joint symptoms. The goal of conservative management is to prevent recurrent giving-way reinjuries that are deleterious to the joint because they frequently result in meniscus tears and subsequent meniscectomy. It is important to categorize the knee joint regarding the extent of the injury that occurred. Repairable meniscus tears almost always indicate a concurrent ACL reconstruction. Otherwise, the success of the meniscus repair may be compromised.[52,181,246] DeHaven and coworkers[52] documented higher failure rates of meniscus repairs in knees with ACL deficiency than in knees with normal ACL function (46% and 5%, respectively) in a 10-year follow-up study. A grade III pivot shift and grossly positive Lachman test results (increased ≥10 mm anterior tibial translation) indicate involvement of the secondary ligamentous restraints and, in our experience, an increased risk of giving-way reinjuries with recreational activities. Patients with physiologic laxity of other ligaments or partial tears (second-degree) of medial or lateral ligaments frequently have a grossly positive pivot shift, as discussed in Chapter 3.

The rationale for the indications for ACL reconstruction is based on a study of 103 patients with chronic ACL ruptures.[214] These knees had no other ligament injuries and had not undergone reconstruction. The patients were evaluated for a mean of 5.5 years after the initial knee injury; a subgroup of 39 patients presented an average of 11 years postinjury. This study was not a natural history study, because all patients sought treatment because of symptoms. After the initial injury, 82% of the patients returned to sports activities, which gave an initial false impression of the seriousness of the ACL disruption. After 5 years only 35% were continuing athletics, often with recurrent symptoms of pain or swelling. A significant reinjury occurred in 36 patients within 6 months and in 53 patients within the first year following the initial injury. Moderate to severe symptoms of pain, swelling, and/or giving-way were reported in 32 patients during walking, in 45 patients during activities of daily living, and in 73 patients during turning or twisting athletic activities. Giving-way occurred in 22 patients during walking, in 34 patients during recreational sports, and in 66 patients during strenuous sports. Patients who had undergone meniscectomy had a twofold to fourfold increase in pain and swelling symptoms. Radiographic findings lagged behind clinical symptoms. Forty-four percent of patients in the subgroup 11 years from injury had moderate to severe arthritic changes. The "ring" sign was noted, which represents an osteophyte (Fig. 7-1) that forms around the circumference of the lateral tibial plateau. This is associated with an absence of a pivot shift phenomena because the lateral femoral condyle translation is restrained by the osteophytes and increased concavity of the lateral tibial plateau.

In a follow-up study, 84 of the initial 103 patients underwent a repeat evaluation 3 years after initiating a conservative and activity modification treatment program.[212] The frequently quoted "rule of thirds" represents the outcome of this study regarding the effects of an ACL injury on subsequent functional activities. Approximately one third of the patients showed improvement in symptoms and functional limitations with daily or recreational activities, one third did not improve, and one third became worse with continuing symptoms and limitations. Thirty percent of the patients (labeled "knee abusers") were noncompliant with the activity modification recommendations and stated they would continue athletics despite symptoms and the increased risk for future arthritis. These patients had the poorest overall prognosis with conservative management. This general rule of

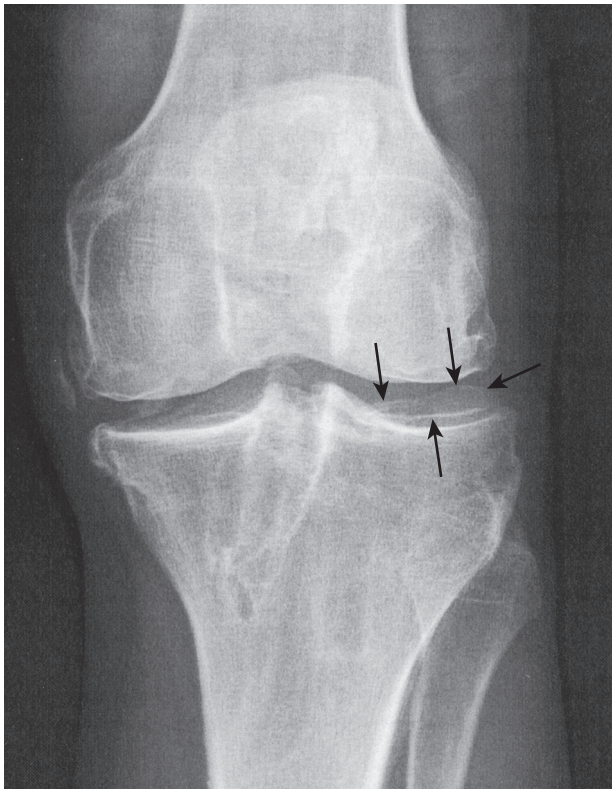


FIG 7-1 The "ring" sign (*arrows*) represents an osteophyte that forms around the circumference of the lateral tibial plateau with degenerative arthritis and meniscectomy, which commonly reduces the pivot shift phenomena caused by increased plateau concavity that limits anteroposterior (AP) translation.

thirds may not always be specific to individual patients with chronic ACL insufficiency because it does not take into account the presence of meniscus and arthritis grading, compliance with activity modification, and maintenance of a muscle strengthening program. The frequency of giving-way episodes correlated with chronic pain, swelling, and functional limitations. The conclusion was reached that any giving-way episode with athletics, even if followed by periods of no giving-way or other symptoms, was to be absolutely avoided because meniscus tears and joint deterioration may occur. The results of this program show the importance of counseling the patient on the possible expected levels of athletic activity and following closely those who do not initially choose to have surgery to lessen the chance of significant arthritis in future years.

Recent systematic reviews have demonstrated that ACL reconstruction reduces the incidence of subsequent meniscus injuries, reduces the need for further operations, and results in greater improvements in activity levels.[40] In patients who undergo reconstruction and in whom the menisci are retained, there is a lower incidence of knee osteoarthritis (OA).[42,154] Mather and associates[170] reported that, in the short term, ACL reconstruction was less costly (cost reduction of $4503) and more effective compared with rehabilitation. In the long term, the mean lifetime cost to society for a patient undergoing ACL reconstruction was calculated to be $38,121 compared with $88,538 for nonoperative treatment with rehabilitation.

Partial ACL tears occur more frequently than suspected and present in a manner similar to complete ACL ruptures. These injuries frequently occur from a noncontact giving-way episode during jumping or pivoting and are often accompanied by a popping sensation and acute hemarthrosis. There is a limitation of full extension with pain on even gentle attempts to passively achieve 0 degrees, mimicking a torn displaced meniscus, which requires magnetic resonance imaging (MRI) to exclude a mechanical block to knee extension. In a study reported by the senior author (F.R.N.) and associates,[213] of 32 knees with a partial ACL tear verified arthroscopically, a tear to one or both menisci occurred in 53% of the knees. In an average of 67 months postinjury (range, 24-110 months), 38% had progressed to complete ACL deficiency. The arthroscopic evaluation of the extent of ACL disruption was related to the prognosis and progression to complete ACL deficiency. Even though the arthroscopic evaluation does not define the true extent of ligament injury on a microscopic or functional basis,[207] 86% of knees in which three fourths of the ACL was torn progressed to ACL deficiency. One half of the knees with an estimated injury involving half of the ligament progressed to ACL deficiency, even though major portions of the ACL were still intact, preventing a pivot shift phenomena. Only 12% of knees that had an estimated one fourth or less of the ligament torn progressed to complete ACL deficiency; therefore these knees had a reasonably good prognosis for return to athletics.

Messner and Maletius[175] followed 22 consecutive patients with partial ACL ruptures (no more than 50% of the ACL fibers torn) a mean of 12 years postinjury; all but one were also reexamined for a mean of 20 years postinjury. No patient required ACL reconstruction. Patients decreased their level of activity from contact sports to recreational activities. Few had an increase in anterior translation or improvement in the pivot shift test, and few differences were noted in symptoms between follow-up evaluations.

Based on these data, the following rules apply for the management of partial ACL tears. Knees with tears of 50% or less of the ACL fibers are not candidates for reconstructive surgery. The patients are advised that they need to be followed yearly. The chance for progression to complete ACL deficiency in the more than 50% tear group is at least one in two knees. In the athletic individual, a hamstring graft augmentation is a consideration (made on a case-by-case basis) to provide stability and retain the remaining function of the ACL. In the more sedentary patient who may wish to choose a nonoperative treatment of a complete ACL rupture, a reconstruction is not warranted.

CONTRAINDICATIONS

Patients who are sedentary and do not experience giving-way or swelling episodes with daily activities and have little exposure to strenuous or high-risk activities are treated conservatively. These patients are advised to maintain an ideal body weight and have periodic knee examinations. In addition, patients who are willing to modify their activity level to avoid high-risk knee motions such as pivoting and cutting are placed in a conservative treatment program. Patients who are unable to participate or be compliant with postoperative rehabilitation are not surgical candidates.

The presence of symptomatic patellofemoral or tibiofemoral arthritis is a general contraindication to ACL surgery because pain symptoms remain postoperatively. Although pain symptoms may be lessened by restoring knee stability, the joint damage will still limit daily activities. Weight-bearing 45-degree posteroanterior (PA) views are important to determine the millimeters of remaining medial or lateral tibiofemoral joint space. In chronic ACL injuries, patients are frequently surprised to learn that the joint space is absent or nearly absent, because their symptoms have not yet limited daily activities. In these knees, conservative measures are instituted until such time that partial or total joint replacement is warranted.

CRITICAL POINTS Contraindications

- Sedentary patients, no symptoms, little exposure to high-risk activities
- Patients unable to participate in postoperative rehabilitation program
- Patients with preexisting severe loss of patellofemoral or tibiofemoral compartment joint space
- Marked muscle atrophy
- Complex regional pain syndrome
- Obesity
- Prior joint infection

Patients with ACL deficiency, symptomatic mild or moderate medial tibiofemoral arthritis, and varus malalignment require corrective valgus-producing high tibial osteotomy (HTO). These patients often do not require subsequent ACL surgery because there are limitations in activities owing to the joint damage. This principle applies to both ACL-deficient knees and those who had a prior failed ACL reconstruction. These patients often report improved joint instability because the varus thrust gait pattern is eliminated with osteotomy.

Patients with marked lower extremity muscle atrophy require a delay in surgery for many months until adequate muscle function has been restored. These patients have an increased risk for postoperative complications, including quadriceps muscle shutdown, patella infera, and arthrofibrosis. In some cases, the restoration of muscle function may lead to increased knee stability, avoiding ACL revision.

The presence of residual signs and symptoms of a complex regional pain syndrome (CRPS) requires careful examination and questioning regarding the presence of burning pain, abnormal skin hypersensitivity, extremity discoloration, and intolerance to cold and ice. Even after resolution of a prior CRPS, there is an increased frequency for return of the syndrome in these knees that must be promptly recognized in the postoperative period (see Chapter 40).

Patients with a body mass index of 30 or greater are usually not surgical candidates. A history of prior infection with subsequent joint arthritis often contraindicates ACL surgery. There may be associated medical conditions contraindicating surgery. The use of nicotine products is strongly discouraged and absolutely contraindicated if osteotomy alignment procedures are required.

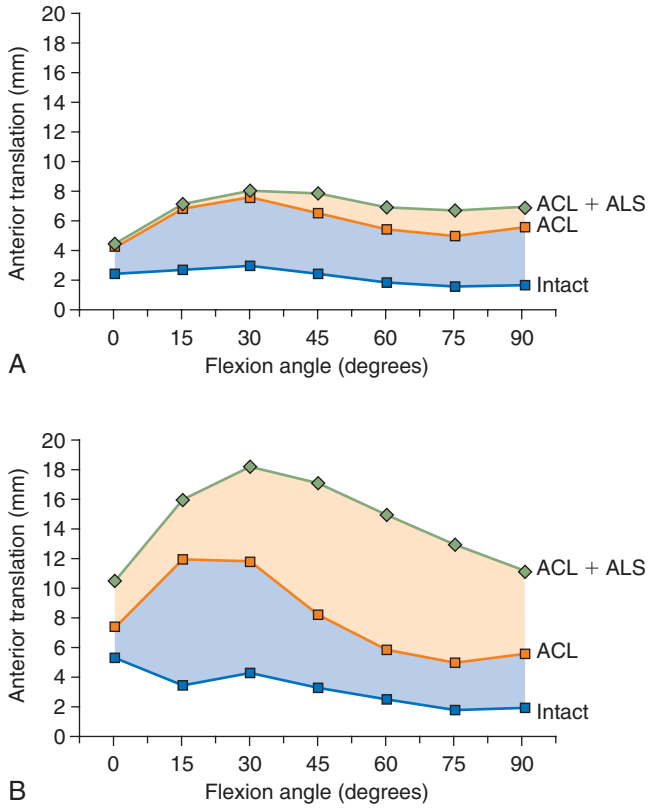


FIG 7-2 Limits of anterior translation (100 N) for intact specimens and with the anterior cruciate ligament (ACL) and ACL/iliotibial band lateral capsule (ALS) cut. **A,** In these specimens, anterior translation in the intact state was low and, with sectioning of the ACL, moderate increases were found throughout the range of motion. Further sectioning of the ALS produced less than 3 mm of an increase in anterior translation, predominantly in the flexed knee. **B,** In this group of specimens, anterior translation in the intact state was higher than in the prior group of specimens at low flexion angles. After cutting the ACL, anterior translation was markedly increased in the 15 to 30 degrees of flexion range. After further sectioning of the ALS, large anterior translation increases were found at all flexion angles, indicating the ALS is a secondary restraint. (**A** and **B**, From Wroble RR, Grood ES, Cummings JS, et al. The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee. *Am J Sports Med.* 1993;21: 257-262.)

CLINICAL BIOMECHANICS

Effect of Anterior Cruciate Ligament and Lateral Structures on Anterior Tibial Translation and Internal Tibial Rotation Limits

The function of the ACL is discussed in Chapter 3. Additional information regarding the restoration of ACL function related to surgical techniques and graft placement issues are discussed in this section. The ACL is the primary restraint to anterior tibial translation, providing 87% of the total restraining force at 30 degrees of knee flexion and 85% at 90 degrees of flexion.[38] The iliotibial band (ITB), mid medial capsule, mid lateral capsule, medial collateral ligament (MCL), and fibular collateral ligament (FCL) provide a combined secondary restraint to anterior tibial translation. The posteromedial (PM) and posterolateral (PL) capsule structures provide added resistance with knee extension. The secondary restraints may become deficient after an ACL injury or repeat giving-way episodes resulting in increased symptoms.

The ACL resists the coupled motions of anterior tibial translation and internal tibial rotation along with the lateral structures. In our laboratory, Wroble and colleagues[297] measured in ACL-deficient knees the simulated effect of lateral soft tissue injuries on internal tibial rotation and anterior tibial translation. The experimental design consisted of a six degrees of freedom (DOF)-instrumented spatial linkage and loading of the knee joint under defined loads of 100-N anteroposterior (AP), 15 N-m varus-valgus, and 5 N-m internal-external tibial rotation torque. The limits of knee motions were determined in the intact knee and then after sectioning the ACL, ITB, lateral capsule (anterolateral ligament),[44] popliteus tendon, popliteofibular ligament, and PL capsule.

The effect of sectioning the ACL first, followed by the ITB and lateral capsule, is shown in Figure 7-2. Two distinct responses were measured. In the first set of knees (see Fig. 7-2, *A*), there were only moderate increases in anterior tibial translation after ACL sectioning and negligible further increases after sectioning the ITB and lateral

CRITICAL POINTS Clinical Biomechanics

- ACL primary restraint anterior tibial translation.
- ITB, mid medial capsule, mid lateral capsule, MCL, FCL combined secondary restraint.
- ACL resists coupled motions anterior tibial translation and internal tibial rotation along with the lateral structures.
- Secondary restraints may become lax after reinjuries, may be physiologically loose or tight.
- Loss of ACL and lateral structures increases anterior tibial translation and internal tibial rotation.
- Increase in coupled motions shifts center of rotation to medial compartment.
- Concurrent injury to medial structures causes center of rotation to shift outside medial compartment, gross anterior subluxation of both compartments.
- Some authors provide evidence of two-bundle division of ACL, others argue that ACL fiber function is too complex to be artificially divided into two bundles.
- Characterization of ACL into two bundles represents gross oversimplification not supported by laboratory studies.
- With substantial anterior tibial loading or coupled motions, majority of ACL fibers are in a load-sharing configuration with different percentages as to fiber tensile loads.
- ACL is not isometric, all ACL fibers anterior to transitional zone lengthen with knee flexion, and posterior fibers lengthen with knee extension.
- Function ACL fibers determined primarily by anterior-to-posterior direction (knee at extension), and secondarily by proximal-to-distal femoral attachment and anterior-to-posterior tibial attachment.
- Placement of graft too far in an anterior or posterior femoral position has a large effect on deleterious lengthening and graft failure.
- Several studies report transtibial drilling techniques select a posterior tibial position, resulting in a vertical ACL graft orientation.
- Variation in ACL anatomy requires surgeon to outline the size and shape of the ACL attachment in each patient, if possible.
- Landmarks for ACL tibial attachment: medial tibial spine, posterior interspinous ridge (RER), attachment of lateral meniscus. PCL is poor landmark.
- Place guide pin eccentric and 2 to 3 mm anterior and medial to ACL center, avoiding posterior tibial attachment location.
- Anterior notchplasty often required with central ACL graft placement.
- Landmarks for ACL femoral attachment: posterior articular cartilage, Blumenstaat line, ACL attachment on lateral femoral wall.
- Central anatomic ACL placement: femoral guide pin 2 to 3 mm above the midpoint of the proximal-to-distal length of the ACL attachment, 8 mm from the posterior articular cartilage edge. Define anatomic attachment with knee 20 to 30 degrees of flexion.
- Majority in vitro robotic studies compare double-bundle graft to a less than ideal vertically placed single graft in a high femoral and posterior tibial location. This graft placement is not recommended.
- Studies of single ACL grafts in the more ideal central tibial and femoral anatomic attachment show restoration of rotational knee stability.
- There appears to be no distinct advantage of the more complex double-bundle technique in comparison to a well-placed central anatomic single graft technique.
- Both ACL bundles function synergistically to resist medial and lateral compartment subluxations during Lachman and pivot shift tests.
- Assessment of ACL graft function takes into account restoration of normal coupled motion limits of anterior tibial translation and internal tibial rotation. No current reliable measuring system is available to measure pivot shift test.
- Important landmarks for the ACL tibial attachments are the medial tibial spine, posterior interspinous ridge of the proximal PCL fossa, and the attachment of the lateral meniscus. ACL tibial attachment location that we recommended for a single graft is directly adjacent to the lateral meniscus anterior horn attachment.
- Important landmarks for the femoral attachment are the posterior articular cartilage, Blumenstaat line, and identification of the ACL attachment on the lateral femoral wall of the notch.
- For single grafts, we recommend a central anatomic ACL placement with the femoral guide pin 2 to 3 mm above the midpoint of the proximal-to-distal length of the ACL attachment (30 degrees of knee flexion) and 8 mm from the posterior articular cartilage edge.

capsule. However, in the second set of knees (see Fig. 7-2, *B*), much larger increases were noted in anterior tibial translation after sectioning the ACL, and even greater increases were found after sectioning the ITB and lateral capsule.

These findings are compatible with clinical tests after ACL injury in which some knees have only moderate increases in anterior tibial translation, whereas other knees have much larger increases. This concept is discussed in Chapter 3, using the analogy of the bumper model to simulate the resistance of the secondary restraints on motion limits once the ACL is removed. Clinically, an ACL graft would be expected to be subjected to greater in vivo forces in the second set of knees without the unloading provided by relatively "tight" secondary restraints. The increase in the magnitude of anterior translation and internal rotation in these physiologically loose knees after loss of the anterolateral structures results in a grade III pivot shift phenomena. These knees require a high-strength, securely fixated ACL graft to resist these major displacements, and autografts are highly recommended in these grossly unstable knees, with preference for a bone-patellar tendon-bone (B-PT-B) graft.

The effect of sectioning the lateral and posterolateral structures (PLS) is shown in Figure 7-3.[297] Sectioning of the FCL or PLS (popliteus tendon, popliteofibular ligament, PL capsule) produced small but statistically significant increases in anterior tibial translation at low flexion angles. The combined ACL-ALS-FCL (where ALS are the anterolateral structures comprising the ITB and anterior and middle portions of the lateral capsule) sectioned knee had large increases in anterior tibial translation, with the greatest changes occurring at higher flexion angles.

The effect of sectioning the ACL and lateral structures on the limits of internal tibial rotation are shown in Figure 7-4. Sectioning of the ACL produced only a small increase in the final internal rotation limit. Sectioning of the ALS and the FCL produced sequentially larger increases in internal tibial rotation. In select revision knees that have large increases in internal tibial rotation, the data support the role of a lateral extraarticular procedure discussed later to unload the ACL graft and restore stability.

The conclusions from this study support the ACL as the primary restraint to anterior tibial translation. The data show that the ultimate limit for internal tibial rotation is resisted by the lateral extraarticular structures that are tightened by the internal tibial rotation. This is an important concept because clinical and biomechanical studies frequently attempt to measure increases in internal tibial rotation after

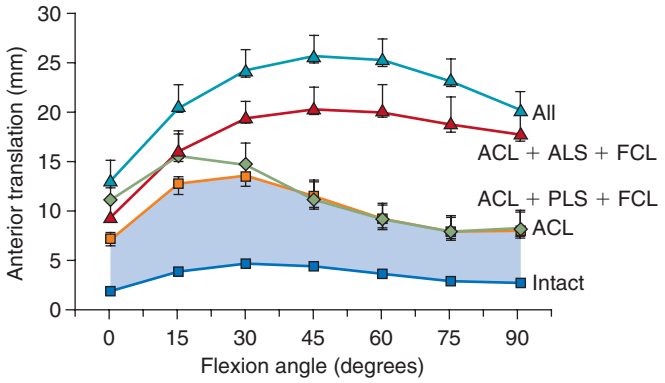


FIG 7-3 Limits of anterior translation (100 N) for intact specimens and with serial sectioning of the anterior cruciate ligament (ACL) and lateral structures. Increases in anterior translation with sectioning of the ACL are statistically significant at all flexion angles. For the ACL/PLS/FCL cut state, the only statistically significant increase was at 0 degrees of flexion. For the ACL/ALS/FCL cut state, increases were statistically significant at 15 degrees of flexion and above. Increases for the all cut state were statistically significant at all flexion angles. Anterior translation at 30 degrees and 90 degrees of flexion is approximately equal when the secondary lateral restraints are removed. *ALS*, iliotibial band, lateral capsule; *FCL*, fibular collateral ligament; *PLS*, posterolateral structures (popliteus tendon and popliteofibular ligament, posterolateral capsule). (From Wroble RR, Grood ES, Cummings JS, et al. The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee. *Am J Sports Med.* 1993;21:257-262.)

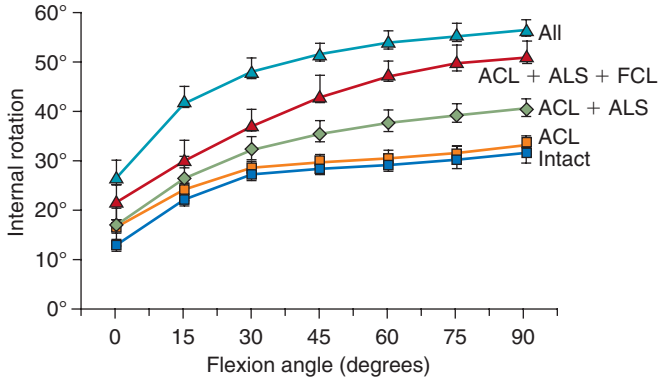


FIG 7-4 Limits of internal rotation (5 N-m) for intact specimens and with the anterior cruciate ligament (ACL), ACL/ALS, ACL/ALS/FCL, and ALL structures (ACL/ALS/FCL/PLS) cut. Increases in internal rotation with the ACL cut (statistically significant) state are so small that they are clinically unimportant. With ACL/ALS sectioning, increases in internal rotation are statistically significant at 30 degrees of flexion and above. Statistically significant increases are found at 15 degrees of flexion and above in the ACL/ALS/FCL cut state, and at all flexion angles for the all cut state. The effect of the PLS on restraining internal rotation in the extended knee can be seen by comparing the ACL/ALS/FCL curve and the ALL cut curve. The differences between these curves reflects sectioning the PLS. The largest differences are found at 15 degrees and 30 degrees of flexion. *ALS*, iliotibial band, lateral capsule; *FCL*, fibular collateral ligament; *PLS*, posterolateral structures (popliteus tendon and popliteofibular ligament, posterolateral capsule). (From Wroble RR, Grood ES, Cummings JS, et al. The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee. *Am J Sports Med.* 1993;21:257-262.)

ACL surgery in an effort to quantify ACL graft function. Accordingly, this approach would not be expected to be successful. When the ITB and lateral capsule are physiologically slack, the FCL and ACL assume increased importance in limiting internal rotation. In summary, ACL function is ideally described by the restraining effect of lateral and medial tibial plateau translation and not by internal rotation limits. A positive pivot shift test represents the effect of abnormal compartment translations and anterior subluxation of both tibiofemoral compartments.

The motions that occur during the pivot shift maneuver are shown in Figure 7-5. At the beginning of the tests, the lower extremity is simply supported against gravity. After ACL disruption, both anterior tibial translation and internal tibial rotation occur as the femur drops back and externally rotates with subluxation of the lateral tibiofemoral compartment. This position is accentuated as the tibia is lifted anteriorly. At approximately 30 degrees of knee flexion, the tibia is pushed posteriorly, reducing the tibia into a normal position with the femur. From position C to position A (see Fig. 7-5, *B*), the knee is extended to again produce the subluxated position.

The effect of the ACL in providing rotational stability is shown in Figure 7-6. After ACL sectioning, there is an increase in medial and lateral compartment translation as the center of rotation shifts from inside the knee joint to outside the medial compartment. The medial ligamentous structures influence the new center of rotation. With injury to the medial ligament structures, the center of rotation shifts so far medially that a tibial rotational displacement is essentially lost, resulting in a gross anterior subluxation of both compartments. The data show the important surgical concept of restoring injured medial and lateral ligament structures to restore anterior knee stability in conjunction with the ACL.

There have been numerous in vitro and in vivo studies published over the past decade on ACL function in regard to providing rotational knee stability.[76,100,134,151,166,285,303] Based on the results of these studies, authors have provided recommendations for ACL single- and double-bundle graft reconstructions, graft placement, and tensioning.[76,77,100,133,134,151,166,174,285,298,303] These investigations involved a simulated Lachman test and, more importantly, the pivot shift test, which correlates with patient subjective giving-way symptoms. In our opinion, there are problematic errors in many studies that the surgeon should be aware of in terms of application of the results to surgical treatment of ACL ruptures. For example, nearly all published studies describe rotational knee stability according to the changes in degrees of internal tibial rotation, without measuring the center of tibial rotation or the position or subluxation of the tibiofemoral compartments. We believe that providing only the changes in degrees of tibial rotation, without specification of the medial and lateral tibiofemoral compartment position or subluxation, is an inadequate descriptor of rotational knee stability. In fact, after ACL rupture, there is a change of only a few degrees of internal tibial rotation as long as the lateral extraarticular structures remain intact as already described.[54,208,219,220]

A second problem we have identified in a majority of in vivo and in vitro pivot shift studies is the loading profile used to induce anterior tibial subluxation. Studies commonly report, in the pivot shift simulation, an abnormal anterior tibial translation after ACL sectioning that is only half that obtained in the Lachman test. However, under clinical conditions, a positive pivot shift test produces greater anterior tibial subluxation than the Lachman test. Accordingly, these prior studies were conducted under low knee displacement conditions in which the loading profile involved an internal rotation-valgus condition. There was an absence of a simultaneous combined anterior tibial loading, which is the major reason the clinical pivot

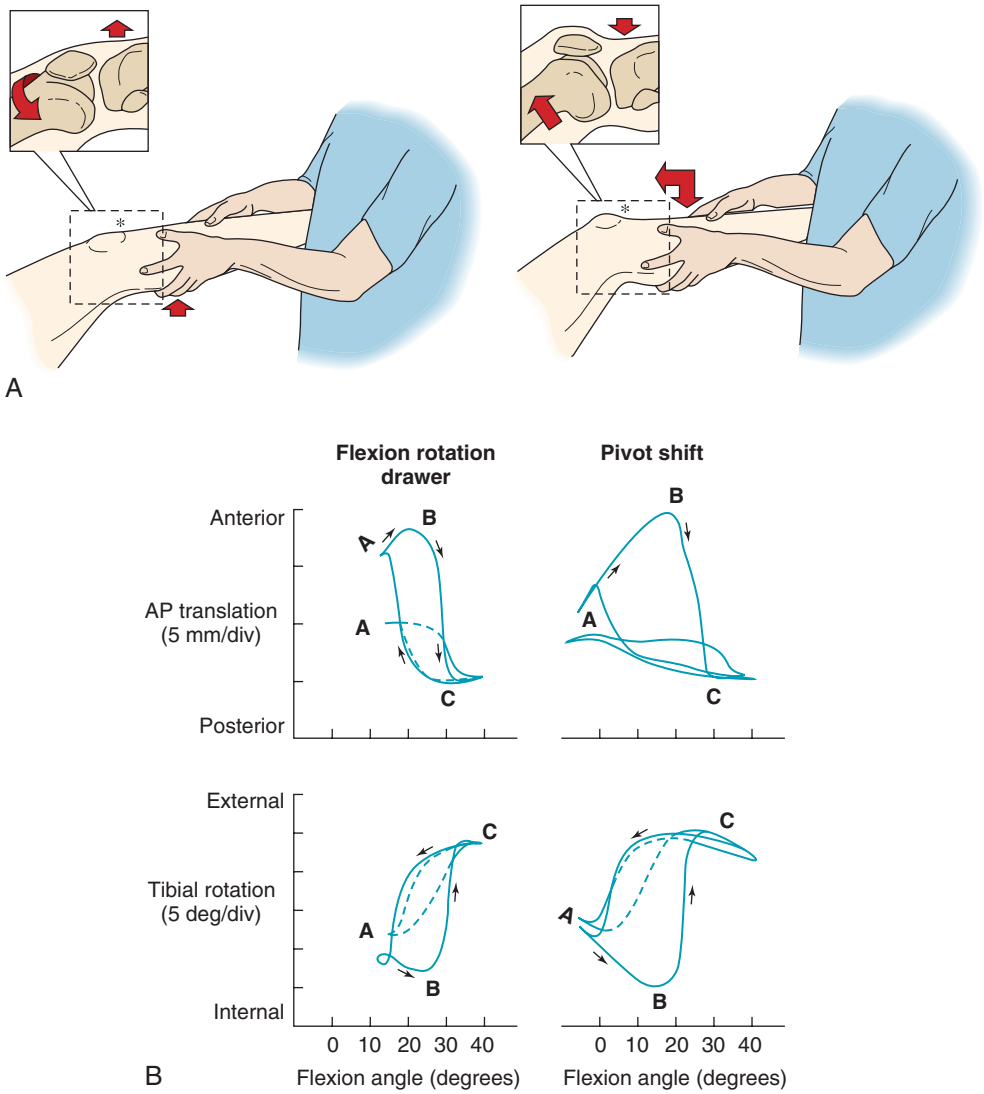


FIG 7-5 Flexion-rotation drawer and pivot shift tests. **A,** With the leg held in neutral rotation, the weight of the thigh causes the femur to drop back posteriorly and rotate externally, producing anterior subluxation of the tibial plateau. Gentle flexion and a downward push on the leg reduce the subluxation. This test allows the coupled motion of anterior translation-internal rotation to produce anterior subluxation of the lateral and medial tibial plateau. **B,** The knee motions during the tests are shown for tibial translation and rotation during knee flexion. The clinical test is shown for the normal knee (*dotted line*) and after ligament sectioning (*solid line*). The ligaments sectioned were the anterior cruciate ligament (ACL), iliotibial band, and lateral capsule. Position A equals the starting position of the test, B is the maximum subluxated position, and C indicates the reduced position. The pivot shift test involves the examiner applying anterior translation and rotational loading to produce the tibial subluxation. The actual changes in the motion limits are shown later where there are major increases in lateral and medial tibiofemoral compartment translations and only small changes in degrees of internal tibial rotation. *AP,* Anteroposterior; *div,* division. (**A,** From Noyes FR, Bassett RW, Grood ES, et al. Arthroscopy in acute traumatic hemarthrosis of the knee. *J Bone Joint Surg Am.* 1980;62:687-695. **B,** From Noyes FR, Grood ES, Suntay WJ. Three-dimensional motion analysis of clinical stress tests for anterior knee subluxations. *Acta Orthop Scand.* 1989;60:308-318.)

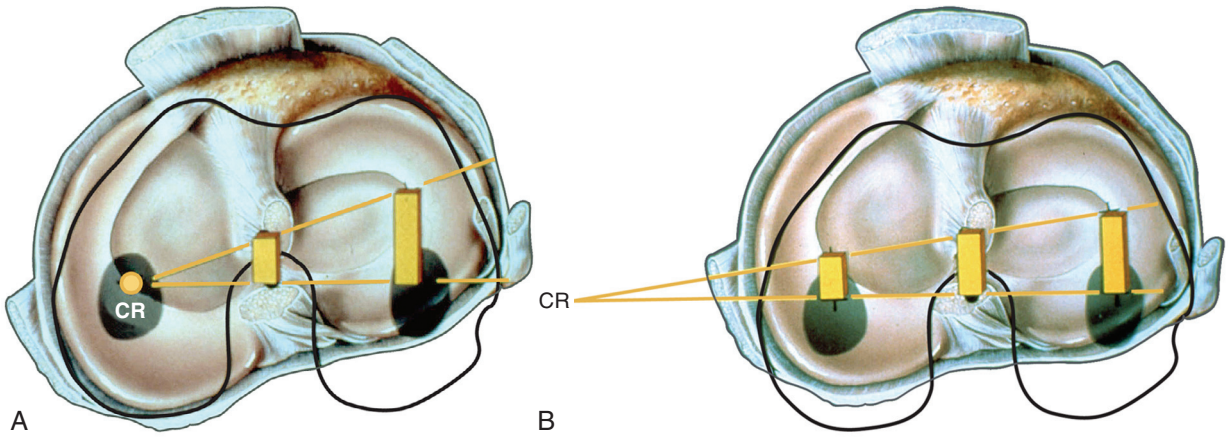


FIG 7-6 Intact knee and after anterior cruciate ligament (ACL) sectioning: response to coupled motions of anterior tibial translation and internal tibial rotation. **A,** Intact knee. The center of rotation (CR) may vary between the medial aspect of the posterior cruciate ligament and meniscus border, based on the loads applied and physiologic laxity of the ligaments. **B,** ACL sectioned; note shift in center of tibial rotation medially. The effect of the increase in tibial translation and internal tibial rotation produces an increase in medial and lateral tibiofemoral compartment translation (anterior subluxation). The millimeters of anterior translation of the tibiofemoral compartments represents the most ideal method to define knee rotational stability (see Chapter 3). The center of rotation under a pivot shift type of test shifts to the intact medial ligament structures. If these are deficient, the center of rotation shifts outside the knee joint.

shift test induces anterior tibial subluxation. A prior published study from our institution[208] that studied orthopedic surgeons performing a pivot shift test on an instrumented lower extremity reported that two types of clinical pivot shift loadings were induced: (1) a predominant internal rotational-valgus torque; and (2) a combined anterior tibial loading with internal rotation-valgus torque. The combined pivot shift loading test produced the greatest amount of anterior tibial subluxation of both tibiofemoral compartments. The predominant internal rotational-valgus torque loading constrained anterior tibial subluxation by reducing the medial tibiofemoral compartment translation.

For reasons not apparent, pivot shift loading with a predominant internal rotation-valgus torque, but without a coupled anterior tibial loading, has been the typical loading profile in nearly all cadaveric studies on ACL function and surgical reconstructions even though this limits anterior tibial subluxation of the medial compartment. In Figure 7-7, the results of a typical cadaveric knee specimen are shown under two pivot shift loading conditions. Three points are important. In the two simulated pivot shift tests, there is a greater anterior tibial subluxation of the lateral and medial compartment, with the pivot shift subluxation produced by a coupled anterior translation-internal rotation during the valgus loading as the knee approaches extension (pivot shift [PS] 4), compared with an absence of the anterior tibial loading component (PS3). Secondly, high tibial internal rotation torques in the pivot shift reduces the medial tibiofemoral compartment (see Fig. 7-7), constraining the amount of medial and central compartment translation. Third, an analysis of rotational knee stability requires knowledge of the resulting subluxations (translations) of the medial and lateral tibiofemoral compartments (see Chapter 3). We recommend that future in vitro and in vivo pivot shift studies use loading profiles of coupled anterior tibial translation and internal tibial rotation, along with valgus loading, to induce a maximum anterior tibial subluxation of both tibiofemoral compartments. Further, rotational torques should remain low to not constrain the maximum subluxation of the medial compartment.

Division of Anterior Cruciate Ligament Into Anteromedial and Posterolateral Bundles

Controversy exists in published studies on the division of the ACL into two distinct fiber bundles. Some authors provide evidence of both an anatomic and functional division, whereas others doubt this division exists and argue that ACL fiber function is too complex to be artificially divided into two bundles. In some studies,[7,47] the anteromedial (AM) bundle is identified functionally at its femoral location as the proximal half of the attachment (knee in extension) that tightens with knee flexion. The PL bundle is identified as the distal half of the ACL femoral attachment that tightens with knee extension. The PL bundle is described to relax with knee flexion, as the ACL femoral attachment changes from a vertical to a horizontal structure. The problem is that this classical description of a reciprocal tightening and relaxation of the AM and PL bundles occurs only under low anterior loading conditions. With substantial anterior tibial loading, and particularly with a coupled motion of anterior translation and internal tibial rotation, the majority of the ACL fibers are brought into a load-sharing configuration to a differing percentage as is presented later.

We believe the characterization of the ACL into two fiber bundles represents a gross oversimplification not supported by biomechanical length-tension laboratory studies.[93,264] Zavras and coworkers[309] published a comparative study on previously published isometric points for the ACL and concluded that the ACL isometric zone was high and proximal in the ACL attachment, close to the posterior end of the Blumensaat line. These data, along with other studies, focused on placing grafts in the proximal aspect of the ACL attachment, in a so-called isometric position. The problem with applying published isometric data to the clinical situation is that the data are valid only for knee flexion-extension and do not indicate the most effective ACL graft position for controlling knee rotational loading as occurs during the pivot shift test.

The length-tension behavior of ACL fibers is primarily controlled by the femoral attachment in reference to the center of femoral

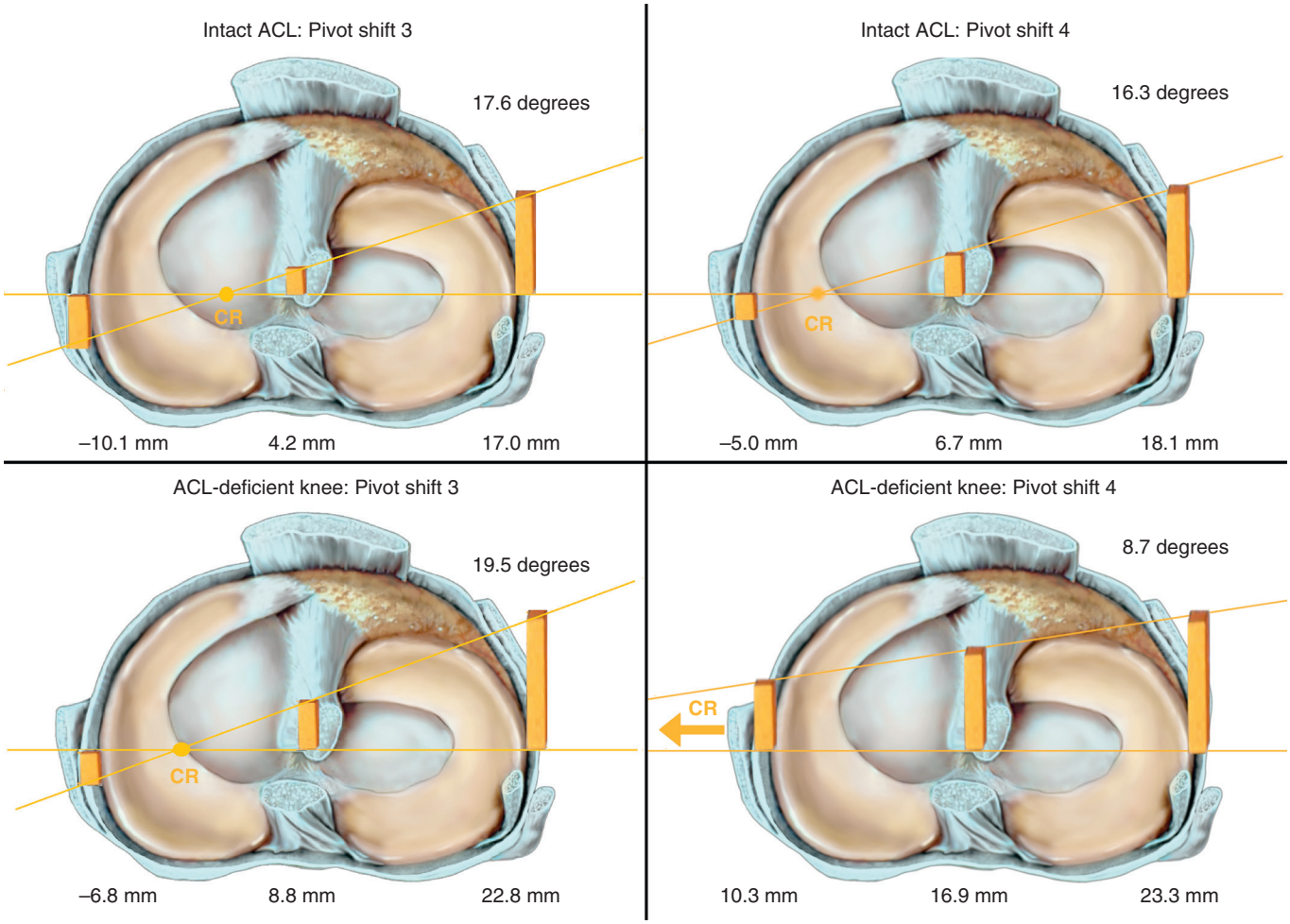


FIG 7-7 A representative right knee specimen showing compartment translations and tibial rotation under two loading conditions: *pivot shift 3* and *pivot shift 4*. In the pivot shift 3 loading, there is a coupled internal rotation-valgus loading with a high internal rotation torque. There is no subluxation of the medial tibiofemoral compartment. In contrast, in the pivot shift 4 loading, there is a coupled anterior tibial translation-internal rotation (low) and valgus loading. There is a medial shift in the center of tibial rotation, with subluxation of the medial, center, and lateral tibiofemoral compartments. Loading conditions for pivot shift 3 were 35 N anterior, 5 N-m internal rotation, and 7 N-m valgus. Loading conditions for pivot shift 4 were 100 N anterior, 1 N-m internal rotation, and 7 N-m valgus. *CR*, Center of tibial rotation.

rotation, the coupled motions applied, the resting length of ACL fibers, and tibial attachment locations. In Chapter 3, the concept of an isometric transition zone or contour plot is presented. The zone represents a central transition zone in which fibers undergo 2 mm of length change during knee flexion and extension. This zone is not an isometric zone because the length change is not zero. All ACL fibers anterior to the zone lengthen with knee flexion, whereas the posterior fibers lengthen with knee extension. Under loading conditions, fibers in both the AM and PL divisions contribute to resist tibial displacements. ACL fibers in the PL division attach in part posterior to the transitional zone and lengthen with knee extension. Note that the function of the ACL fibers is determined by the anterior-to-posterior direction (knee at extension) as well as the proximal-to-distal femoral attachment. Placement of a graft in an anterior or posterior position has a large effect in producing deleterious lengthening and graft failure. The obvious example is a graft placed anterior to the "resident's ridge," which is anterior to the femoral ACL attachment. The femoral proximal-to-distal division of the ACL used in two-bundle descriptions of fiber length in knee flexion and extension oversimplifies the functional behavior of the ACL fibers, which are more dependent on their anterior and posterior femoral attachments.

The division of the ACL into two bundles was historically based on the tibial attachment site and not on a corresponding femoral attachment site. Recent studies project the tibial bundles onto two corresponding femoral sites. In these studies, to be described later, we usually divide the ACL femoral attachment site at a midpoint into a corresponding AM and PL bundle. In our opinion, there is not at present convincing anatomic data to support a division of the ACL into two separate bundles, although one study[68] reported a bony ridge between the two femoral attachment bundles. Because of the lack of a clear anatomic division of the ACL into two bundles, there is discrepancy among authors on anatomic descriptions of the ACL bundles and

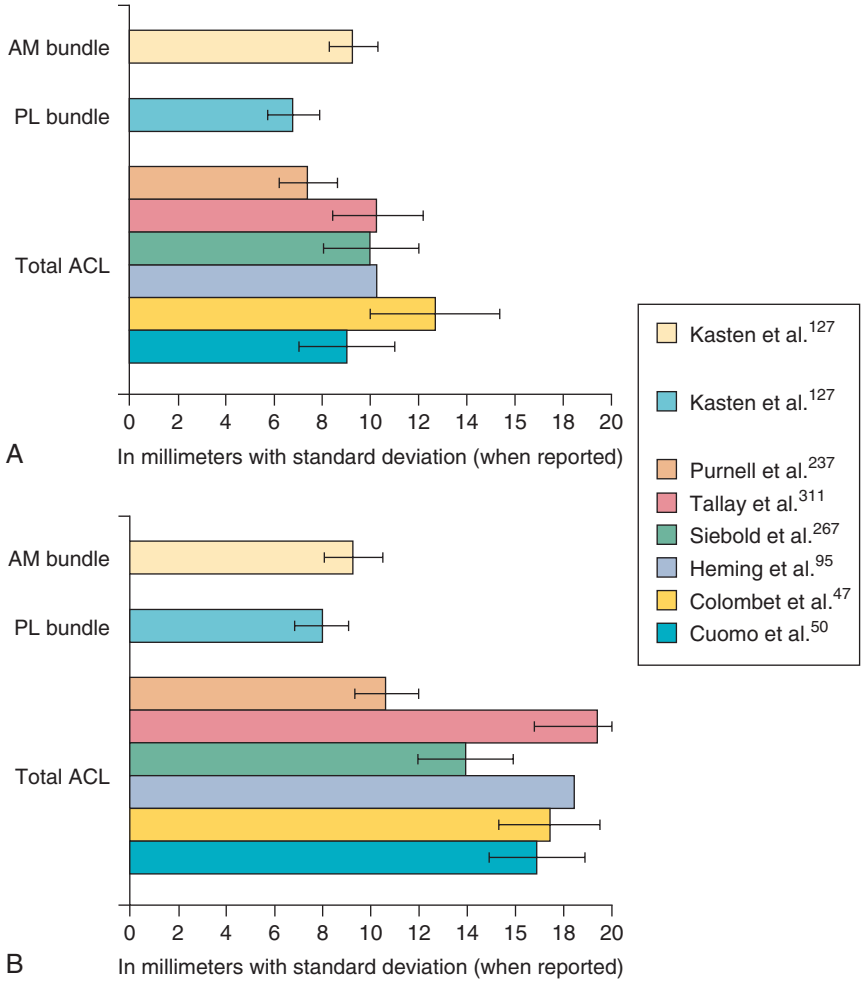


FIG 7-8 Anterior cruciate ligament (ACL) tibial insertion size width **(A)** and length **(B)** by publication, bundle, or footprint as a whole (total ACL). *AM,* Anteromedial; *PL,* posterolateral. (From Hwang MD, Piefer JW, Lubowitz JH. Anterior cruciate ligament tibial footprint anatomy: systematic review of the 21st century literature. *Arthroscopy.* 2012;28:728-734.)

recommendations for the surgical technique on tibial and femoral tunnels for two bundle graft reconstructions.

Tibial and Femoral Footprint Anatomy

Hwang and associates[112] performed a systematic review of the ACL tibial footprint in which 19 studies were analyzed. The authors noted wide variability in the reported size and shape of the native tibial footprint (Fig. 7-8). As a general guideline, on a lateral radiograph, the AM bundle was located at one third the anterior-to-posterior distance, the PL bundle was located at one half this distance, and the ACL center was located midway between (Fig. 7-9 and 7-10). The authors mentioned that although the line described by Amis and Jakob[8] was parallel to the medial plateau and the line described by Staubli and Rauschning[270] was perpendicular to the tibial axis, both lines yielded approximately the same results (Table 7-1). The approximate arthroscopic landmarks of the reviewed studies are shown in Table 7-2. These measurements need to be adjusted according to the relative size of the knee joint and potential anatomic variations. Even so, these measurements allow identification of the anterior two thirds of the ACL footprint for a 10-mm tunnel that avoids any portion of the tunnel occupying the posterior one third (PL bundle portion), ensuring that the tunnel remains anterior to the posterior lateral meniscus attachment.

Edwards and coworkers[59] defined the ACL tibial attachment in 55 cadaveric specimens. In Figure 7-11, the tibial bony landmarks are depicted. The "over-the-back" ridge (posterior interspinous ridge [RER]) corresponds to the interspinous ridge just anterior and proximal to the posterior cruciate ligament (PCL) attachment. Figure 7-12 presents these authors' recommendations for best-fit central and two-tunnel positions. The center of the ACL attachment was 15 ± 2 mm (range, 11-18 mm) from the RER at 36% of the anteroposterior (AP) depth of the tibia. The center of the PL bundle anterior from the RER was 10 ± 1 mm (range, 8-13 mm) and the AM bundle was 17 ± 2 mm (range, 13-19 mm), corresponding to 29% and 46% of the tibial depth, respectively. These authors were not able to define two separate anatomic ACL bundles. Instead, they defined two functional bundles by observing the tightening and slackening behavior of the ACL fibers during flexion and extension.

Stabuli and Rauschning[270] reported the center of the ACL tibial attachment at 43% of the AP depth, which extended from 25% to 62% of the tibial width. These important landmarks provide a reference to measure lateral radiographs before and after ACL graft

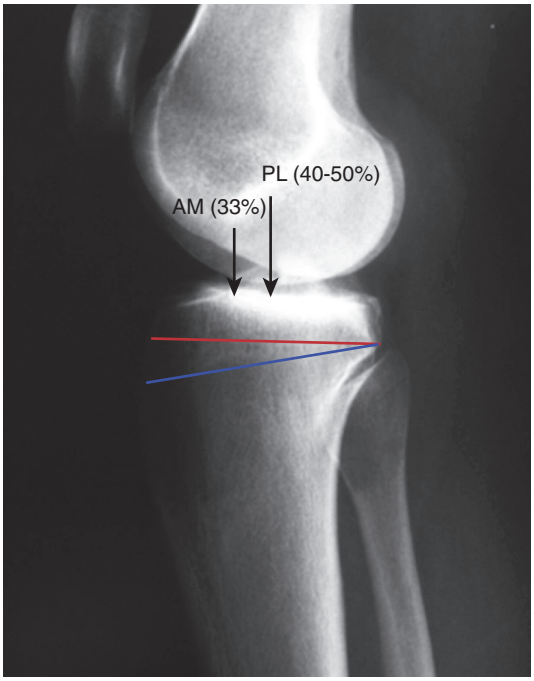


FIG 7-9 Lateral knee radiograph centered on the proximal tibia illustrates two anterior-to-posterior (AP) lines that may be used to identify the anatomic centrum of the anterior cruciate ligament (ACL) anteromedial (AM) and posterolateral (PL) bundles. The line (red) described by Amis and Jakob[8] is parallel to the medial tibial plateau. The line described (blue) by Stäubli and Rauschning[33] is perpendicular to the tibial axis. Systematic review of the literature shows that both lines yield similar results: the center of the AM bundle of the ACL is approximately one third of the AP distance along either line, and the center of the PL bundle is approximately 50% of the AP distance along either line. (From Hwang MD, Piefer JW, Lubowitz JH. Anterior cruciate ligament tibial footprint anatomy: systematic review of the 21st century literature. *Arthroscopy*. 2012;28:728-734.)

placement to avoid a posterior and vertical graft placement (Fig. 7-13). Siebold and associates[267] performed a cadaveric study in 50 knees and documented the ACL tibial insertion using a digital image analysis system and divided the ACL into AM and PL bundles. The average AP length of the ACL tibial attachment was 14 mm (range, 9-18 mm). The average male ACL tibial insertion area was 130 mm^2 versus the average female knee of 106 mm^2. The average AP length of the ACL footprint in females was 14 mm (range, 9-18 mm) and in males, 15 mm (range, 12-18 mm). The average width of the ACL in all knees was 10 mm. The study concluded that two tibial bone tunnels cannot be placed at the anatomic centers of the AM and PL bundles because the space is too narrow and the tunnels would overlap. This highlights the difficulty of the ACL double-bundle technique in recreating the native ACL fiber attachment.

Forsythe and colleagues[71] quantified the position of AM and PL bone tunnels in ACL reconstruction using arthroscopic dissection and computed tomography (CT) images in cadaveric knees (Figs. 7-14 and 7-15). Three-dimensional models were created from the CT scans and aligned into an anatomic coordinate system. The tibial and femoral measurements were similar to those published by other studies (Table 7-3).

In 2012, Piefer and associates[230] conducted a systematic review of studies that described the location of the ACL femoral footprint. Using the 20 articles selected for analysis, the authors provided general

Text continued on p. 151

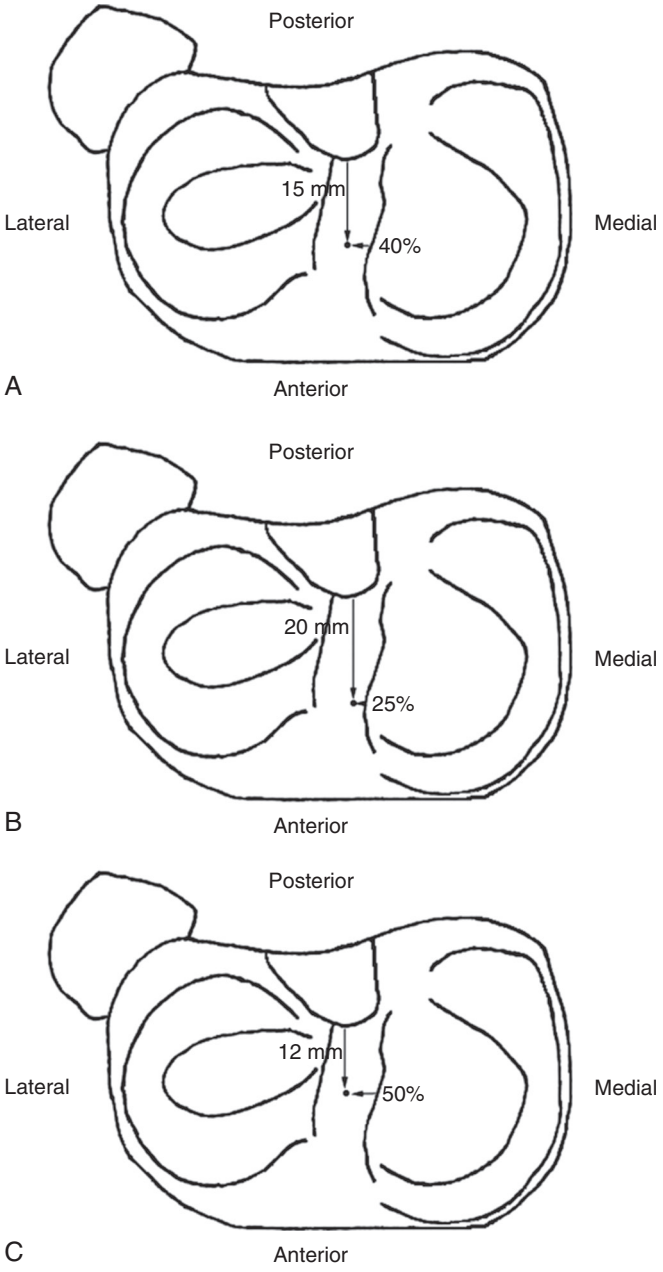


FIG 7-10 Illustrated is the proximal tibia and anterior border of the posterior cruciate ligament (PCL). Between the menisci, lines running from superior to inferior represent the lateral (left) and medial (right) intercondylar eminences (tibial spines). **A,** The black dot represents the centrum of the anterior cruciate ligament (ACL) tibial footprint as a whole, located approximately 15 mm anterior to the PCL and approximately two fifths the interspinous distance from the medial to the lateral intercondylar eminence. **B,** The black dot represents the centrum of the ACL tibial anteromedial bundle footprint, located approximately 20 mm anterior to the PCL and approximately one fourth the interspinous distance from the medial to the lateral intercondylar eminence. **C,** The black dot marks the centrum of the ACL tibial posterolateral bundle footprint, located approximately 12 mm anterior to the PCL and approximately one half the interspinous distance from the medial to the lateral intercondylar eminence. (Modified from Hwang MD, Piefer JW, Lubowitz JH. Anterior cruciate ligament tibial footprint anatomy: systematic review of the 21st century literature. *Arthroscopy*. 2012;28:728-734.)

TABLE 7-1 Studies That Used Lateral Knee Radiographs to Describe Location of Tibial Insertions of ACL AM and PL Bundles

Reference	Center of AM Bundle (Mean ± SD [Range])	Center of PL Bundle (Mean ± SD [Range])
Amis & Jakob[8]		
Kasten et al.[127] (2010)	35% ± 4% (23%-42%)	48% ± 4% (39%-58%)
Doi et al.[55] (2009)	34.6% ± 4.3% (24.0%-42.9%)	38.5% ± 4.3% (28.6%-48.1%)
Colombet et al.[47] (2006)	36% ± 3.8% (NA)	52% ± 3.4% (NA)
Staubli & Rauschning[270]		
Iriuchishima et al.[116] (2010)	31% ± 3% (NA)	50% ± 3% (NA)
Zantop et al.[308] (2008)	30% (NA)	44% (NA)

From Hwang MD, Piefer JW, Lubowitz JH. Anterior cruciate ligament tibial footprint anatomy: systematic review of the 21st century literature. *Arthroscopy.* 2012;28:728-734.

The lateral knee radiograph method for describing the anatomic centrum of the anterior cruciate ligament (ACL) and its anteromedial (AM) and posterolateral (PL) bundles may be based on either the proximal tibial line described by Amis and Jakob[8] or the line described by Staubli and Rauschning[270] (see Fig. 7-13). The findings described by one of these two methods are summarized by published articles, with regard to the center of each bundle (and range when reported), as the percent distance along the line from anterior to posterior. In sum, both lines yield similar results; the center of the AM bundle of the ACL is approximately one third of the anterior-to-posterior distance along either line, and the center of the PL bundle is approximately 40% to 50% of the anterior-to-posterior distance along either line.

NA, not available; *SD*, standard deviation.

TABLE 7-2 Arthroscopically Useful Landmarks for Identifying ACL Tibial Footprint or Centrum of ACL Tibial AM or PL Bundles

Reference	Key Findings
Iriuchishima et al.[116] (2010)	Distance between center of AM and PL footprints and anterior margin of PCL is 23 ± 4 mm and 12 ± 3 mm, respectively.
Purnell et al.[237] (2008)	Distance from posterior fibers of ACL to anterior margin of PCL is 16.5 ± 2 mm (range, 12.7-19.1 mm).
Siebold et al.[267] (2008)	Posterior horn of lateral meniscus is adjacent to posterior border of PL footprint; centrum of PL footprint is 5 mm anterior.
Heming et al.[95] (2007)	Centrum of tibial footprint is 15.0 mm anterior to tibial notch of PCL.
Edwards et al.[59] (2007)	Centrum of tibial footprint is 15 ± 2 mm (range, 11-18 mm) from anterior PCL; center of PL bundle is 10 ± 1 mm (range, 8-13 mm) and AM is 17 ± 2 mm (range, 13-19 mm) from anterior PCL.
Luites et al.[156] (2007)	Centrum of AM bundle is one fourth interspinous distance from ML intercondylar eminence; PL bundle centrum is 4 mm more lateral, approximately halfway between spines; tibial footprint centrum as a whole is two fifths ML (interspinous distance).
Cuomo et al.[50] (2006)	Anterior border of ACL tibial footprint is 22 ± 3 mm (range, 16-27 mm) anterior to "over the back position" (ridge just anterior to PCL); posterior border is 6 ± 2 mm (range, 2-8 mm) anterior to ridge.
Colombet et al.[47] (2006)	Mean distance between AM bundle and anterior border of PCL is 17.5 ± 1.7 mm.

Modified from Hwang MD, Piefer JW, Lubowitz JH. Anterior cruciate ligament tibial footprint anatomy: systematic review of the 21st century literature. *Arthroscopy.* 2012;28:728-734.

ACL, Anterior cruciate ligament; *AM*, anteromedial; *ML*, medial to lateral; *PCL*, posterior cruciate ligament; *PL*, posterolateral.

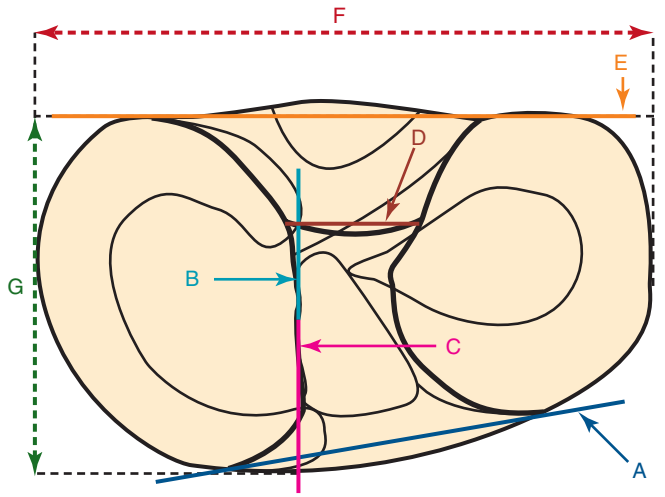


FIG 7-11 Schematic diagram of the tibial plateau depicting the landmarks used in this study. *A,* Anterior tibial surface; *B,* apex of medial tibial spine; *C,* lateral border of medial tibial spine; *D,* "over the back" ridge; *E,* posterior tibial axis; *F,* width; *G,* depth. (From Edwards A, Bull AM, Amis AA. The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament: part 1: tibial attachment. *Knee Surg Sports Traumatol Arthrosc.* 2007;15:1414-1421, 2007.)

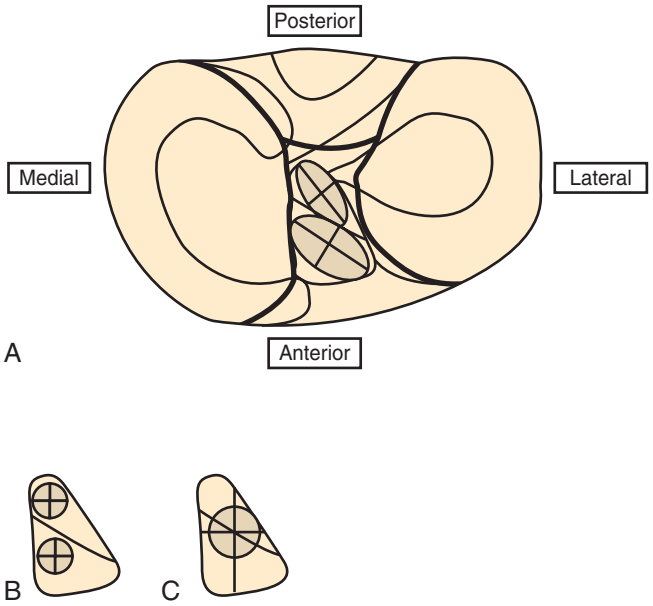


FIG 7-12 Schematic diagram of a left knee depicts the best-fit ellipses marking the centers of the anteromedial (AM) and posterolateral (PL) bundles **(A)**; the positions of 6-mm tunnels placed in the posteromedial limits of the AM and PL bundles **(B)**; and the center of the anterior cruciate ligament attachment **(C)**. (From Edwards A, Bull AM, Amis AA. The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament: part 1: tibial attachment. *Knee Surg Sports Traumatol Arthrosc.* 2007;15:1414-1421, 2007.)

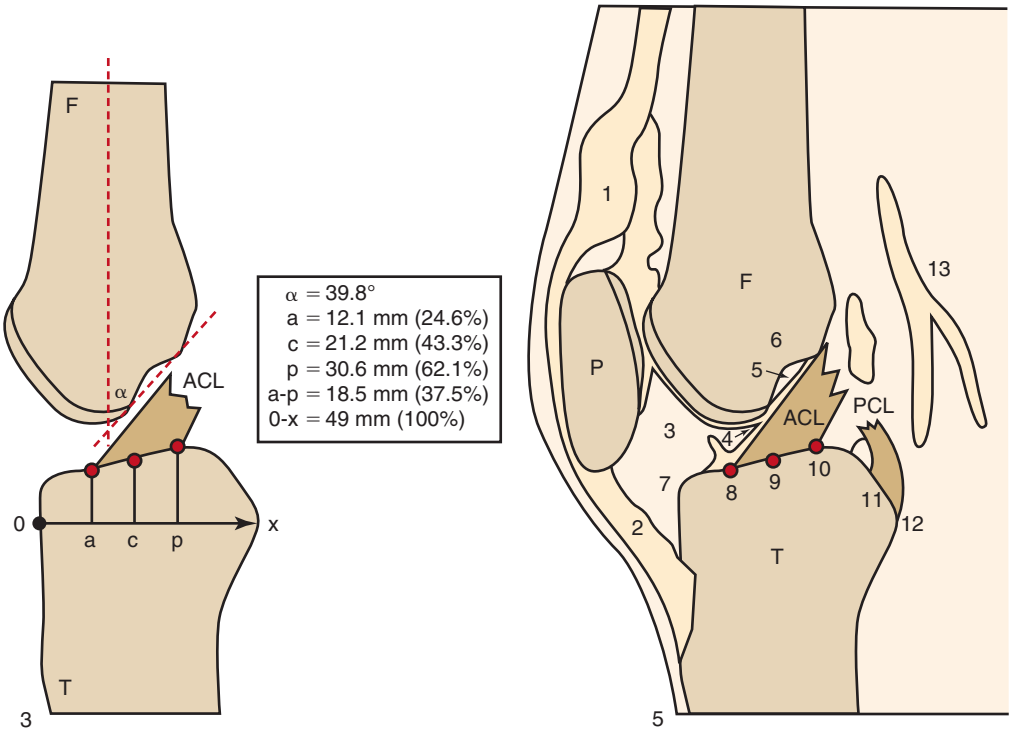


FIG 7-13 Schematic drawing of tibial insertion of anterior cruciate ligament (ACL) and its orientation with the knee in extension. In this cryosectional knee specimen (right knee, midsagittal plane, medial view at 0 degrees of flexion, that is, in the extended knee position, specimen 5), the inclination of a tangent constructed to the intercondylar roof formed an angle of 42 degrees with respect to the midsagittal femoral shaft axis. The anterior limit of the ACL was located at 11 mm (23.4%), the central part at 20 mm (42.6%), and the posterior limit at 29 mm (61.7%) when determined from the anterior tibial margin and calculated over the total sagittal diameter of the tibia, which measured 47 mm (100%). *F*, femur; *P*, patella; *T*, tibia; *1,* quadriceps tendon; *2,* patellar tendon; *3,* Hoffa's fat pad (corpus adiposum intrapatellare); *4,* infrapatellar plica; *5,* synovial fold of posterior cruciate ligament (PCL); *6,* roof of intercondylar fossa; *7,* anterior tibial margin; *8,* anterior limit of ACL; *9,* central part of ACL; *10,* posterior limit of ACL; *11,* tibial attachment site of PCL at posterior intercondylar area; *12,* posterior tibial margin at posterior intercondylar area; *13,* popliteal artery. (From Staubli HU, Rauschning W. Tibial attachment area of the anterior cruciate ligament in the extended knee position. Anatomy and cryosections in vitro complemented by magnetic resonance arthrography in vivo. *Knee Surg Sports Traumatol Arthrosc.* 1994;2:138-146.)

TABLE 7-3 Summary of Studies on Tibial and Femoral Positions of the AM and PL Bundles and Bone Tunnels

	TIBIAL MEASUREMENTS				FEMORAL MEASUREMENTS WITH QUADRANT METHOD			
	ANTERIOR TO POSTERIOR (%)		MEDIAL TO LATERAL (%)		PARALLEL TO BLUMENSAAT LINE (%)		PERPENDICULAR TO BLUMENSAAT LINE (%)	
REFERENCE	AM	PL	AM	PL	AM	PL	AM	PL
Tsukada et al.[289] (2008)	37.6	50.1	46.5	51.2				
Forsythe et al.[71] (2010)	25	46.4	50.5	52.4	21.7	35.1	33.2	55.3
Colombet et al.[47] (2006)					26.4	47.6	25.3	32.3
Zantop et al.[308] (2008)					18.5	29.3	22.3	53.6

From Forsythe B, Kopf S, Wong AK, et al. The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *J Bone Joint Surg Am.* 2010;92:1418-1426.
AM, Anteromedial; *PL*, posterolateral.

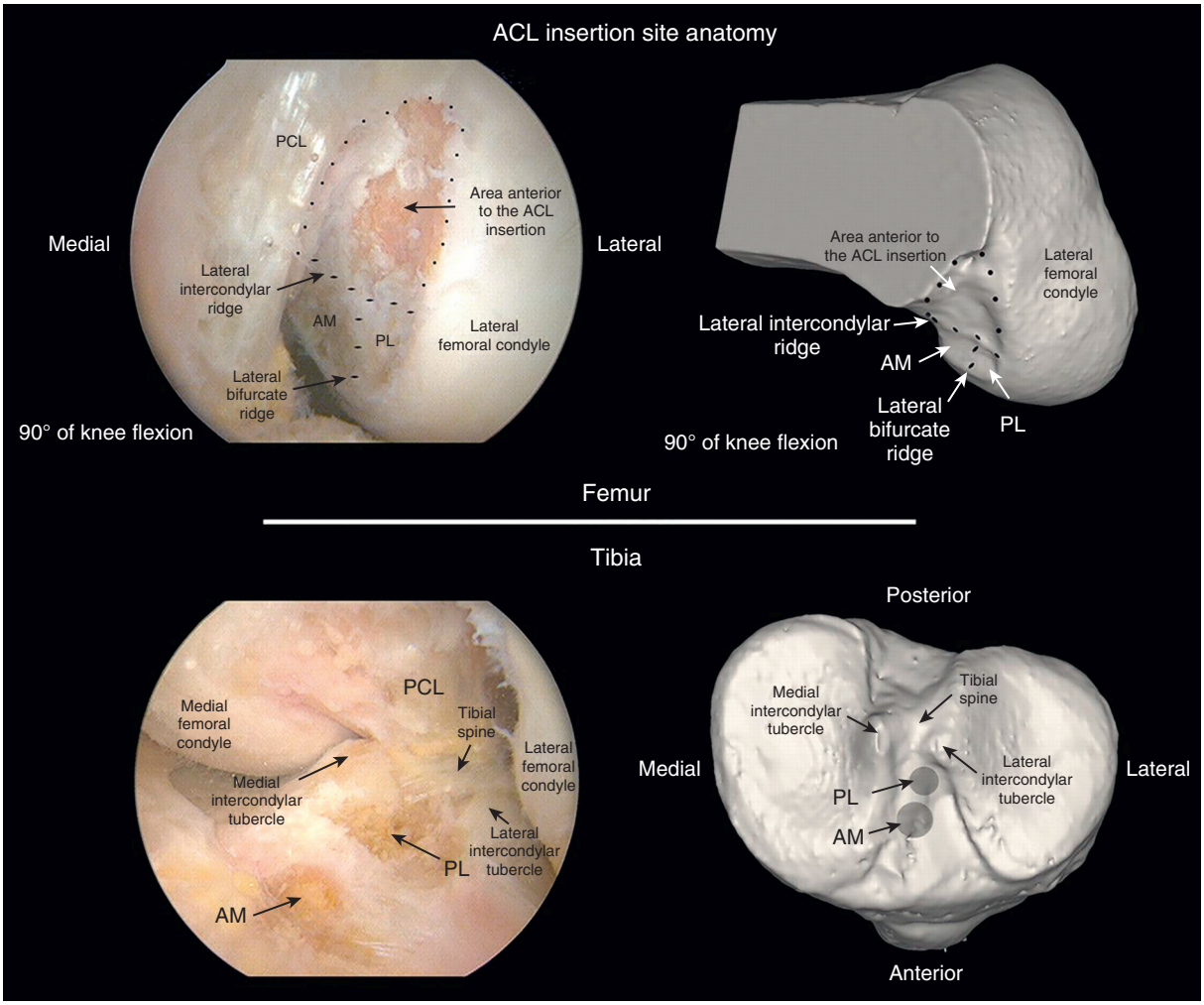


FIG 7-14 Following careful arthroscopic dissection and removal of soft tissue remnants, key insertion site anatomy was identified. On the femoral side, the lateral bifurcate and intercondylar ridges were identified. On the tibial side, the tibial spine, the medial and lateral intercondylar tubercles, and the posterior cruciate ligament were identified. Corresponding 3-dimensional computed tomography reconstructions delineate these topographic osseous landmarks. *ACL*, Anterior cruciate ligament; *AM*, anteromedial; *PCL*, posterior cruciate ligament; *PL*, posterolateral. (From Forsythe B, Kopf S, Wong AK, et al. The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *J Bone Joint Surg Am*. 2010;92:1418-1426.)

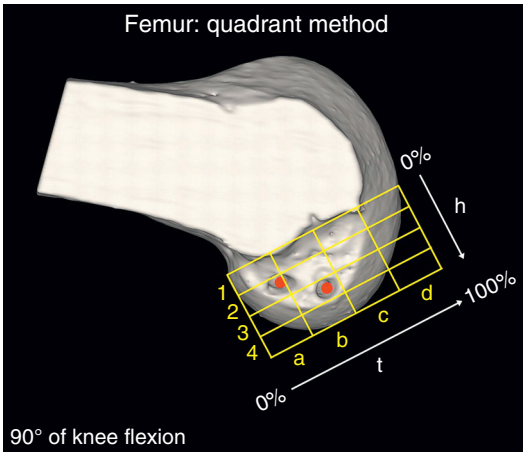


FIG 7-15 On the femoral side, the locations of the anteromedial and posterolateral tunnel aperture centers were established within a 4 × 4 grid, which was oriented along the most anterior edge of the notch roof. *h,* Line perpendicular to the Blumensaat line; *t,* line parallel to the Blumensaat line. (From Forsythe B, Kopf S, Wong AK, et al. The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *J Bone Joint Surg Am.* 2010;92:1418-1426.)

TABLE 7-4 Arthroscopically Useful Landmarks for Identifying ACL Femoral Footprint or Centrum or AM or PL Bundles by Bony Landmarks, Angle to Femoral Anatomic Axis, and Distance From Articular Cartilage Margins

Reference	Bony Landmarks	Angle to Femoral Anatomic Axis (Degrees)	Distance of Centrum or Footprint to Articular Cartilage Margin
Heming et al.[95] (2007)	NA	28.8	Footprint is 4 mm from posterior*
Purnell et al.[237] (2008)	Lateral intercondylar resident's ridge is anterior border	34.9 ± 3.7	Footprint is 3.5 ± 0.9 mm from posterior*
Siebold et al.[266] (2008)	AM is 3.6 ± 1.2 mm posterior to "over the top" position; distance between AM and PL centers is 7 ± 2 mm	12	PL centrum is 6 ± 3 mm from "shallow" (distal) articular cartilage
Yasuda et al.[305] (2004)	Anatomic centrum of AM bundle is 5-6 mm distal from "back" of femur	30	PL centrum is 5-8 mm from posterior
Ferretti et al.[67] (2007)	Lateral intercondylar ridge is anterior border; bifurcate ridge separates AM and PL bundles	NA	NA
Steckel et al.[271] (2010)	Bundles are oriented more horizontally when knee is flexed past 90 degrees	19 when knee is flexed to 90	NA
Luites et al.[156] (2007)	Centrum is 7.9 ± 1.4 mm shallow (distal) along notch roof and 4.0 ± 1.3 mm posterior to notch roof; footprint includes notch roof in 31 of 35	NA	NA
Takahashi et al.[281] (2006)	AM bundle is 4.1 ± 0.8 mm from notch roof perpendicular to Blumensaat line; PL bundle is 11.3 ± 1.8 mm from notch roof perpendicular to Blumensaat line	NA	AM bundle is 7.6 ± 1.5 mm (24.5% ± 4.7%) from posterior margin of article surface; PL bundle is 7.0 ± 1.4 mm (22.9% ± 4.7%) from posterior margin of articular surface
Edwards et al.[61] (2008)	AM bundle extends to posterior proximal notch	37 ± 16 to femoral axis	Measured parallel to femoral axis: AM centrum is 4.3 ± 1.1 mm from posterior at 10:30 o'clock position; PL centrum is 8.9 ± 2.1 mm from posterior at 10 o'clock position
Zantop et al.[308] (2008)	AM bundle is 5.3 ± 0.7 mm from roof of notch	NA	AM centrum is 18.9 ± 0.5 mm from shallow cartilage margin; PL centrum is 6.5 ± 0.9 mm from shallow (distal) cartilage margin and 5.8 ± 0.6 mm from posterior cartilage margin
Colombet et al.[47] (2006)	Center of AM bundle is 1.8 ± 1.3 mm from over-the-top position	NA	Footprint is 2.5 ± 1.1 mm from posterior articular cartilage*; distal border of footprint is 2.8 ± 1.5 mm from distal margin of articular cartilage
Iwahashi et al.[117] (2010)	Anterior border in line with posterior cortical border of femoral diaphysis resident's ridge	Parallel to roof of intercondylar notch	Footprint extends to posterior cartilage margin*
Hara et al.[90] (2009)	Lateral intercondylar resident's ridge is anterior border	NA	NA

From Piefer JW, Pflugner TR, Hwang MD, Lubowitz JH. Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. *Arthroscopy.* 2012;28:872-881.
*Descriptions of the distance from the posterior edge of the footprint as a whole to the posterior border of the articular cartilage.
AM, Anteromedial; *NA,* not available; *PL,* posterolateral.

recommendations regarding the arthroscopic identification of the femoral footprint (Table 7-4). Already appreciated was the ACL location, which was noted to be in the posterior third of the lateral wall, posterior to the lateral intercondylar ridge (resident's ridge). The anatomic centrum of the ACL femoral footprint was 43% of the proximal-to-distal length of the lateral femoral intercondylar notch wall and femoral socket radius plus 2.5 mm anterior to the posterior articular cartilage margin. There is a well-known anatomic variability of size and shape in the majority of knees in which the ACL fibers can be visualized (Table 7-5 and Fig. 7-16).

TABLE 7-5 ACL Femoral Footprint Insertion Size (Proximal to Distal by Anterior to Posterior) and Shape for Footprint as a Whole or by Individual Bundle

Reference	Size (mm)	Shape
Heming et al.[95] (2007)	18.4 × 9.5	NA
Purnell et al.[237] (2008)	12.9 ± 0.1 × 7.6 ± 1.4	NA
Steckel et al.[271] (2010)	NA	Semilunar
Siebold et al.[266] (2008)	15 ± 3 × 8 ± 2	Long oval
Yasuda et al.[305] (2004)	NA	Egg shaped
Ferretti et al.[67] (2007)	17.2 ± 1.2 × 9.9 ± 0.8	Segment of a circle with straight anterior border and convex posterior border
Luites et al.[156] (2007)	NA	Oval
Takahashi et al.[281] (2006)	AM: 11.3 ± 1.6 × 7.5 ± 1.3 PL: 11 ± 1.7 × 7.6 ± 1.0	Elliptic
Edwards et al.[61] (2008)	14 ± 2 × 7 ± 1	Variable
Mochizuki et al.[177] (2006)	AM: 9.2 ± 0.7 × 4.7 ± 0.6 PL: 6.0 ± 0.8 × 4.7 ± 0.6	Oval
Colombet et al.[47] (2006)	13.9 ± 9.5 × 9.3 ± 7.1	Variable
Iwahashi et al.[117] (2010)	17.4 ± 0.9 × 8 ± 0.5	Oval
Stijak et al.[272] (2009)	14.4 ± 2.3 × 6.8 ± 0.7	NA

AM, Anteromedial; *NA*, not available; *PL*, posterolateral.
From Piefer JW, Pflugner TR, Hwang MD, Lubowitz JH. Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. *Arthroscopy*. 2012;28:872-881.

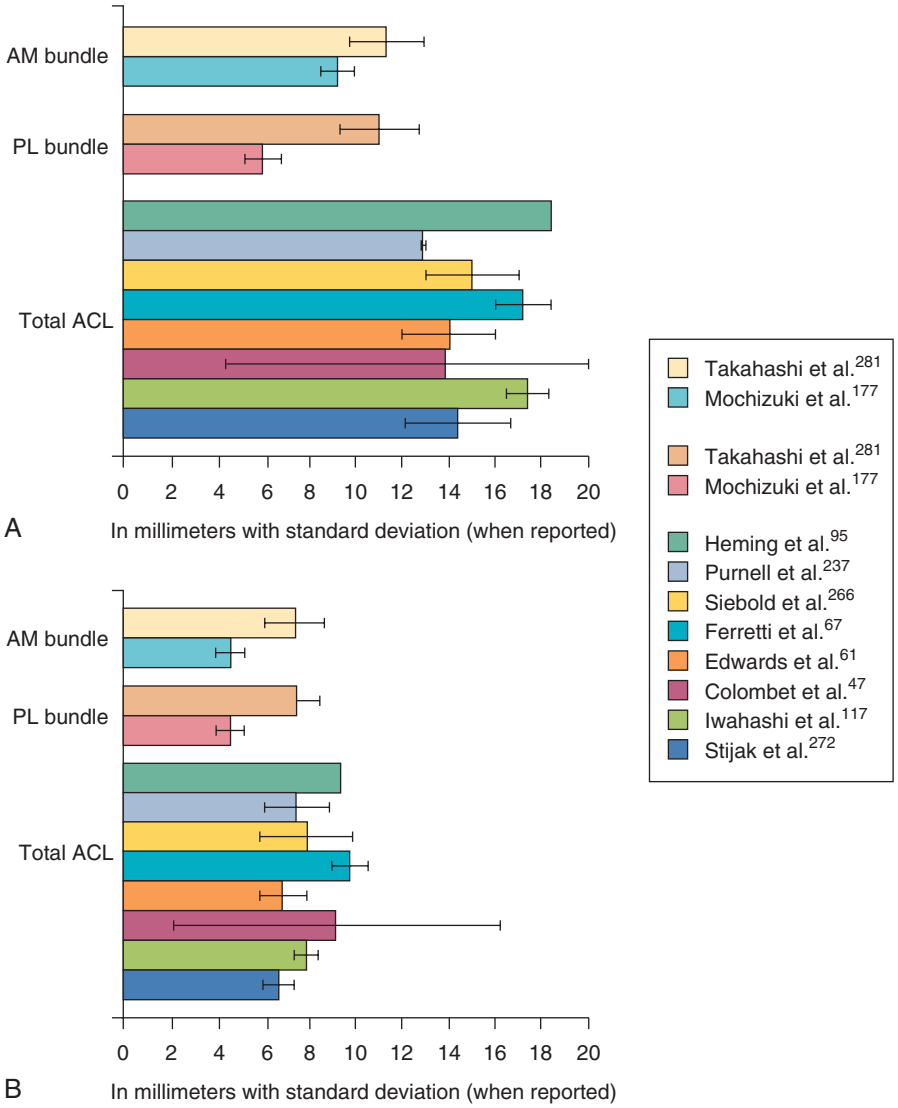


FIG 7-16 Anterior cruciate ligament (ACL) femoral origin size proximal to distal **(A)** and anterior to posterior **(B)** by publication, bundle, or footprint as a whole (total ACL). *AM,* Anteromedial; *PL,* posterolateral. (From Piefer JW, Pflugner TR, Hwang MD, Lubowitz JH. Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. Arthroscopy. 2012;28:872-881.)

TABLE 7-6 Radiographic Description of Anatomic Centrum of ACL Femoral Footprint, by Bundle or as a Whole, by Method of Description

Reference	Center of Anteromedial Bundle (%)	Center of Posterolateral Bundle (%)	Center of Anterior Cruciate Ligament Footprint (%)
Bernard & Hertel Method			
Colombet et al.[47] (2006)	26.4 ± 2.6 × 25.3 ± 4.2	32.3 ± 3.9 × 47.6 ± 6.5	29.35 × 36.45
Iriuchishima et al.[116] (2010)	15 ± 6 × 26 ± 8	32 ± 9 × 52 ± 5	23.5 × 39
Forsythe et al.[71] (2010)	21.7 ± 2.5 × 33.2 ± 5.6	35.1 ± 3.5 × 55.3 ± 5.3	28.4 × 44.25
Zantop et al.[308] (2008)	18.5 × 22.3	29.3 × 53.6	23.9 × 37.95
Tsuda et al.[288] (2010)	25.9 ± 2 × 17.8 ± 2.9	34.8 ± 2 × 42.1 ± 3.9	30.35 × 29.95
Pietrini et al.[231] (2011)	21.6 ± 5.6 × 14.2 ± 7.7	28.9 ± 4.6 × 42.3 ± 6	25.25 × 28.25
Guo et al.[86] (2009)	NA	NA	43.1 ± 4.6 × 38.3 ± 1.3
Steckel et al.[271] (2010)	NA	NA	26.9 ± 3.5 × 27.5 ± 3.2
Mean	21.5 × 23.1	32 × 48.8	28.5 × 35.2
Mochizuki Method			
Mochizuki et al.[177] (2006)	28.3 ± 2.1 × 28 ± 2	59.8 ± 4.1 × 53 ± 2	44.05 × 40.5
Edwards Grid Method			
Edwards et al.[59] (2007)	21 × 24	27 × 57	24 × 40.5
Takahashi Method			
Takahashi et al.[281] (2006)	31.9 × 26.9	39.8 × 53.2	35.85 × 40.05

From Piefer JW, Pflugner TR, Hwang MD, Lubowitz JH. Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. *Arthroscopy* 28:872-881, 2012.

The Bernard-Hertel method describes the centrum as the percent distance along the Blumensaat line (from proximal and posterior to distal and anterior) by the percent distance along a line perpendicular to the Blumensaat line (from proximal and anterior to distal and posterior). The Mochizuki method describes the centrum as the percent distance from proximal to distal by the percent from anterior to posterior (referencing the roof of the intercondylar notch). The Edward method describes the centrum as the percent distance from shallow (proximal and posterior) to deep (distal and anterior) by the percent from proximal and anterior to distal and posterior (referencing the roof of the intercondylar notch). The Takahashi method describes the centrum as the percent distance from proximal to distal by the percent from anterior to posterior (referencing the roof of the intercondylar notch).

ACL, Anterior cruciate ligament; *NA,* not available.

These data indicate that a 10-mm drill would produce a central point at the 43% proximal-to-distal line (just proximal to the midpoint). Assuming a 5-mm radius, plus a 3-mm back wall (to the articular cartilage bone margin), there would be an 8-mm point for the posterior articular cartilage margin. We prefer arthroscopic identification of the ACL femoral footprint compared with the various radiographic techniques shown in Table 7-6. The goal is to avoid a distal ACL footprint location (thereby producing a short graft) but to place the ACL graft into the proximal two thirds of the native footprint. This means the surgeon should select a point just proximal to the 43% line. We recommended the use of standard anatomic descriptions (anterior, posterior, proximal, and distal), rather than terms such as shallow, deep, high, and low.

Edwards and coworkers[59] described the anatomic locations of the ACL femoral attachments of the AM and PL bundles in a companion study in 22 cadaveric knees using a measurement grid system shown in Figure 7-17. The authors reported a wide variation in the size and shape of the ACL attachment and bundle arrangement that was selected (Fig. 7-18). The femoral attachment was oriented at 37 degrees to the long axis of the femur. The authors reported that the AM bundle extended to the posterior proximal limit of the femoral notch between the 10:30 and 11:30 o'clock positions. The PL bundle was located between the 9:00 and 10:30 o'clock positions. They reported that a 6-mm graft tunnel had the best fit if the AM bundle was located at 11 o'clock, 6 mm from the posterior outlet, and the PL bundle was located at 10 o'clock, 9 mm from the posterior outlet. They noted that other studies had different recommendations for the placement of two femoral tunnels in the double-bundle technique.

Zantop and colleagues[308] performed a cadaveric study in 20 knees that outlined the AM and PL bundle locations at the tibial and femoral sites. The authors arrived at different conclusions from those of Siebold and associates.[267] The tibia ACL division into the AM bundle was oriented from medial lateral, occupied the anterior one half of the ACL footprint, and was aligned with the anterior horn of the lateral meniscus. The center of the PL bundle was located 11 mm posterior and 4 mm medial to the anterior insertion of the lateral meniscus. The center of the AM bundle was located at 30% and the PL bundle was located at 40% on the lateral transtibial line.

Rue and associates,[248] in a cadaveric study, used a transtibial-drilled femoral tunnel, placed at the 10:30 position, and determined the location of a single-graft femoral tunnel in relation to the AM and PL bundles. The authors placed the guide pin for the tibial tunnel approximately 7 mm anterior to the PCL, which would represent a posterior one-third tibial attachment. They reported that the transtibial drilling of the femoral tunnel resulted in the AM bundle occupying an average of 32% (range, 3%-49%) of the ACL attachment and the PL bundle occupying an average of 26% (range, 7%-41%) of the ACL attachment. In addition, the remainder of the area of the 10-mm tunnel did not overlap the ACL footprint. The wide ranges reported in this study for the location of the femoral tunnel in terms of the native ACL femoral attachment highlight the problems of using the tibial tunnel to drill the femoral tunnel.

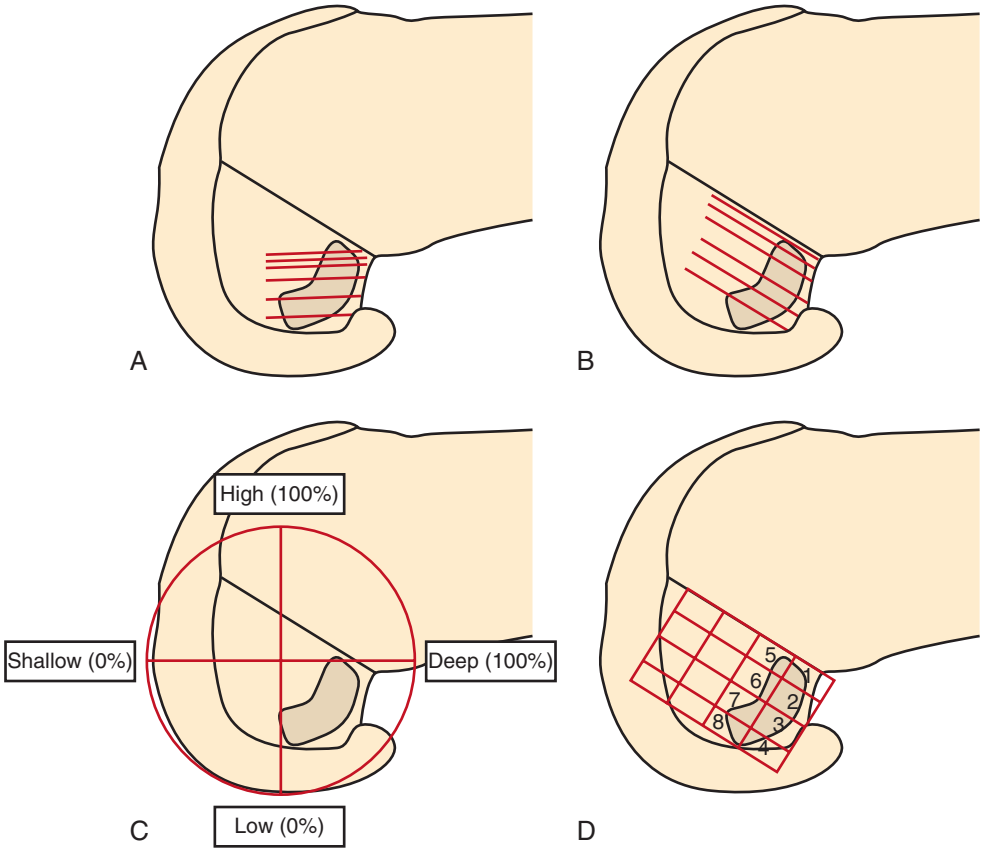


FIG 7-17 **A,** Measurement lines drawn parallel to the femoral shaft at clock-face positions. **B,** Measurement lines drawn parallel to the femoral notch roof from clock-face positions. **C,** The posterior condyle circle reference system. **D,** Measurement grid for describing the position of the centers of the two functional anterior cruciate ligament bundle attachments, with numbered zones. (From Edwards A, Bull AM, Amis AA. The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament: part 2: femoral attachment. *Knee Surg Sports Traumatol Arthrosc.* 2007;16:29-36.)

Heming and colleagues[95] reported the ACL tibial and femoral footprints in 12 cadaveric knees (Fig. 7-19). Note in Figure 7-19, *C*, the orientation of the clock face places the 9 to 3 o'clock horizontal line at the base of the femoral condyles and not within the center of the notch, which is typically used by other authors. A guide pin placed between the ACL anatomic femoral and tibial attachment centers (as in a transtibial drilling technique) was only possible if the tibial tunnel started in a medial position close to the joint line that would be too short to be functional for ACL grafts. The study concluded that transtibial drilling techniques resulted in a more vertical graft orientation.

Anterior Cruciate Ligament Function Defined by the Role of Anteromedial and Posterolateral Divisions

Biomechanical studies have reported marked differences in the function of the AM and PL bundles. Sakane and coworkers,[251] in one of the first cadaveric robotic studies, reported the PL bundle provided the primary restraint to anterior tibial translation at low flexion angles. Increasing forces were reported in the AM bundle with knee flexion; these remained lower than the calculated in situ forces of the PL bundle. However, subsequent studies have shown an increased role of the AM bundle and decreased role of the PL bundle in limiting anterior tibial translation.

The role of the ACL bundles in restraining rotational motions was examined by Zantop and associates[307] in a robotic study. A 134-N anterior tibial load or a combined 10 N-m valgus and 4 N-m internal tibial torque were applied to cadaveric knees. Sectioning the PL bundle at 30 degrees of flexion resulted in an approximate 7-mm increase in anterior tibial translation, whereas sectioning the AM bundle produced at 60 degrees an approximate 9-mm increase in anterior translation. Similar data were reported at low flexion angles for the combined rotational loads. These data imply a near-absence of function of the remaining "intact" bundle that is not supported by other studies. For example, Markolf and colleagues,[164] in a cadaveric study, reported that cutting the PL bundle resulted in an increase of only 1.1 mm at 10 degrees of flexion and 0.5 mm at 30 degrees of flexion. These authors questioned the need to reconstruct the PL bundle in ACL reconstructions.

Gabriel and coworkers,[74] in a robotic cadaveric experiment, removed all of the soft tissues to produce a femur-ACL-tibia specimen. For anterior tibial loading (Fig. 7-20), the AM bundle was reported to be nearly equal to the PL bundle at 15 degrees of flexion, with increasing AM forces with knee flexion. Under the rotation loads of valgus and internal tibial rotation, the forces in the AM bundle exceeded those of the PL bundle (Fig. 7-21).

Li and associates[145] used MRI and fluoroscopic images of subjects performing a lunge to create 3-dimensional models in which the AM and PL attachments were outlined. The study reported that the AM and PL bundles reached their maximum elongation between full extension and 30 degrees of flexion and did not demonstrate a reciprocal behavior with knee flexion-extension.

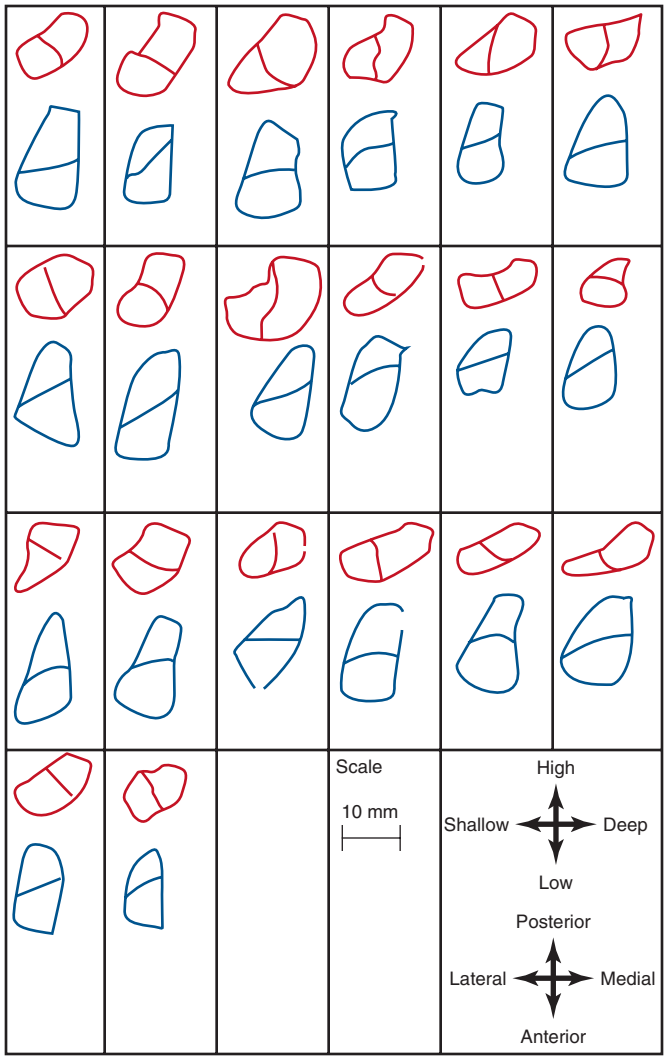


FIG 7-18 Anterior cruciate ligament attachment outlines on the femur and the corresponding outlines on the tibia; femur above tibia in each case; all shown for the right knee. (From Edwards A, Bull AM, Amis AA. The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament: part 2: Femoral attachment. *Knee Surg Sports Traumatol Arthrosc.* 2007;16:29-36.)

Giron and colleagues,[84] in a cadaveric experiment, determined that a "deep" (proximal) femoral tunnel position could be achieved with either one of three techniques (double incision, transtibial, or AM portal). However, Arnold and coworkers[15] showed in cadaveric experiments that the ACL is entirely attached to the lateral femoral wall and that this attachment position was not able to be accessed through a transtibial tunnel (40% AP tibial tunnel measurement). The transtibial tunnel method resulted in the guide pin and drill hole placed at the junction of the proximal ACL attachment and femoral roof (Fig. 7-22).

Mae and associates,[158] in a cadaveric knee study, used a robotic simulator to study the effect of single- versus two-femoral tunnel ACL graft reconstruction. A single tibial tunnel was placed in the center of the ACL tibial attachment. The locations of the single and two tunnels were described at the 1 o'clock and 2:30 positions. The data for AP translation and in situ graft forces at 44-N graft pretension showed little difference between the single- and double-bundle grafts, both of which produced a mild to moderate overconstraint that limited anterior tibial translation. The study reported on the load-sharing between the normal ACL bundles (Fig. 7-23), which demonstrated the PL bundle functioned more at low flexion angles, equal to the AM at 10 degrees of flexion, with a further increase in AM bundle function with increasing knee flexion. A study of load-sharing between the two bundles of a simulated pivot shift type of loading was not performed.

Yagi and colleagues[303] compared single- and double-bundle ACL hamstring reconstructions. A double-looped single-bundle hamstring graft was placed at approximately the 11 o'clock position and tensioned to 44 N, whereas each bundle of the double-bundle graft was tensioned to 44 N. The double-bundle graft had a total of 88 N of tension versus 44 N for the single-graft reconstruction. In response to a 134-N anterior load at 30 degrees of flexion, the data showed an unexplained residual anterior tibial translation (intact, 6.4 mm ± 2.4 mm: single bundle, 10.2 ± 2.5 mm), which would not be anticipated from a single graft in terms of resisting translation. The finding of a lax single graft most likely explains the reported decreased ability of the single graft to resist the combined rotation-translation motions.

Petersen and coworkers[229] concluded that the location of the ACL double-bundle grafts in clinical studies varied markedly at both the femoral and tibial sites. In a cadaveric study, Petersen et al.[229] found that a two-tunnel tibial technique provided an advantage in resisting combined rotatory loads, simulating the pivot shift (anterior tibial translation, 7.5 mm versus 9.5 mm, 30 degrees of flexion, 5 N-m internal rotation, 10 N-m valgus torque). Of note, the single tibial tunnel and graft were placed 7 to 8 mm anterior to the PCL; the authors stated that this was a position recommended by some surgeons.[106,180] As previously discussed, the posterior tibial tunnel position results in a more vertical ACL graft, with portions of the graft possibly even posterior to the native ACL tibial attachment. The addition of a second graft placed in a more anterior tibial position within the ACL footprint would be expected to provide better resistance to the loading conditions. Although the data do not provide evidence for a double-bundle ACL procedure, it does provide evidence to avoid placement of a single ACL graft in the posterior one third of the ACL tibial attachment.

Yamamoto and associates[304] conducted a cadaveric robotic study that compared a single ACL graft placed in the 10 o'clock position on the lateral wall with an anatomic double-bundle reconstruction. This is one of the few published studies in which a single-graft lateral wall placement was used, avoiding a more proximal graft placement. Similar loading conditions were used as in the other robotic studies (anterior tibial load 134 N, combined rotatory load 10 N-m valgus and 5 N-m internal tibial torque). There was no statistical difference in the anterior tibial translation or in situ force at 30 degrees of knee flexion between the intact ACL, the single bundle, or the anatomic double-bundle reconstructions. Under the combined rotatory loading conditions, there were no differences in anterior tibial translation, internal tibial rotation, and ACL in situ graft forces, which is in direct contrast to other robotic experiments.

Markolf and colleagues[165] measured in cadaver knees a simulated pivot shift in the intact knee and then after single-bundle and double-bundle ACL reconstruction. The single-bundle reconstruction (placed at the anatomic AM bundle site) restored mean tibial rotations and lateral plateau displacements to levels similar to those of the intact knee, whereas the double-bundle reconstructions reduced coupled rotations and displacements to levels less than those in the intact knee. The authors concluded that the overconstraint induced by the double-bundle reconstructions has unknown clinical consequences and that the need for the added complexity of this procedure is questionable.

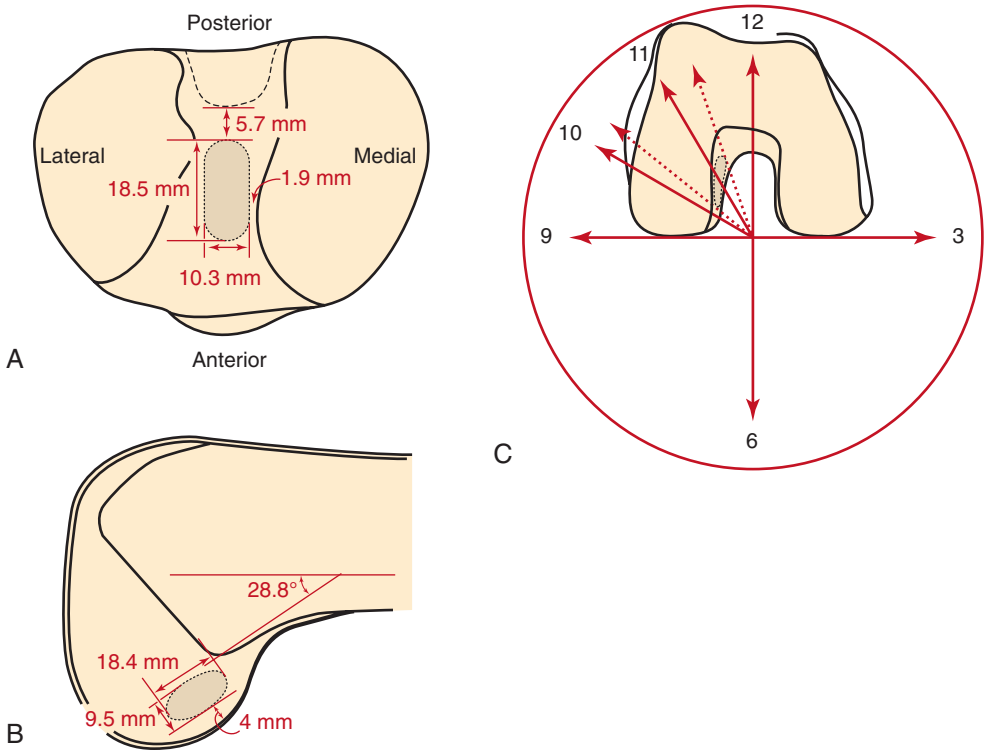


FIG 7-19 **A,** Right knee anterior cruciate ligament (ACL) tibial insertion. Measurements are the mean for the anterior-posterior length, medial-lateral width 10 mm from the posterior margin, distance from the posterolateral cruciate ligament notch, and distance to the medial plateau articular cartilage. **B,** Right knee ACL femoral insertion. Measurements are the mean for the length, width 10 mm from the proximal margin, distance to the articular cartilage, and angle to the long axis of the femur in the sagittal plane. **C,** Right knee ACL femoral insertion in the coronal plane with the knee flexed 90 degrees. The ACL insertion spanned the clock face from 10:14 to 11:23. The vertical 12 o'clock axis was perpendicular to the 3 to 9 o'clock axis drawn between the posterior femoral condyles. The vertical axis extended superiorly from a point midway between the walls of the notch to the apex of the notch. (From Heming JF, Rand J, Steiner ME. Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. *Am J Sports Med.* 2007;35:1708-1715.)

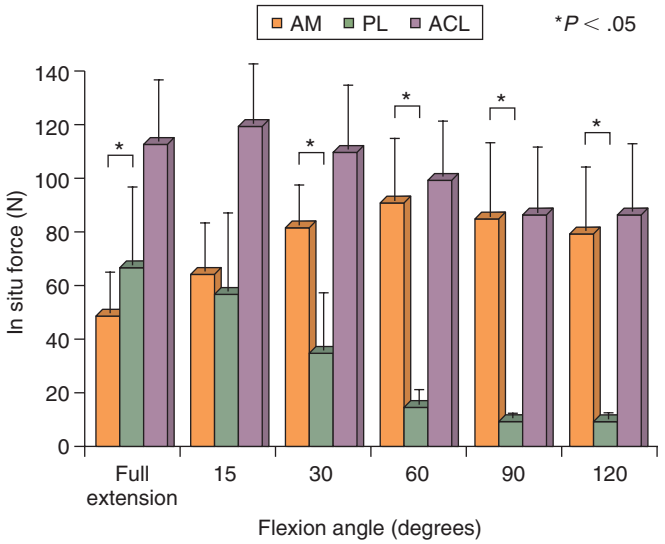


FIG 7-20 In situ force in the intact anterior cruciate ligament (ACL) and its anteromedial (AM) and posterolateral (PL) bundles in response to 134-N anterior tibial load. (From Gabriel MT, Wong EK, Woo SL, et al. Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. *J Orthop Res.* 2004;22:85-89.)

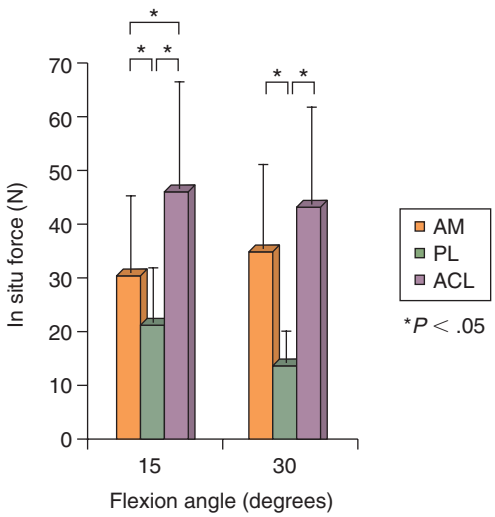


FIG 7-21 In situ force in the intact anterior cruciate ligament (ACL) and its anteromedial (AM) and posterolateral (PL) bundles in response to combined rotatory load (10 N-m valgus and 5 N-m internal tibial torque). (From Gabriel MT, Wong EK, Woo SL, et al. Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. *J Orthop Res.* 2004;22:85-89.)

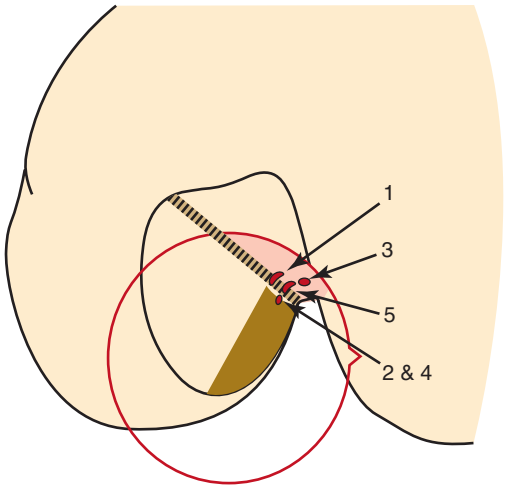


FIG 7-22 Schematic drawing shows the undesirable location on the femur of a guide pin placed though the tibial tunnel (notch view, summary guiding pinholes; knees 1 to 5). (From Arnold MP, Kooloos J, van Kampen A. Single-incision technique misses the anatomical femoral anterior cruciate ligament insertion: a cadaver study. *Knee Surg Sports Traumatol Arthrosc.* 2001;9:194-199, 2001.)

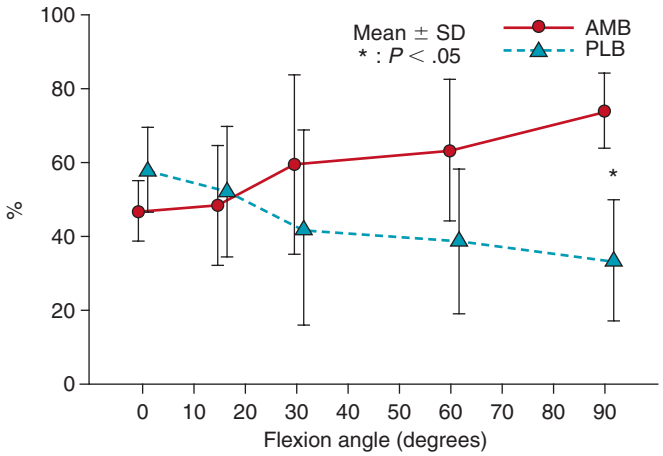


FIG 7-23 Graph showing force sharing between the normal anterior cruciate ligament bundles under 100 N of anterior load. *AMB,* Anteromedial bundle; *PLB,* posterolateral bundle. (From Mae T, Shino K, Miyama T, et al. Single-versus two-femoral sockets anterior cruciate ligament reconstruction technique: Biomechanical analysis using a robotic simulator. *Arthroscopy.* 2001;17:708-716.)

Cuomo and coworkers[51] reported on the effects of tensioning single- and double-bundle ACL reconstructions in cadaveric knees instrumented with a six-DOF system under defined loading conditions (anterior translation, 90 N; 5 N-m internal rotation torque). Different flexion positions were used for tensioning each of the grafts in the double-bundle construct. The single graft was tensioned at 20 degrees of knee flexion. All grafts had sufficient tension applied to restore normal intact knee translation. Tensioning each of the grafts individually (AM bundle at 90 degrees, PL bundle at 20 degrees, varying which was tensioned first) resulted in overconstraining AP translation. In contrast, tensioning both the AM and PL grafts simultaneously at 20 degrees provided the best match for the intact knee AP translation throughout knee flexion. The data show the difficulty in tensioning two ACL grafts at the time of surgery in terms of matching the intact ACL load-sharing among fibers. With anterior loading, both the AM and PL fibers participate in load-sharing, but at different percentages as already discussed. For single-bundle ACL grafts placed within the center of the femoral and tibial attachments, higher overall graft tension occurred under anterior loading compared with the two graft bundles tensioned at 20 degrees of flexion. Importantly, the data show that tensioning of the AM and PL grafts under low tensions (20 N) provided the best results. The single graft required 38 ± 27 N to restore the native knee laxity.

Scopp and associates,[257] in cadaveric experiments, reported that a more oblique femoral tunnel placement (60 degrees from vertical) was more effective in resisting internal rotational torques (difference 4.4 degrees, 6.5 N-m) than a "standard" tunnel placement (30 degrees from vertical). The femoral tunnel was drilled using a transtibial technique and, most likely, a posterior tibial tunnel placement. Anterior tibial translation values were not restored to normal (increased 2.5 mm and 2.2 mm, standard and oblique femoral tunnels).

Simmons and colleagues,[268] in cadaver experiments, showed the deleterious effects of a more vertical tibial tunnel (70 degrees and 80 degrees) with impingement against the PCL and higher graft tension. A more oblique tibial tunnel and femoral tunnel in the 60-degree coronal plane did not impinge against the PCL. The study recommended a posterior tibial tunnel placement and more proximal ACL femoral attachment with use of a transtibial drilling technique, again showing from a historical perspective the studies in the literature in which a more vertical graft orientation results.

Arnold and coworkers[16] showed in cadavers that the passive ACL tension flexion-extension tension curve was not reproduced by femoral tunnels placed at the 10 and 11 o'clock positions, but was reproduced by grafts in the 9 o'clock positioned tunnels. However, a less ideal posterior ACL tibial tunnel was used in this experiment.

In summary, a majority of in vitro robotic studies compare a double-bundle graft construct with a hybrid proximal femoral and posterior tibial orientation of a more vertical single-bundle graft construct and not a centrally placed femoral and tibial graft construct. Therefore, the published data apply specifically to this type of single-graft construct and show as expected that a vertical single graft is not positioned to resist rotational loading. It may be concluded that there is sufficient experimental data to recommend this hybrid graft orientation be avoided in clinical practice.

There are incomplete in vitro data on the comparison of an anatomic single-graft construct (within central tibial and femoral tunnels) with a double-bundle construct.[153] There are also incomplete experimental data on the function of individual regions of ACL fibers in resisting coupled motions as occurs in the pivot shift phenomena, which is an important area for future study (Fig. 7-24). Other biomechanical studies reviewed show that a single ACL graft placed within the anatomic femoral and tibial attachments (avoiding a high femoral and posterior tibial position) restore rotatory stability and question the need for a double-bundle procedure.[165]

One theoretical advantage of a double-graft construct tensioned appropriately is that there is initially less graft tension in each of the graft strands compared with the overall tension in a single graft. Stated differently, a single graft will always exhibit much higher graft tension to resist anterior loading than two graft arms in which load-sharing occurs. There is also the theoretical advantage of tensioning the two graft strands at different knee flexion positions to exhibit a different percent sharing of the overall tension than a single graft. From an experimental standpoint, either a single-graft or double-graft construct can be tensioned to restore normal motion limits; however, this may occur at the expense of high graft tensions,

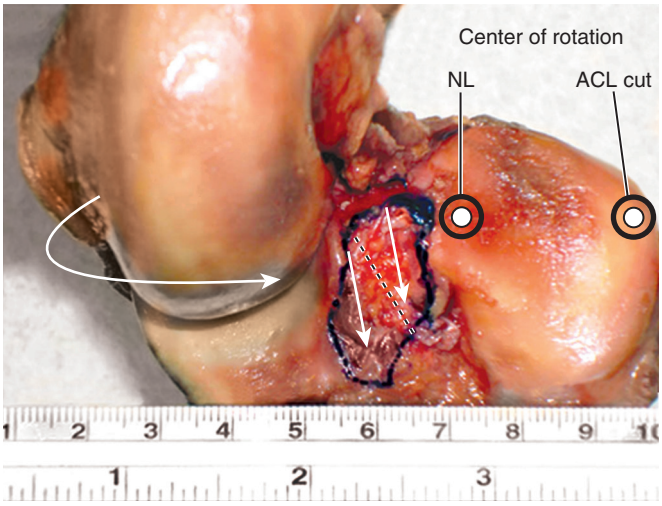


FIG 7-24 The anterior cruciate ligament (ACL) attachment on the tibia is outlined, along with an approximated center of tibial rotation. After ACL sectioning, the center of tibial rotation shifts medially, restrained in part by the medial ligament structures. The ACL tibial fibers are divided into anteromedial and posterolateral bundles. It should be noted that the anteromedial bundle is anatomically positioned to limit the coupled motions of internal tibial rotation and anterior translation under loading conditions; this effect has been frequently underestimated in biomechanical studies. *NL,* Normal.

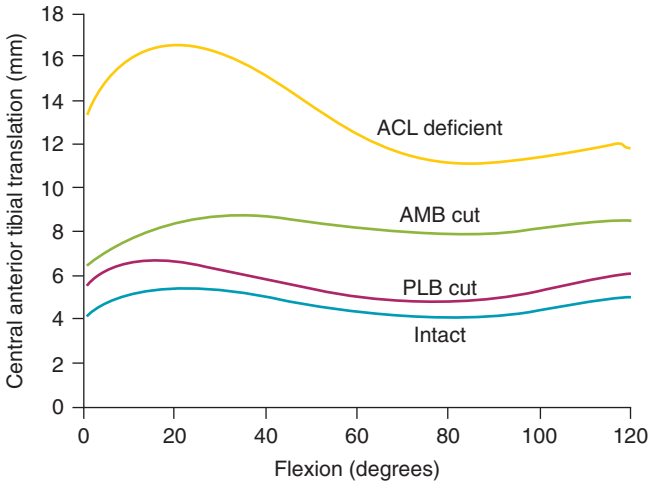


FIG 7-25 Anterior tibial translation of the central tibiofemoral compartment under a 100-N anterior load test from 0 to 120 degrees of flexion for intact, posterolateral bundle (PLB) cut, anteromedial bundle (AMB) cut and anterior cruciate ligament (ACL) deficient conditions. (From Gardner EJ, Noyes FR, Jetter AW, et al. *Effect of anteromedial and posterolateral ACL bundles on resisting medial and lateral tibiofemoral compartment subluxations. Arthroscopy.* 2015;31(5):901-910.)

particularly in a single-graft construct. Thus, the advantage of a double-graft construct (either ACL or PCL) is to restore normal knee motion limits under the lowest graft tensile loads, which is advantageous during graft healing and remodeling. A graft under lower loads has the theoretical advantage of less risk in stretching out with return of the abnormal motion limits. In addition, an ACL or PCL graft under higher tension, under cyclic loading conditions, is at high risk of graft stretching and failure.[261] Again, it should be noted that either one or two ACL grafts does not restore native ACL fiber length-tension properties.

Our Robotic Studies on Anterior Cruciate Ligament Anteromedial Bundle and Posterolateral Bundle Function and Single Anterior Cruciate Ligament Graft Reconstruction

We conducted a series of robotic cadaveric in vitro studies on the kinematic function of the AM and PL bundles of the ACL.[78,91,209] The studies involved a six-DOF robotic testing protocol on intact knees, knees in which either the AM or PL bundle was sectioned, and knees in which complete ACL sectioning was performed. As previously described, the robotic testing protocol involved, for the first time, the simulation of the pivot shift event using four DOF; namely, anterior tibial translation with internal tibial rotation with valgus loading of the limb during knee flexion-extension to induce maximum anterior tibial subluxation. The studies also involved, for the first time, digitization of the tibial plateau to determine medial and lateral tibiofemoral compartment translations and centers of tibial rotation in the simulated pivot shift test.

The results showed both ACL bundles functioned synergistically to resist medial and lateral compartment subluxations during the simulated Lachman and pivot shift tests. The AM bundle provided more restraint to anterior tibial translation under both tests than the PL bundle. Both ACL bundles had to be sectioned to produce tibiofemoral compartment subluxations during pivot shift loading (Figs. 7-25, 7-26, and 7-27). Neither bundle contributed to resisting internal rotation during pivot shift loading tests. We concluded that an ACL graft designed to duplicate the AM bundle restores medial and lateral compartment translations under multiple loading conditions; however, the PL bundle only provides a back-up restraint at low flexion angles. Neither ACL bundle resists internal tibial rotation or, in its absence, allows a positive pivot shift subluxation. Furthermore, the PL bundle is not the primary restraint for providing rotational knee stability, as has been quoted in the literature.[110,120,124]

We conducted a robotic cadaveric in vitro study that found that a single ACL graft placed into the anatomic center of the femoral and tibial attachment sites restored normal tibiofemoral compartment translations and rotations under simulated Lachman and pivot shift testing conditions. The study involved a six-DOF robotic testing protocol on intact knees, ACL-sectioned knees, and ACL-reconstructed knees. The reconstruction restored rotational stability as defined by normal motion limits and normal medial and lateral compartment translations under simulated pivot shift loading conditions (Fig. 7-28).

The results of this study support the recommendations in this chapter on the use of a single ACL graft instead of a double-bundle ACL graft construct. This finding is supported by Markolf and associates[166] who studied the effect of single- and double-bundle ACL grafts in cadaveric knees. As described in this chapter, prior robotic pivot shift studies on double-bundle ACL reconstructions used loading profiles that did not involve a coupled anterior tibial translation and internal rotation to induce maximum anterior tibial subluxations, and, in addition, did not measure resulting tibiofemoral compartment translations or subluxations. We question the validity of these studies in terms of the conclusions that a single ACL graft does not restore knee rotational stability or that a double-bundle ACL construct is required.

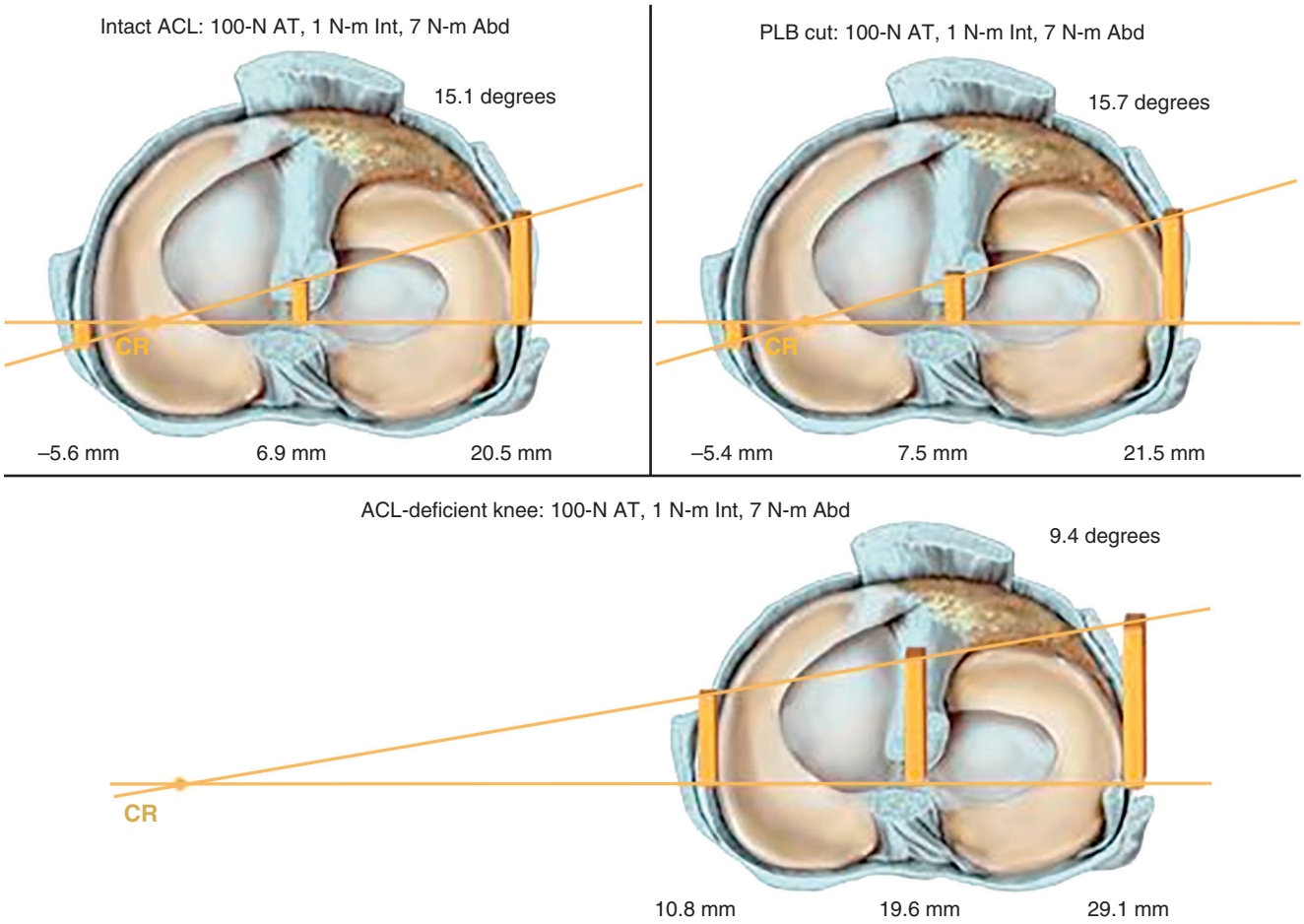


FIG 7-26 A representative right knee specimen showing compartment translations and tibial rotation under pivot shift 4 loading conditions (100-N anterior, 1 N-m internal rotation, 7 N-m valgus) for intact, posterolateral bundle (PLB) cut, and anterior cruciate ligament (ACL)-deficient states. PLB sectioning alone resulted in no statistically significant change in tibiofemoral compartment translations. *Abd*, Abduction; *AT*, anterior translation; *CR*, center of tibial rotation; *Int*, internal. (From Gardner EJ, Noyes FR, Jetter AW, et al. Effect of anteromedial and posterolateral ACL bundles on resisting medial and lateral tibiofemoral compartment subluxations: *Arthroscopy*. 2015;31(5):901-910.)

Clinical Measurement of Anterior Cruciate Ligament Graft Function During and After Anterior Cruciate Ligament Surgery

The assessment of ACL graft function must take into account the restoration of the normal coupled motion limits of anterior tibial translation and internal tibial rotation during the pivot shift phenomenon, which strongly correlates with patient giving-way symptoms. During KT-2000 (MEDmetric) testing, only anterior tibial translation is assessed. If the knee joint has a 3-mm or lower increase in central anterior tibial translation over the opposite knee, it can be assumed that there is no positive pivot shift because this amount of constraint to anterior tibial translation also limits anterior subluxation of the lateral tibial plateau. Conversely, if a greater than 5-mm increased anterior tibial translation exists, there may occur a positive pivot shift test and patient complaints of giving-way. The problem is in knees that demonstrate 3 to 5 mm of increased anterior tibial translation, which may represent 20% to 30% of patients in clinical investigations,[1,14,218,259,260] especially when allografts are used.[203] This mild to moderate increase in anterior tibial translation results in a mildly positive Lachman test with a hard endpoint. However, these knees may demonstrate a positive pivot shift and giving-way symptoms. Since the pivot shift test is highly subjective and variable among examiners (see Chapter 3), an author may report a successful result based on the KT-2000 (anterior tibial translation) or a pivot shift test, whereas another examiner may grade the knee as a failure, based on the method in which the pivot shift test is performed. There is a pressing need for clinical examination methods that simulate the pivot shift phenomenon and the resultant subluxations (in millimeters) of the medial and lateral tibiofemoral compartments.

Bull and associates[35] were among the first authors to report intraoperative measurement of tibial translations and rotations using a 3-dimensional motion analysis system. In the operative setting, there was a marked variability in knees in the amount of medial and lateral tibial plateau displacements during the pivot shift test. Robinson and colleagues[245] performed an ACL double-bundle reconstruction using computerized navigation techniques in 22 patients. The exact location of ACL grafts and the loads applied by the examiner are variables still to be determined.

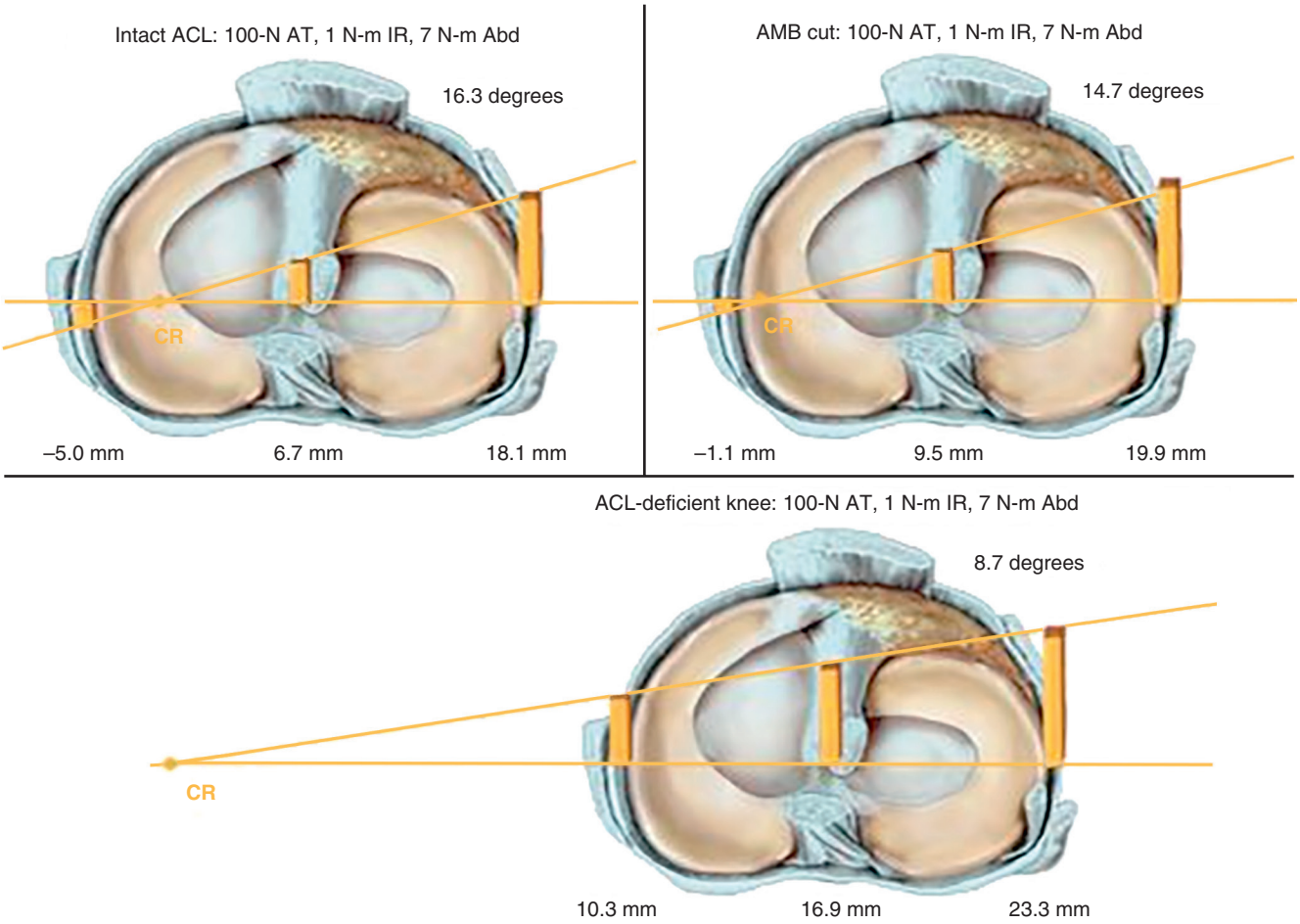


FIG 7-27 A representative right knee specimen showing compartment translations and tibial rotation under pivot shift 4 loading conditions (100-N anterior, 1 N-m internal rotation, 7 N-m valgus) for intact, anteromedial bundle (AMB) cut and anterior cruciate ligament (ACL)-deficient states. AMB sectioning alone resulted in a small but statistically significant change in tibiofemoral compartment translations. *Abd*, Abduction; *AT*, anterior translation; *CR*, center of tibial rotation; *Int*, internal. (From Gardner EJ, Noyes FR, Jetter AW, et al. Effect of anteromedial and posterolateral ACL bundles on resisting medial and lateral tibiofemoral compartment subluxations: *Arthroscopy*. 2015;31(5):901-910.)

In a frequently quoted study, Tashman and coworkers[282] devised a unique methodology of dynamic in vivo measurements of patients who had undergone ACL reconstruction. The investigators used a biplanar radiographic system to measure tibiofemoral displacements while the patients ran downhill on a treadmill. The reconstructed knees showed an increase in mean values of external tibial rotation (3.8 ± 2.3 degrees) and adduction (2.8 ± 1.6 degrees). The effect of these small differences from a clinical standpoint is unknown and future studies are required that involve more dynamic rotational movements in comparison to straight-ahead running to measure the rotational kinematics of the knee joint. The specific ACL graft femoral and tibial tunnel placement was not identified in this study.

Ristanis and associates[244] assessed 11 patients who had undergone B-PT-B reconstruction using kinematic data from a six-camera optoelectronic system obtained during a jump landing and pivoting maneuver. The ACL reconstruction did not restore tibial rotation to normal values of the opposite uninvolved extremity or controls. The femoral tunnel was placed through an AM approach with the knee joint flexed to 120 degrees to achieve a 10 to 11 o'clock lateral wall position. The tibial tunnel was placed into the center of the ACL footprint. The authors noted that a limitation of the study was the movement of skin markers that may not have accurately represented true tibiofemoral joint translations.

Monaco and colleagues[179] evaluated the effect, on internal tibial rotation, of a single-bundle ACL reconstruction combined with an extraarticular procedure compared with a double-bundle ACL reconstruction. Computerized navigation instrumentation was used in the operating room before and after the ACL procedures. The addition of the PL bundle after the AM bundle did not have an effect in reducing AP translation or the limit of internal tibial rotation, and there were no significant differences between the single- and double-bundle reconstructions. The extraarticular reconstruction significantly reduced the internal tibial rotation limit, as would be expected. The tibial placement of the graft was performed with the guide pin 7 mm anterior to the PCL insertion into the posterior ACL attachment. The authors did not determine the effect of either graft configuration on the coupled motions of the pivot shift test but only on the limit of internal tibial rotation alone.

Our conclusions of single-graft versus double-bundle graft ACL studies are summarized in Table 7-7. The hypothesis presented is that an ideally placed single-graft construct (central femoral and tibial ACL attachments, avoiding a vertical graft orientation) provides control of

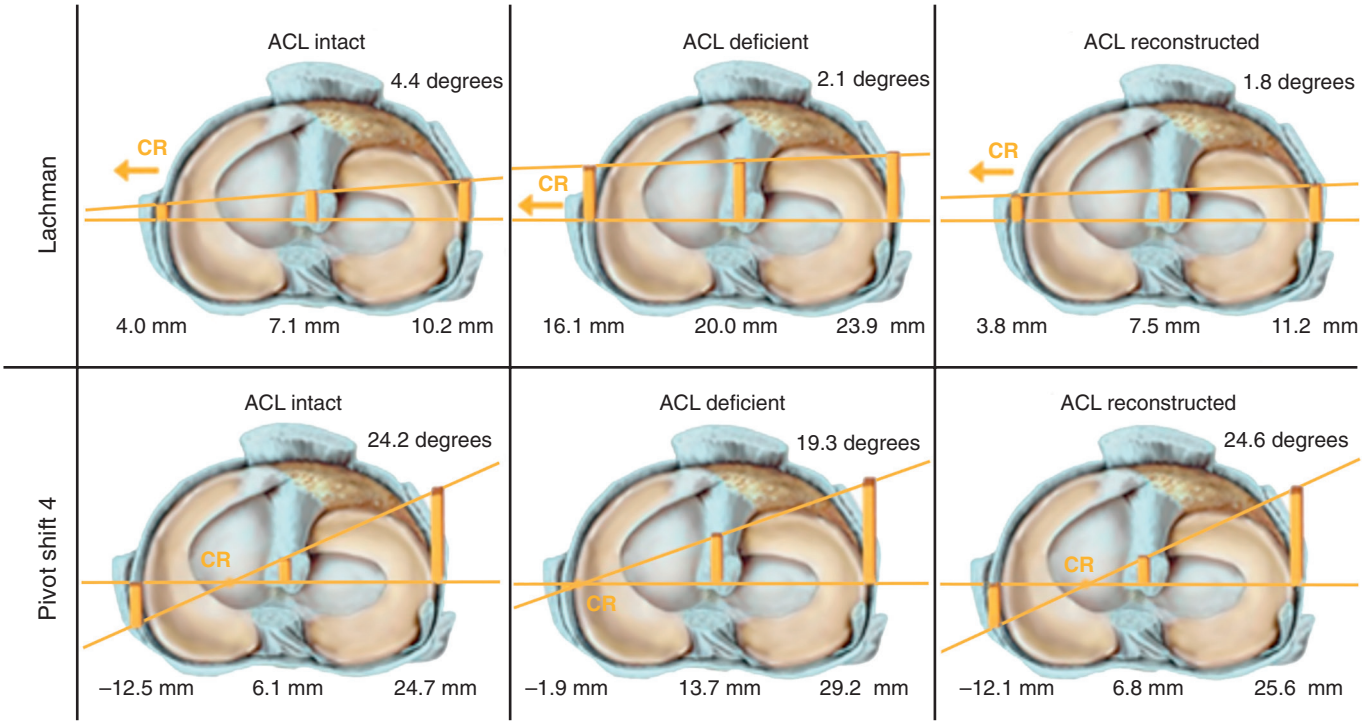


FIG 7-28 Compartment maps of a representative right knee specimen under the Lachman (100 N) and pivot shift 4 loading conditions (100-N anterior, 1 N-m internal rotation, 7 N-m valgus) for intact, anterior cruciate ligament (ACL)-deficient, and ACL-reconstructed conditions. A single bone-patellar tendon-bone graft placed in the central tibial and femoral ACL attachment sites restored translational and rotational stability, as measured by tibiofemoral compartment translations. *CR*, Center of tibial rotation.

TABLE 7-7 Our Conclusions of Single- vs. Double-Bundle Anterior Cruciate Ligament Reconstructions

1. The anterior cruciate ligament (ACL) is not an isometric structure and the length-tension behavior of its fibers cannot be represented by a functional division into two fiber bundles. Native ACL function cannot be replicated by either single- or double-bundle grafts. Oversimplification of ACL anatomy into two bundles is firmly established in the orthopedic literature. However, some studies suggest that there is no true anatomic division. In the future, a better understanding of which ACL femoral and tibial attachment regions represent the most ideal graft placement sites (and their appropriate tensioning) and the surgeon's ability to reproduce these conditions at surgery will result in a distinct advance for ACL surgery.
2. A common recommendation for placement of a single ACL graft into the proximal femoral attachment and posterior one-third tibial attachment (7-8 mm from the posterior cruciate ligament [PCL] fossa) produces a vertically oriented graft that does not provide adequate control of the coupled motions of the pivot shift.
3. Arthroscopic transtibial techniques commonly result in ACL grafts placed into a proximal femoral position through a tibial tunnel that is too posterior. Grafts in this location may decrease anterior tibial translation, but not the rotational motions of the pivot shift phenomena, and are not recommended.
4. A single ACL graft appears to be most ideally placed in the central femoral and tibial attachments, using an anteromedial (AM) portal with the knee in hyperflexion (or flexible guide pin, drill) or a two-incision technique (retrograde drill, flip drill) for the femoral tunnel. Transtibial arthroscopic drilling techniques are not recommended.
5. The double-bundle ACL technique has the theoretical advantage of locating grafts and collagen fibers throughout the entire ACL anatomic attachment sites (in contrast to single grafts). Robotic laboratory and clinical studies supporting ACL double-bundle grafts appear to reference the results to a hybrid single-bundle (proximal femoral, posterior tibial location), which is less ideal in resisting rotational loading.
6. It has not been experimentally proven from robotic or clinical studies that there is any difference (resisting the abnormal motions of the pivot shift phenomenon) between a central anatomic single ACL graft and a double-bundle graft.
7. The concepts of ACL double-bundle grafts have prompted a worthwhile reevaluation of ACL anatomy and study of the ideal location for both single- and double-bundle grafts. The added operative complexity of a double-bundle graft is not required compared with a well-placed single centrally located anatomic graft. In addition, revision procedures for failed double-bundle ACL reconstructions may represent an added and unnecessary complexity.
8. ACL double-bundle techniques often use soft tissue allografts to achieve the desired graft cross-sectional area. Allografts pose the added problem of a higher failure rate owing to delayed graft incorporation and healing compared with autografts. Prospective, randomized Level I clinical studies comparing anatomic single- and double-bundle autografts are required to provide clinical data without the added variables related to allografts.
9. Further clinical studies and objective clinical testing methods to measure rotational knee stability are required. Measurements of the coupled motions in the pivot shift test are required. The limits of anterior tibial translation of the lateral and medial tibiofemoral compartments with these coupled motions provide the best description of the anterior joint subluxations and rotational stability.

the abnormal pivot shift motions, avoiding the necessity and added complexity of a double-bundle graft reconstruction.

Recommended Tibial and Femoral Anterior Cruciate Ligament Graft Locations

Given the variation in ACL anatomic shapes among specimens, it is important during surgery to outline the individual size and shape of the ACL attachment for each knee. This can be done in a primary ACL reconstruction, but usually not in revisions. The cadaveric studies provide important anatomic reference landmarks. Because of the variation in ACL attachment shapes, it would be expected that there would exist variation among surgeons on the locations chosen for both single- and double-bundle ACL graft locations. Newer computer navigation techniques have been studied to aid in the placement of ACL grafts; however, it is still unknown at present which anatomic points to select for graft tunnels that would correlate with clinical stability results.

The important landmarks for the ACL tibial attachments are the medial tibial spine, RER of the proximal PCL fossa, and the attachment of the lateral meniscus. The PCL is a poor soft tissue landmark for the posterior extent of the native ACL attachment. It should be noted that some authors[107] have advocated a guide pin and tibial tunnel placement 6 to 8 mm from the PCL, which would place the tibial tunnel in the posterior portion of the ACL. In some knees, the tibial tunnel would be posterior to the native ACL attachment and just a few millimeters from the RER or interspinous ridge. This posterior tibial tunnel produces a near-vertical ACL graft that would not be expected to resist rotational loads in obliterating the pivot shift phenomenon, as already discussed.

The ACL tibial attachment location we recommend for a single graft is directly adjacent to the lateral meniscus anterior horn attachment as shown in Figure 7-29. The ACL attachment can be easily mapped at surgery based on the anatomic references provided. In some knees, the anterior extent of the ACL attachment may be obscured by soft tissues, and in these cases, the RER or posterior interspinous ridge of the PCL fossa is an important landmark. The center of the ACL will be 16 to 20 mm anterior to the RER. The guide pin is most ideally placed eccentric and 2 to 3 mm anterior and medial to the true ACL center, because the ACL graft displaces to the posterior and lateral aspect of the tibial tunnel.[45] The tunnel places the majority of the graft within the central tibial attachment and avoids the posterior attachment location. It is important that graft impingement against the anterior intercondylar notch does not occur because the circular graft may occupy a portion of the native flattened ACL tibial attachment. An anterior notchplasty is required, particularly in knees with an A-shaped notch. In many ACL revision knees, the bony ridge posterior to the ACL attachment ("no-man's land," Fig. 7-30) has been disrupted with a prior graft tunnel that extends 1 to 2 mm from the RER and requires a bone graft before the revision procedure. To avoid a vertical graft orientation, it is important that during the ACL tibial tunnel preparation (primary or revision surgery), the tibial drill does not inadvertently penetrate into or beyond the posterior one-third ACL attachment and adjacent RER.

Important landmarks for the femoral attachment are the posterior articular cartilage, the Blumenstaat line, and identification of the ACL attachment on the lateral femoral wall of the notch (in the regions outlined on the grid systems). The goal is to locate the tunnel in the central to proximal thirds to maintain ACL graft length, and within the central direct ACL native insertion that occurs through fibrocartilage and not within the posterior indirect insertion of fibers adjacent to the femoral articular cartilage edge. A tunnel distance (posterior or deep) from the femoral condyle articular cartilage of 3 mm prevents an excessive posterior graft placement that would be slightly lax with increasing knee flexion (flexion laxity). Again, the emphasis is made that no ACL fibers extend to the intercondylar roof; all of the fibers are on the lateral wall. Tsukada and coworkers[290] reported that the osseous ridge on the lateral femoral wall of the intercondylar notch (resident's ridge) had major positional and dimensional variations and should not be used as a reference for femoral tunnel creation.

Bird and associates[28] reported in a cadaveric study that, with the knee at 90 degrees of flexion, the central location of the ACL attachment was 50% of the AP depth of the femoral condyle (junction articular cartilage) along the lateral bifurcate ridge. The possible error in this technique is the distance that the central point is measured along the bifurcate ridge to avoid a tunnel adjacent to the femoral articular cartilage. Piefer and colleagues,[230] in a systematic review of 20 ACL femoral footprint publication, noted differences in techniques among studies; however, these investigators arrived at recommended arthroscopic osseous landmarks on the lateral wall of the intercondylar notch (Fig. 7-31) which are very useful for the arthroscopic surgeon. These include, when possible, identification of the native ACL attachment, the resident's ridge or intercondylar ridge, the bifurcate ridge, the notch roof where no ACL fibers attach, and the articular cartilage junction of the lateral femoral condyle. We first place the knee at 30 degrees (see Fig. 7-30), making sure the radius of the tunnel plus 3 mm is followed. For example, a 10 mm drill hole would have a radius of 5 mm plus 3 mm, or 8 mm from the articular cartilage. We measure tunnel placement at both 30 degrees and 90 degrees of knee flexion and each method is different in terms of measurements as discussed. The question regarding the ideal femoral graft placement at time zero (for example, proximal two thirds, central two thirds) and its effects on subsequent biologic remodeling cannot be answered and still requires more kinematic and clinical studies. It is our impression based on current knowledge that there would be no difference between these two femoral placements that would affect final clinical results. With femoral tunnel placement try to ensure the placement is not too anterior or posterior or distal in the femoral footprint.

Hensler and associates[97] conducted a study on the ACL femoral tunnel morphology induced by use of an AM portal drilling technique with knee hyperflexion. From a review of the literature, the authors determined that the average femoral ACL insertion size was 8.9 mm wide, 16.3 mm long, and 136 mm^2 in area. The femoral tunnel aperture was influenced by drill-bit diameter, transverse drill angle, and knee flexion angle (Fig. 7-32). The femoral tunnel aperture best matched the native ACL footprint at 102 degrees of knee flexion, whereas at 130 degrees of flexion, a mismatch in area of 13.5% was calculated (Fig. 7-33). Even so, the higher knee flexion angle of 115 degrees to 120 degrees lessens the chance of a posterior femoral wall blow-out. This study shows how the AM accessory portal drilling of the femoral ACL tunnel requires clinical experience and precise guide pin placement. The surgeon must determine that the exiting guide pin position is in the midlateral plane, above the femoral epicondyle, and maintain a 3- to 4-mm osseous posterior rim from the tunnel wall to the femoral articular cartilage. An angled flexible guide pin and drill are useful in larger patients when the AM portal drilling technique is selected because it is difficult to achieve 120 degrees of knee hyperflexion.

For single grafts, we recommend a central anatomic ACL placement with the femoral guide pin 2 to 3 mm above the midpoint of the proximal-to-distal length of the ACL attachment (30 degrees of knee flexion) and 8 mm from the posterior articular cartilage edge (see Fig. 7-30). This will produce a 10-mm tunnel, leaving a 3-mm thick posterior tunnel wall. The senior author prefers to define the ACL

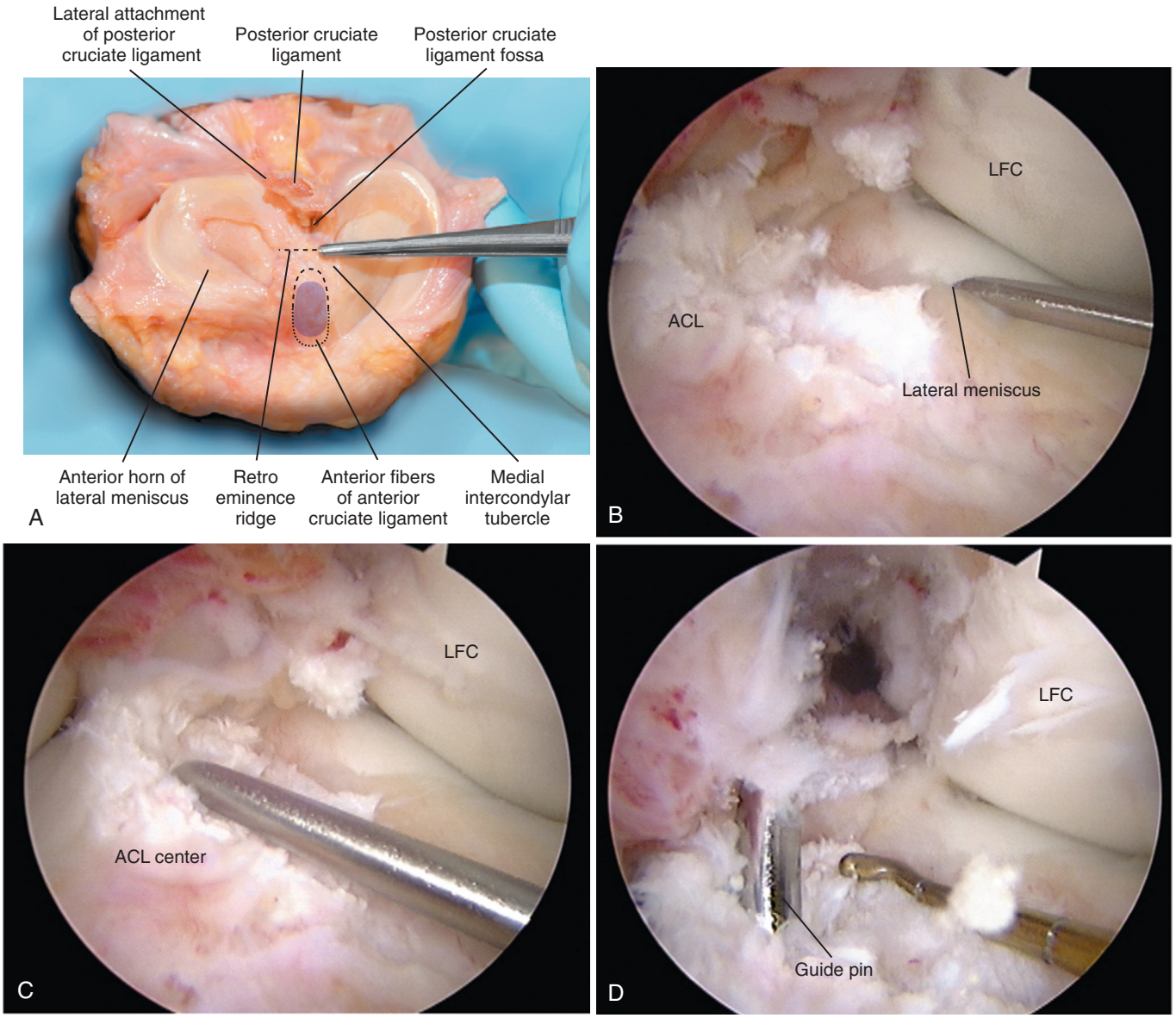


FIG 7-29 **A,** Anterior cruciate ligament (ACL) tibial attachment is outlined along with the shaded region, indicating a central placement of an ACL graft and tibial tunnel. **B,** Arthroscopic ACL attachment anterior to the posterior edge of the lateral meniscus. **C,** Center of ACL attachment is marked and is anterior to the lateral meniscus posterior edge. **D,** Placement of central guide pin for single-tunnel ACL reconstruction. *LFC,* Lateral femoral condyle.

attachment at 20 degrees to 30 degrees of flexion with the arthroscope in the AM portal. After the femoral site is marked, the knee can be placed in 120 degrees of flexion if an AM portal arthroscopic drilling technique is selected. A 9- to 10-mm diameter tunnel occupies the central ACL attachment, leaving only the most proximal and distal few millimeters of the attachment not occupied by a graft. It is important that the ACL femoral tunnel not be placed too far posteriorly because this produces excessive graft tension with knee extension. In addition, the graft should not be too distal at its femoral attachment because this shortens the intraarticular graft tibiofemoral length. The location for a single-tunnel ACL reconstruction is more distal than recommendations for a 1 o'clock tunnel that replaces only the proximal portion of the ACL femoral attachment. However, it has not been determined in clinical studies if a difference exists between the 1 o'clock and central femoral graft placement sites.

In Figure 7-34, *A*, the hybrid graft position of a proximal femoral and posterior tibial position is shown, which we do not recommend. The preferred central anatomic tibial and femoral position is presented in Figure 7-34, *B*, and the femoral position is presented in Figure 7-34, *C*. In our opinion, it would not be possible from a clinical standpoint to examine the difference in knee stability (pivot shift and Lachman tests and subjective symptoms) between a central femoral ACL graft location (that occupies the central two thirds, single graft) and a proximal femoral ACL graft location (that occupies the proximal two thirds, single graft). Both graft locations are described as anatomic and avoid placing the graft in the distal two thirds that would represent a shortened ACL construct. A recent study[242] suggested that a central femoral anatomic placement, achieved using an AM approach, was associated with a higher failure rate compared with grafts placed through a transtibial approach (5.16% and 3.20%, respectively).

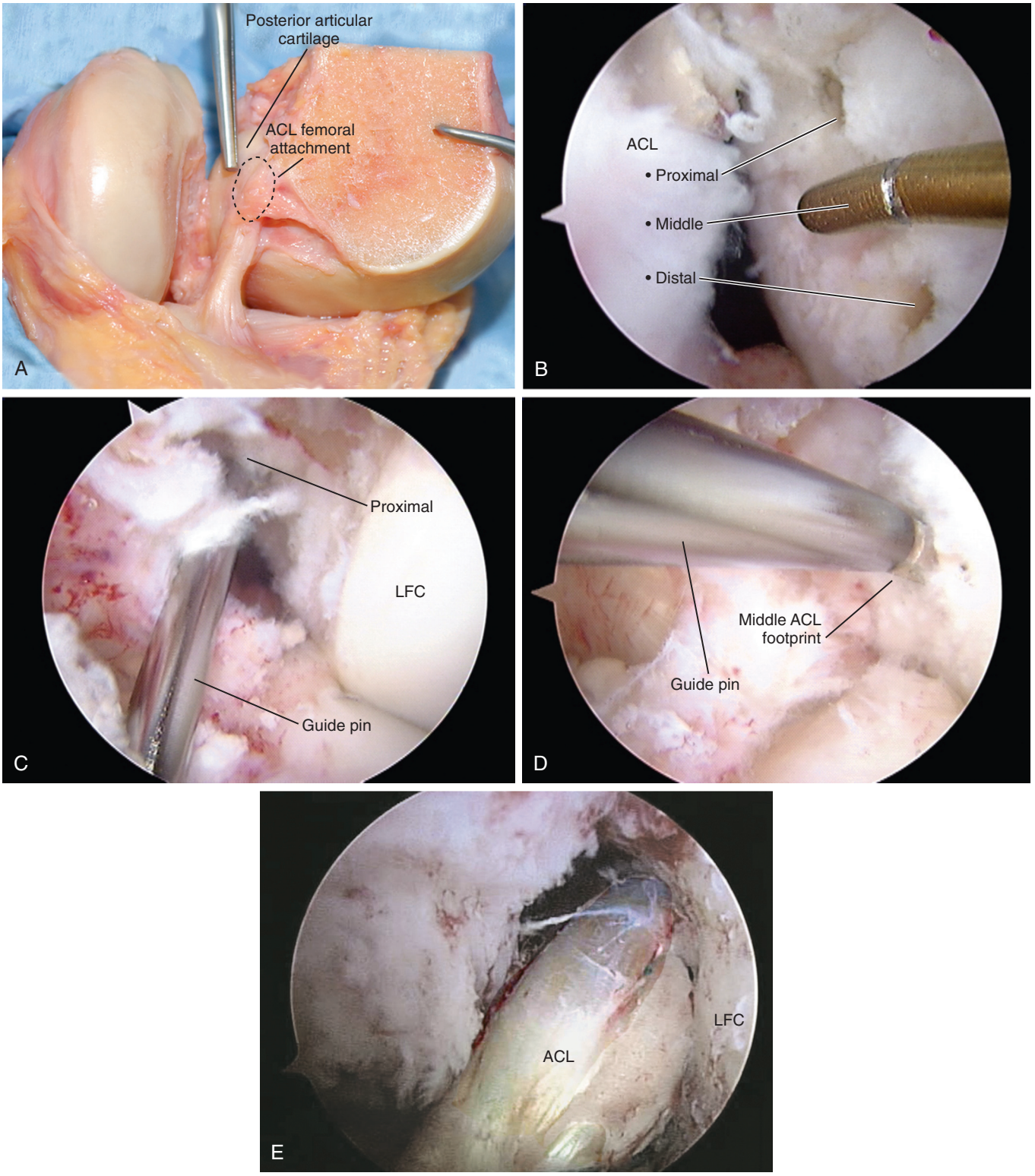


FIG 7-30 **A,** Anterior cruciate ligament (ACL) femoral attachment at 30 degrees of knee flexion (our preference rather than 90 degrees) shows the entire attachment on lateral wall of notch. **B,** Three points identified in proximal, middle, and distal portions of ACL attachment. **C,** Transtibial guide pin placement reaches only proximal one third of ACL attachment with a portion of the femoral tunnel extending onto the notch roof when a central ACL tibial tunnel is used. **D,** ACL central point reached with knee hyperflexion and anteromedial portal or with two-incision rear-entry technique. **E,** Final graft appearance on lateral wall. *LFC,* Lateral femoral condyle.

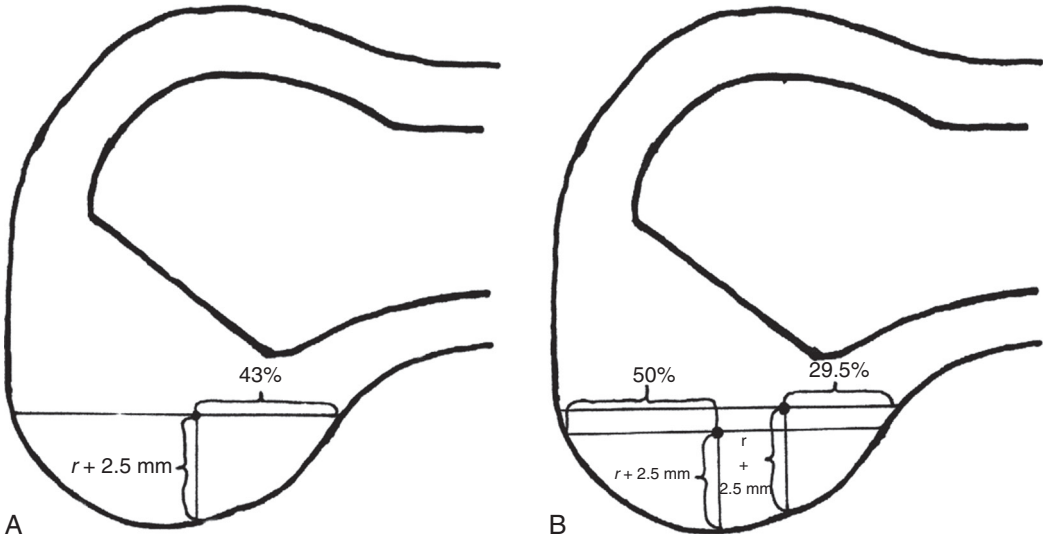


FIG 7-31 **A,** Sagittal section drawings representing the lateral wall of the intercondylar notch, right femur, with mean anatomic centrum of the anterior cruciate ligament (ACL) femoral footprint marked. **A,** The anatomic centrum of the ACL femoral footprint is 43% of the proximal to distal length of the lateral, femoral intercondylar notch wall and femoral socket radius (r) plus 2.5 mm anterior to the posterior articular margin. **B,** The anatomic centrum of the ACL femoral footprint anteromedial bundle (point on right) is 29.5% of the proximal to distal length of the lateral, femoral intercondylar notch wall. The anatomic centrum of the ACL femoral footprint posterolateral bundle (point on left) is 50% of the proximal to distal length of the lateral, femoral intercondylar notch wall. From posterior to anterior, the anteromedial bundle appears slightly anterior to the posterolateral bundle, and both bundles appear as r (socket radius) + 2.5 mm anterior to the posterior cartilage margin. (From Piefer JS, Pflugner TR, Hwang MD, Lubowitz JH. Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. *Arthroscopy.* 2012;28:872-881.)

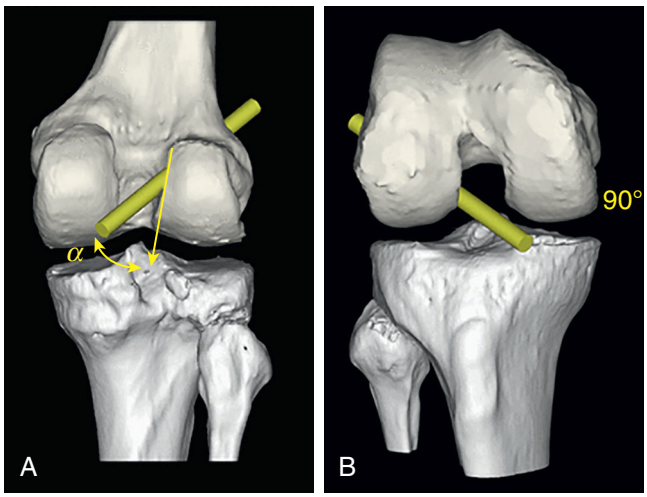


FIG 7-32 Three-dimensional model showing different transverse drill angles. **A,** Posterior view. **B,** Anterior view. α, angle at which the drill bit intersects the bone. (From Hensler D, Working ZM, Illingworth KE, et al. Medial portal drilling: effects on the femoral tunnel aperture morphology during anterior cruciate ligament reconstruction. *J Bone Joint Surg Am.* 2011;93:2063-2071.)

However, this study only used revision surgery in the calculation of failure and patients were followed only for a mean period of 22 months postoperatively.

ANTERIOR CRUCIATE LIGAMENT GRAFT HEALING

The process of biologic healing of ACL grafts is discussed in detail in Chapter 5. The potential use of MRI to document healing of the collagenous portion of the graft, the osseous tunnels, and the bone-ligament insertion sites after surgery is well known. However, standard MRI techniques that use echo times longer than a few milliseconds acquire very low signal from the tendon graft, which is subsequently viewed through negative contrast with surrounding tissues.[240] In addition, fixation materials cause local signal loss that results in low contrast between the graft and hardware.

In an effort to improve these problems, contrast-enhanced MRI was used to evaluate ACL grafts serially over the first postoperative year by Muramatsu and colleagues[182] and Ntoulia and associates.[216] In 2008, Muramatsu and colleagues[182] compared the signal/noise quotient (SNQ) of 20 ACL B-PT-B autografts with 24 fresh-frozen B-PT-B allografts at 1, 4, 6, and 12 months postoperatively. The center of the intraarticular portion of the ACL graft was evaluated before and after contrast enhancement. The authors reported statistically significant differences at all time periods, with the autografts demonstrating higher SNQ values. They did not provide any clinical data in regard to knee stability or sports activities resumed postoperatively.

In 2011, Ntoulia and associates[216] described the use of contrast-enhanced MRI to study changes in signal intensity in three distinct graft sites over time. The sites were (1) the intraarticular portion of the graft, (2) the site of the graft location inside the osseous tunnels, and (3) site of the graft that was adjacent to the fixation material inside the tunnels. The cohort included 32 males who underwent ACL B-PT-B reconstruction and MRI evaluations at the third postoperative day and 6 and 12 months postoperatively. All patients had a clinically stable knee postoperatively (negative Lachman and pivot shift tests) and resumed their preinjury sports activity level by 12 months. Distinct signal changes were noted between 3 days postoperative and 6 and 12 months later. The intraarticular site was the first and fastest to achieve satisfactory contrast medium uptake, which was noted at the 6-month test with no further alteration found at the 12-month test.

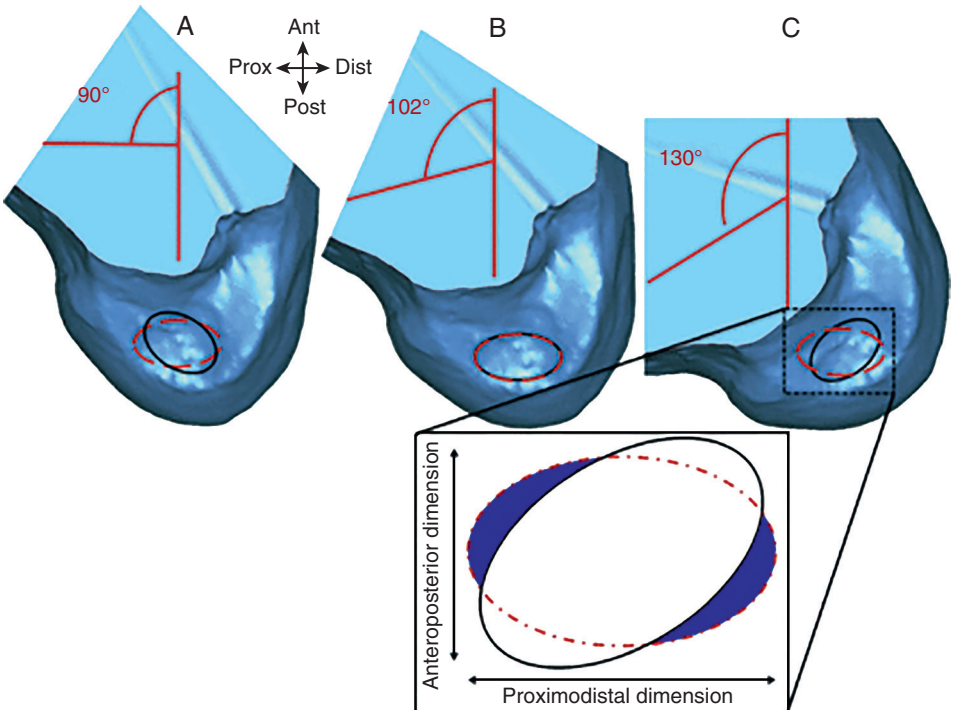


FIG 7-33 Examples of different knee flexion angles, where the anterior cruciate ligament (ACL) footprint is shown by the black oval lines and the tunnel aperture is shown by the red dotted lines. **B,** Overlapping ACL footprint and tunnel aperture at a knee flexion angle of 102 degrees. **A** and **C,** Mismatch between the ACL footprint and tunnel aperture in different knee flexion angles. The inset for **C** shows the resulting nonanatomic aperture area. *Ant,* anterior; *Dist,* distal; *Prox,* proximal. (From Hensler D, Working ZM, Illingworth KE, et al. Medial portal drilling: effects on the femoral tunnel aperture morphology during anterior cruciate ligament reconstruction. *J Bone Joint Surg Am.* 2011;93:2063-2071.)

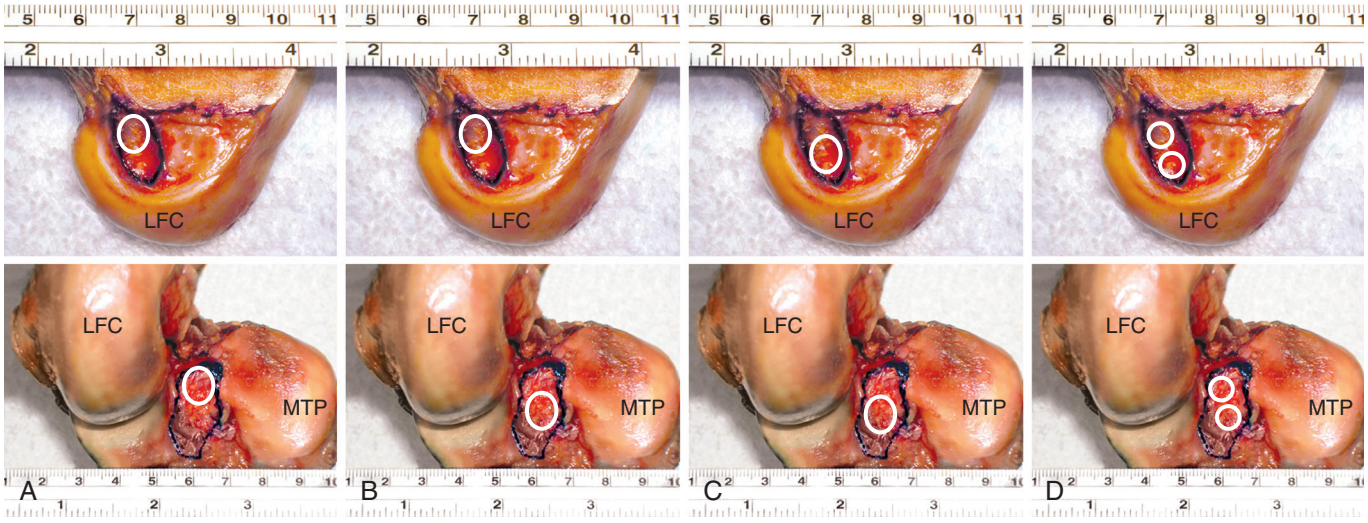


FIG 7-34 Summary of different femoral and tibial graft positions that are possible using anteromedial (AM) and posterolateral (PL) bundle terminology. **A,** Classic AM femur to PL tibia results in a vertical graft with a tibial tunnel placed too far posteriorly. **B,** A more central tibial tunnel is advantageous for control of rotational stability. **C,** The ideal central femoral-tibial tunnel locations for a single graft reconstruction. **D,** The placement of a two-bundle anterior cruciate ligament reconstruction. *LFC,* Lateral femoral condyle; *MTP,* medial tibial plateau.

The other sites showed a slower progression of remodeling that was still in progress at the 12-month test.

Other studies have more recently advocated the use of ultrashort echo-time (UTE) MRI techniques to study ACL grafts after implantation.[240] Three-dimensional UTE techniques allow visualization of short-T_2 components in tendons, ligaments, and menisci that provide superior contrast between ACL grafts and fixation material.[26,27,41,69,132,238-240,295] At the time of writing, only one in vivo study documented the use of 3-dimensional UTE in three asymptomatic men who had undergone semitendinosus-gracilis (STG) autograft

reconstruction 3 to 8 years previously.[240] The tests demonstrated a high graft signal that allowed visualization of the graft's internal structure (allowing homogeneity of the graft to be judged) and superior depiction of the fixation material. The authors commented that the addition of contrast agents may even further enhance the image contrast.

In 2014, Biercevicz and colleagues[27] further improved UTE MRI techniques by using high-resolution 3-dimensional images with no slice gap, volume and relaxation time (instead of signal intensity), and T_2 mapping in a porcine model. The authors reported that a multiple regression model based on ligament volume and its corresponding T_2 values significantly predicted the ligament's maximum load, yield load, and linear stiffness (that were determined with tensile testing) after 52 weeks of healing ($R^2 = 0.92, 0.82, 0.33$, respectively; $P < .001$). The T_2 relaxation time was believed to represent an MRI parameter that would be applicable across scanners of the same strength and among institutions. Further studies are required to evaluate the efficacy of using this method to predict structural ACL properties in vivo for longitudinal analysis.

In 2015, Ge and associates[79] used MRI to obtain 3-dimensional dual-echo steady-state images that were imported into solid modeling software that created 3-dimensional model reconstructions of bone tunnels in 36 patients. Eighteen patients had autograft and 18 had allograft ACL reconstructions and all were at least 2 years postoperative at the time of the study. The study found SNQs of the allograft group were consistently higher than those in the autograft group in the tibial tunnel. The authors concluded that the allograft tendons may have inferior remodeling in the bone tunnel; however, all knees had bone tunnel enlargement at the femoral aperture most likely because of the biomechanical effect of graft motion (sagittal and longitudinal graft-tunnel motion).

CLINICAL EVALUATION

A thorough history is performed, including a detailed account of all knee injuries and the operative procedures that have been performed. A comprehensive physical examination involving assessment of knee flexion and extension, patellofemoral indices, tibiofemoral crepitus, tibiofemoral joint line pain, muscle strength, and gait abnormalities is also completed. The surgeon must determine all of the abnormal translations and rotations in the knee joint. The medial posterior tibiofemoral step-off on the posterior drawer test is done at 90 degrees of flexion. Quantification of posterior tibial translation may be performed using stress radiography in knees with PCL ruptures to determine if the rupture is partial or complete (see Chapter 16).[99] The appropriate tests to determine the integrity of the ACL are performed, including KT-2000 arthrometer testing at 20 degrees of flexion (134-N force) to quantify total AP displacement. The pivot shift test is recorded on a scale of 0 to III, with a grade of 0 indicating no pivot shift; grade I, a slip or glide; grade II, a jerk with gross subluxation or clunk; and grade III, gross subluxation with impingement of the posterior aspect of the lateral side of the tibial plateau against the femoral condyle.

Insufficiency of the PLS and medial ligament structures are determined by varus and valgus stress testing at 0 and 30 degrees of knee flexion. The surgeon estimates the amount of joint opening (in millimeters) between the initial closed contact position of each tibiofemoral compartment, performed in a constrained manner avoiding internal or external tibial rotation, to the maximal opened position. The result is recorded according to the increase in the tibiofemoral compartment of the affected knee compared with that of the opposite normal knee. Abnormal medial or lateral joint opening may be measured with stress radiographs. The tibiofemoral rotation dial test at 30 and 90 degrees detects increases in external tibial rotation with posterior subluxation of the lateral tibial plateau or anterior subluxation of the medial tibial plateau because of medial ligament injury. A word of caution is necessary; it is possible to confuse increased external tibial rotation for a PL injury and miss the medial side ligament injury that requires correction.[206] The presence of a varus recurvatum in both the supine and standing positions is carefully assessed. Gait analysis is performed to detect a varus or valgus thrust or hyperextension thrust. Patients can often demonstrate their knee instability on standing, with a few degrees of knee flexion, by producing an external femoral rotation, which reproduces the pivot shift phenomena. Abnormal varus or valgus tibiofemoral joint opening may also be demonstrated by the patient.

Radiographs taken during the initial examination include standing AP at 0 degrees, lateral at 30 degrees of knee flexion, weight-bearing physical activity (PA) at 45 degrees of knee flexion, and patellofemoral axial views. Double-stance full-standing radiographs of both lower extremities, from the femoral heads to the ankle joints, are obtained in knees in which varus or valgus lower extremity alignment is detected on clinical examination. The mechanical axis and weight-bearing line are measured as discussed in Chapter 26. MRI is performed to provide further details of the condition of the articular cartilage and menisci. Fast-spin-echo techniques and 3-Telsa articular cartilage T_2 mapping are available when deemed necessary to obtain superior-quality articular cartilage images.[205,234]

At our center, patients complete questionnaires and are interviewed for the assessment of symptoms, functional limitations, sports and occupational activity levels, and patient perception of the overall knee condition according to the Cincinnati Knee Rating System (see Chapter 41).[22] The forms are available online for the patient to obtain before their consultation.

CRITICAL POINTS Clinical Evaluation

- Perform thorough history.
- Comprehensive physical examination assesses knee flexion and extension, patellofemoral indices, tibiofemoral crepitus, tibiofemoral joint line pain, muscle strength, gait abnormalities.
- Perform all stability tests to document abnormal tibial translation, rotations, and tibiofemoral compartment translation.
- Knee arthrometer test: 134 N.
- Radiographs: standing anteroposterior at 0 degree, lateral at 30 degrees; weight-bearing posteroanterior at 45 degrees; patellofemoral axial views; double-stance hip-knee-ankle alignment; lateral and posterior stress views as indicated.
- MRI, including articular cartilage image techniques.
- Cincinnati Knee Rating System for subjective, objective, functional scoring.

PREOPERATIVE PLANNING

All abnormalities or potential problems are addressed preoperatively, including patient expectation issues, muscular weakness, painful

CRITICAL POINTS Preoperative Planning

- Obtain full knee motion, muscle reeducation, and return of function before surgery.
- Address patient expectation and goals of surgery.
- Determine need for concomitant procedures, extraarticular procedures, and other ligament reconstructions to correct all instabilities.

neuromas, residual CRPS, and anterior knee pain caused by patellofemoral cartilage damage. A loss of full knee extension creates problems. It is important to obtain full knee motion before surgery. The exception is a bucket-handle meniscus tear that produces a mechanical block to full extension or flexion.

Considerable counseling and patient education are required on the expected results and outcomes from the reconstruction, as previously discussed. This is especially important in knees with preexisting arthritis or loss of meniscal function or those that require additional major operative procedures. A surgeon-rehabilitation team is required to provide instruction on rehabilitation to ensure that the postoperative exercise program will be successfully followed by the patient. The patient and family consult with the physical therapy team before surgery to ensure that the postoperative rehabilitation requirements are thoroughly understood. We have written specific patient-oriented electronic books (eBooks) for ACL surgery that provide extensive preoperative information and counseling.

Knees with grossly positive clinical laxity tests have involvement of the secondary ligament restraints, primarily the lateral structures. Associated medial or lateral ligament laxity is an indication for medial or lateral ligament reconstruction. In the ACL Reconstruction Clinical Studies section that follows, the results of autografts and allografts are discussed in further detail.

INTRAOPERATIVE EVALUATION

All knee ligament subluxation tests are performed after the induction of anesthesia in both the injured and contralateral limbs. The amount of increased anterior tibial translation, posterior tibial translation, lateral and medial joint opening, and external tibial rotation are documented. A thorough arthroscopic examination is conducted, noting articular cartilage surface abnormalities and the condition of the menisci. Appropriate debridement and meniscus repair or partial excision are performed as necessary.

The lateral and medial gap tests are done during the arthroscopic examination (see Chapter 17).[202] The knee is flexed to 30 degrees and a varus load of approximately 89 N applied. A calibrated nerve hook is used to measure the amount of tibiofemoral compartment opening. Knees that have 12 mm or more of joint opening at the periphery or 10 mm at the midpoint of the tibiofemoral compartment require a PL or medial ligament reconstructive procedure.

OPERATIVE TECHNIQUES

Graft Selection

The principles of ACL surgery are summarized in Table 7-8. Currently, there is no standard graft choice for ACL reconstruction. Autograft

CRITICAL POINTS Operative Techniques: Graft Selection, Patient Setup and Positioning, Graft Harvest

Graft Selection
- Primary knees: Prefer B-PT-B autograft in athletes, STG in recreational, more sedentary patients or those with patellofemoral problems.
- Allografts reserved for multiligament procedures, special cases where graft harvest is to be avoided.

Patient Set up and Positioning
- Patient uses chlorhexidine wash operative limb three days before surgery.
- Antibiotic infusion 1 hour before surgery.
- Nonsteroidal antiinflammatory medication morning of surgery, continued 72 hours postoperative.
- Knee to be reconstructed initialed by surgeon, time-out in operating room.
- Patient supine, place tourniquet middle thigh for use only as necessary.
- Use leg holder for initial arthroscopy, meniscus repairs.
- Knee portion bed flexed 60 to 90 degrees, bed midportion retroflexed 15 degrees.
- Uninvolved extremity placed in well-cushioned padded holder.
- After initial arthroscopy, adjust bed to allow 120 degrees of knee flexion.

Graft Harvest, B-PT-B Autograft
- Inflate tourniquet 275-mm pressure.
- 3- to 4-cm incision adjacent medial border patellar tendon, medial to inferior pole of patella, mobilize skin flaps for cosmetic approach.
- Retinaculum middle patellar tendon incised, limited dissection only for width of graft to be removed.
- 50% of patients will have small area of numbness just lateral to the patellar tendon counsel preoperatively.
- Use precut 10-mm and 22-mm paper ruler to define graft dimensions.
- Patellar tendon incised in midportion.
- Trapezoidal bone block graft from patella removed with fine saw cuts, osteotome, and similar procedure for tibial bone block.
- Sutures placed each bone block, prepared for passage.
- Graft wrapped in blood-soaked sponge.
- Diameter of tunnels 1 mm larger than diameter of bone block.
- End of procedure, loosely approximate tendon graft harvest site with sutures.
- Meticulous bone graft from core reamer patella, tibia defects. Place two horizontal mattress sutures inferior pole patella, superior tibial tendon attachment to hold bone grafts in defects, close anterior tissues.

Graft Harvest: Quadriceps Tendon-Patellar Tendon Autograft
- 5- to 6-cm longitudinal incision from superior pole patella, extending proximally.
- Graft harvest: 10 mm wide through all 3 layers, length 60 to 70 cm.
- Bone graft sized 9- to 10-mm diameter.
- Close quadriceps tendon defect with sutures.
- Meticulous bone grafting patellar defect, closure soft tissues

Graft Harvest: STG Autograft
- 3- to 4-cm oblique incision over pes tendons.
- Identify, palpate STG tendons.
- Turn down confluent tibial attachment.
- Grasp each tendon 90-degree angle distal end, roll two to three times about straight hemostat.
- Superficial tissues removed, overlying sartorius fascia protected.
- Proximal fascia bluntly dissected, ST tendon attachment medial gastrocnemius fascia incised, avoid saphenous nerve.
- Displace each tendon 10 cm in push-pull maneuver.
- Pass graft harvester, transect each tendon 20 cm for a four-strand graft or 24 cm for a six-strand graft.
- Prepare, wrap in blood-soaked sponge.
- Six-strand graft used in women and patients of small stature.

Iliotibial Band Extraarticular Tenodesis
- Goal is to reconstruct the posterior femoral tibial ITB attachment, which is an important restraint to abnormal internal tibial rotation.
- Procedure is described in detail in Chapter 8.

TABLE 7-8 Principles of Anterior Cruciate Ligament Surgery

1. The principles for successful anterior cruciate ligament (ACL) reconstruction are the same for both primary and revision ACL procedures. The goal is to obtain a stable knee joint with improved function without a complication.
2. The indications for ACL surgery involve profiling the patient's future athletic pursuits, as discussed. Athletic patients participating in turning, twisting, and jumping activities are candidates for ACL reconstruction, whereas sedentary patients are treated conservatively. The recreational athlete has time to choose; however, it would be incorrect to return this patient to strenuous athletic pursuits with an ACL-deficient knee. A primary goal is to prevent a meniscus tear occurring from a repeat giving-way injury. All studies show that the loss of meniscus function results in a high rate of future joint arthritis.
3. ACL grafts should be placed in an anatomic position within the femoral and tibial footprint (single- or double-bundle graft). In single ACL grafts, the central portion of the femoral and tibial attachment site is recommended. The graft should not be placed in a femoral tunnel located solely in the proximal one third of the ACL footprint. This results in an orientation that is not effective in controlling anterior tibial translation and internal tibial rotation. This proximal placement may also occur in double-bundle techniques, such as smaller knees in which a more proximal femoral tunnel is selected to make room for the second femoral tunnel. The native ACL femoral attachment is located entirely on the lateral wall; no fiber attachments extend to the intercondylar roof.
4. A less than ideal graft placement may also occur at the ACL tibial attachment when the tibial tunnel location is in the posterior one third of the ACL footprint. A commonly used ACL tibial guide system references the tibial tunnel 6 to 8 mm from the posterior cruciate ligament (PCL) at the tibia. This places the tibial tunnel in the posterior one third of the ACL attachment and, in some knees, posterior to the native ACL attachment, resulting in a vertical graft orientation.
5. A limited notchplasty is usually required during ACL primary and revision surgery, with an anatomic central tibial ACL placement to prevent roof impingement in extension and to have an adequate graft space between the lateral notch and the PCL.
6. Associated ligament injuries overload an ACL graft and require diagnosis and correction to prevent failure of the ACL reconstruction. Abnormal medial or lateral gap tests during arthroscopy indicate that the ACL graft alone will not correct the instability. There exists a select group of knees with significant physiologic laxity of associated knee ligaments that should be treated as a concurrent pathologic instability. An abnormal lateral tibiofemoral gap of 12 mm on varus testing at arthroscopy requires surgical correction regardless of whether the gap resulted from injury, physiologic laxity, or a combination of both problems.
7. Abnormal knee hyperextension of 12 to 15 degrees may overload an ACL graft and requires operative correction. The recommended posterolateral graft reconstructive procedures for a severe hyperextension varus recurvatum deformity are described in Chapter 17. Certain ACL revision knees with stretching or injury to the secondary ligament restraints and a gross grade III pivot shift have a higher revision failure rate, and a lateral extraarticular procedure is warranted.
8. The selection of an autograft or allograft to provide the highest success remains controversial. We recommend autografts (ipsilateral or contralateral) for both primary and ACL revision surgery owing to the superior healing, graft incorporation, overall higher success rates in clinical studies, and avoidance of transmission of disease (even though of rare incidence). Allografts are reserved for multioperated revision knees with concurrent instability where suitable graft sources are not available or special clinical cases in which a graft harvest is to be avoided. Use of extraarticular allografts is discussed in subsequent chapters for medial and lateral ligament reconstructions.
9. During revision surgery, a variety of instruments and techniques are required for graft placement and fixation when the tibial or femoral tunnels are enlarged. If anatomic graft placement cannot be achieved using existing tunnels, staged bone grafting is required. The integrity and quality of the surrounding bone must be restored to allow a close approximation between the tunnel and graft interface for graft incorporation and a successful healing process.
10. Proper rehabilitation supervised by professionals trained in problems related to complex knee surgery is essential for success and the return of lower extremity function and avoidance of arthrofibrosis. Rehabilitation principles and protocols are addressed in Chapters 10 to 12.
11. Patient education is required regarding expected outcomes and return to athletic activities. A primary ACL patient may have sustained articular cartilage damage or loss of meniscus function that will affect future athletic activities. A majority of revision knees have associated articular cartilage damage and partial or total loss of meniscus function. Many patients who have joint stability restored believe their preinjury athletic activities may be possible without modification. Counseling on the associated damage to other joint structures and need for activity modification allows for an active lifestyle over the long-term.

tissue sources include B-PT-B, quadriceps tendon-patellar bone (QT-PB),[157] and STG tendons. We prefer B-PT-B autogenous grafts in athletes, a recommendation supported by several long-term studies[56,92,98,142,224] and in investigations showing a higher rate of ACL primary reconstruction failure after allografts compared with autografts, especially in younger patients.[24,62,122,137,224] A B-PT-B autograft is not recommended if there is associated patellofemoral arthritis (grade 2B classification, see Chapter 44), anterior knee pain, or history of patellar subluxation or dislocation. A B-PT-B autograft is not performed when patient issues suggest a decreased ability to follow the more involved rehabilitation program and cope with the initial pain related to this graft. In recreational athletes and more sedentary patients, a four-strand or six-strand STG autograft is recommended. Modern STG graft fixation methods have increased the success rate, and the rehabilitation postoperatively is easier on the patient. There is a suggestion in the literature of increased STG failure rates with associated physiologic posterolateral laxity. Although allografts offer technical ease and reduced donor site pain, there are risks of disease transmission, a biomechanically inferior graft, and biologic reaction to irradiation and chemical sterilization processing.[81] A recent meta-analysis demonstrated that, when compared with low-dose irradiated allografts (<2.5 mrad), nonirradiated allografts produced superior stability (Lachman, pivot shift, KT-2000 tests), had a lower risk of revision, and higher Lysholm scores.[226] The orthopedic surgeon should understand the sterilization techniques used by the tissue bank and use grafts supplied by banks accredited by the American Association of Tissue Banks.

Patient Setup and Positioning

The patient is instructed to use a chlorhexidine wash of the operative limb ("toes to groin") 3 days before surgery, including the evening before and morning of surgery. Lower extremity hair is removed by

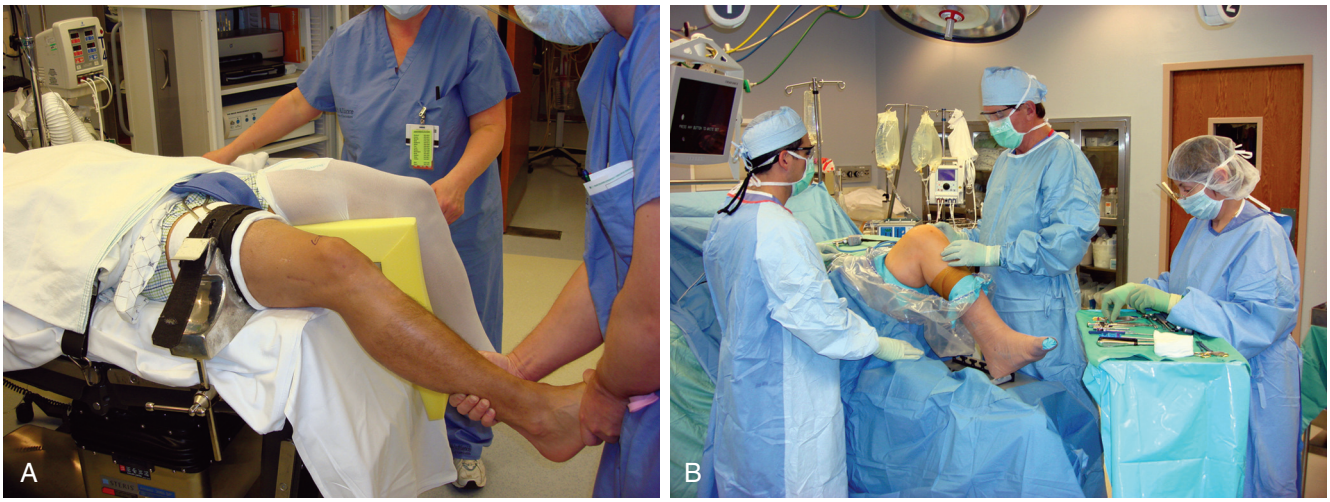


FIG 7-35 Initial operating room setup and patient positioning. **A,** Use of thigh holder to achieve maximum medial/lateral joint opening, particularly for meniscus repairs, that may be removed for the anterior cruciate ligament procedure (our preference). **B,** Patient in supine position with leg holder used to allow selected knee flexion positions, particularly hyperflexed position with anteromedial portal pin placement for femoral tunnels.

clippers, not a shaver. Antibiotic infusion is begun 1 hour before surgery. The use of a nonsteroidal antiinflammatory drug (NSAID) and a postoperative firm double-cotton, double-Ace compression dressing for 72 hours (cotton, Ace, cotton, Ace layered dressing) has proven effective in diminishing soft tissue swelling in knee surgery cases. In complex multiligament surgery, the antibiotic is repeated at 4 hours and continued for 24 hours. A urinary indwelling catheter is not used unless there are specific indications. The patient's urinary output and total fluids are carefully monitored during the procedure and in the recovery room. The knee skin area is initialized by the surgeon before entering the operating room, with a nurse observing the procedure. The identification process is repeated with all operative personnel with a "time out" before surgery to verify the knee undergoing surgery, procedure, allergies, antibiotic infusion, and special precautions that apply. All personnel provide verbal agreement.

A single femoral nerve block is administered preoperatively or in the recovery room, which markedly decreases the need for analgesic medication. The patient is instructed to use crutches with limited weight bearing for 24 hours owing to decreased quadriceps function. Bupivacaine (Marcaine) or lidocaine joint installation is contraindicated because high local doses may alter chondrocyte function and viability.[88,126,291] A fluid inflow-pressure-regulated pump is recommended over gravity infusion because hemostasis can be controlled and tourniquet use limited in most cases. An electrocautery device is always available to control bleeding points.

With the patient in a supine position on the operative table and all extremities well padded, a tourniquet is placed on the middle to proximal thigh (Fig. 7-35, *A*). A leg holder is used for the initial arthroscopic examination to provide for maximum opening of the medial and lateral tibiofemoral compartments during the gap tests and to provide necessary distraction for a meniscus repair or partial resection. A leg holder provides better visualization of the posterior meniscus regions over a lateral post. A low-profile leg holder is used, which is pressed into the operative bed mattress to decrease posterior thigh pressure; this is removed following the initial diagnostic arthroscopic procedure. The knee portion of the bed is flexed 60 to 90 degrees and the bed midportion is retroflexed 15 degrees to allow flexion of the hips to relieve undue tension on the femoral neurovascular structures. The uninvolved extremity is placed in a well-cushioned padded holder. An alternative approach described in the literature is to place the uninvolved extremity in an abducted and flexed position with a thigh and leg holder. However, this position does not make it possible to perform inside-out meniscus repairs when indicated.

After the arthroscopic procedures and removal of the leg holder, two positions may be used for the lower limb. The first is to adjust the operative bed to allow 90 degrees of knee flexion. The knee can be flexed to 120 degrees or more during the procedure, if necessary, by having the operative assistants flex the hip joint and knee joint. The second option is to position the operative bed flat and use an Alvarado foot and leg holder or sandbag taped to the table to allow the knee joint to be flexed to the desired position (see Fig. 7-35, *B*). The senior author prefers the first position that allows medial, lateral, or PCL procedures to be performed. With concurrent medial or lateral reconstructions, the surgical procedure is performed at 20 to 30 degrees of flexion with a roll placed beneath the thigh. The knee joint can also be brought to full extension to determine that posterior capsular reconstructions do not constrain full knee extension.

Graft Harvest: Bone-Patellar Tendon-Bone Autograft

A tourniquet is inflated to 275 mm of pressure. This is usually the only time the tourniquet is inflated in the reconstructive procedure. A 3- to 4-cm vertical medial incision is made just adjacent to the medial border of the patella tendon, avoiding the tibial tubercle (Fig. 7-36). The incision is located just medial to the inferior pole of the patella. A proximal skin incision over the patella is not required because the patella is easily displaced distally during removal of the patella bone portion of the graft.

A cosmetic approach is used where the plane beneath the subcutaneous tissues is dissected to allow for a limited skin incision. The skin incision is displaced proximally and distally as required for the graft harvest. Four vein retractors are placed into the proximal, distal, medial, and lateral aspects of the skin incision to allow for a rectangular skin opening for the graft harvest. An alternative technique is to use a proximal and distal skin incision, avoiding a vertical skin incision, which has less chance of a sensory skin loss but a greater chance of skin hypertrophic scar formation.

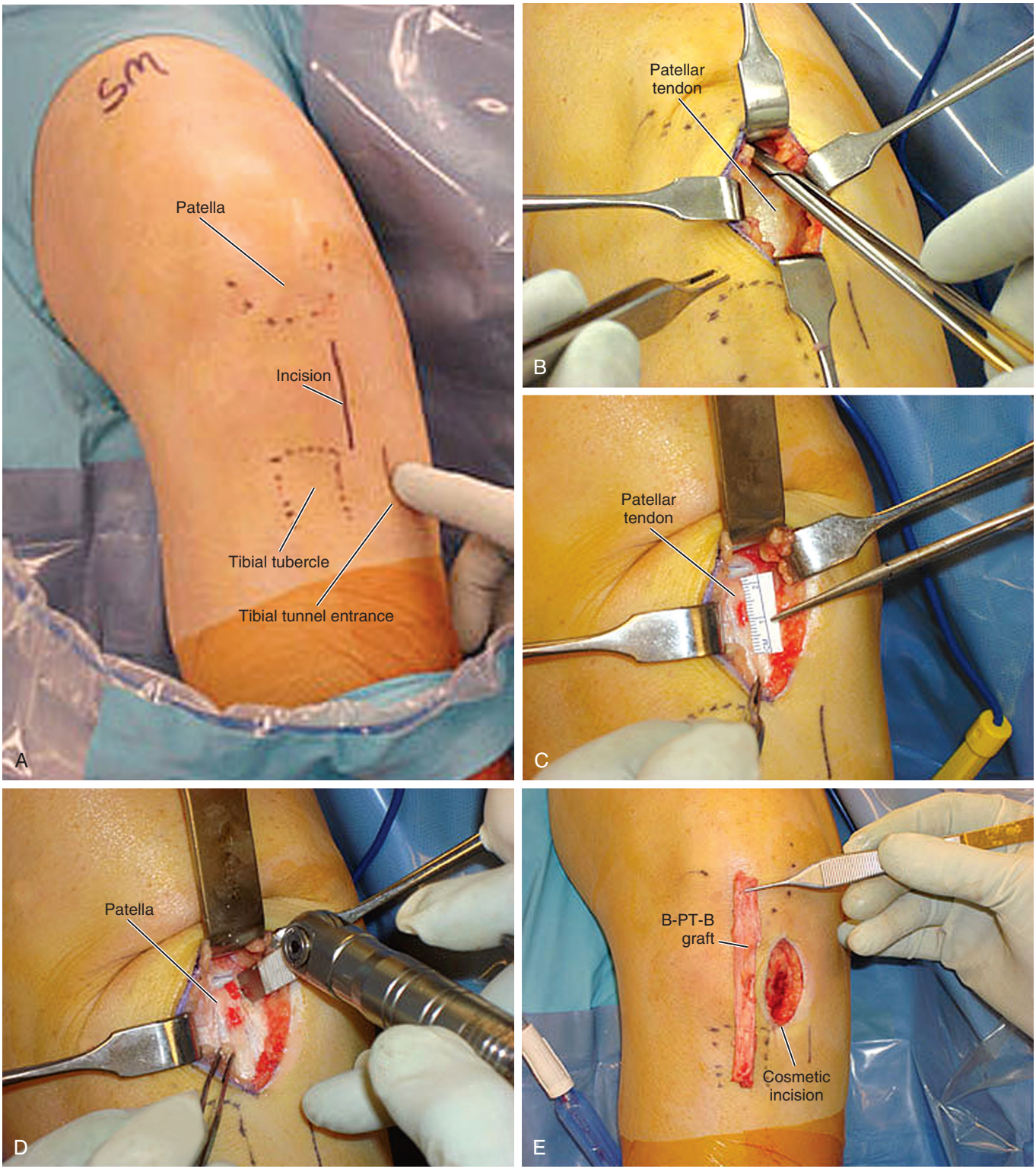


FIG 7-36 The technique we recommends for harvest of a bone-patellar tendon-bone (B-PT-B) autograft is shown. **A,** A 3- to 4-cm skin incision, just medial to the patellar tendon, is made to avoid the bony prominence of the patella and tibial tubercle. The index finger points to the planned tibial tunnel, which can be reached through this cosmetic incision. **B,** Mobilization of subcutaneous tissues to allow the cosmetically placed incision to be moved in a proximal-distal and medial fashion. Infrapatellar nerves when present are protected. **C,** A ruler measures the length of the patellar tendon and a 10 mm wide patellar tendon graft is marked by two or three ink dots. **D,** The patella is displaced distally and the patellar bone block removed. Note the saw has a tape marking a 9-mm depth to prevent from cutting too deep into the patella. The saw is angled 10 to 15 degrees to produce a trapezoidal bone block. The saw carefully cuts the medial and lateral borders, making sure the bone beneath the tendon insertion has been cut to prevent a fracture of the graft. A similar technique is used for the tibial tubercle. **E,** Appearance of the graft after harvest.

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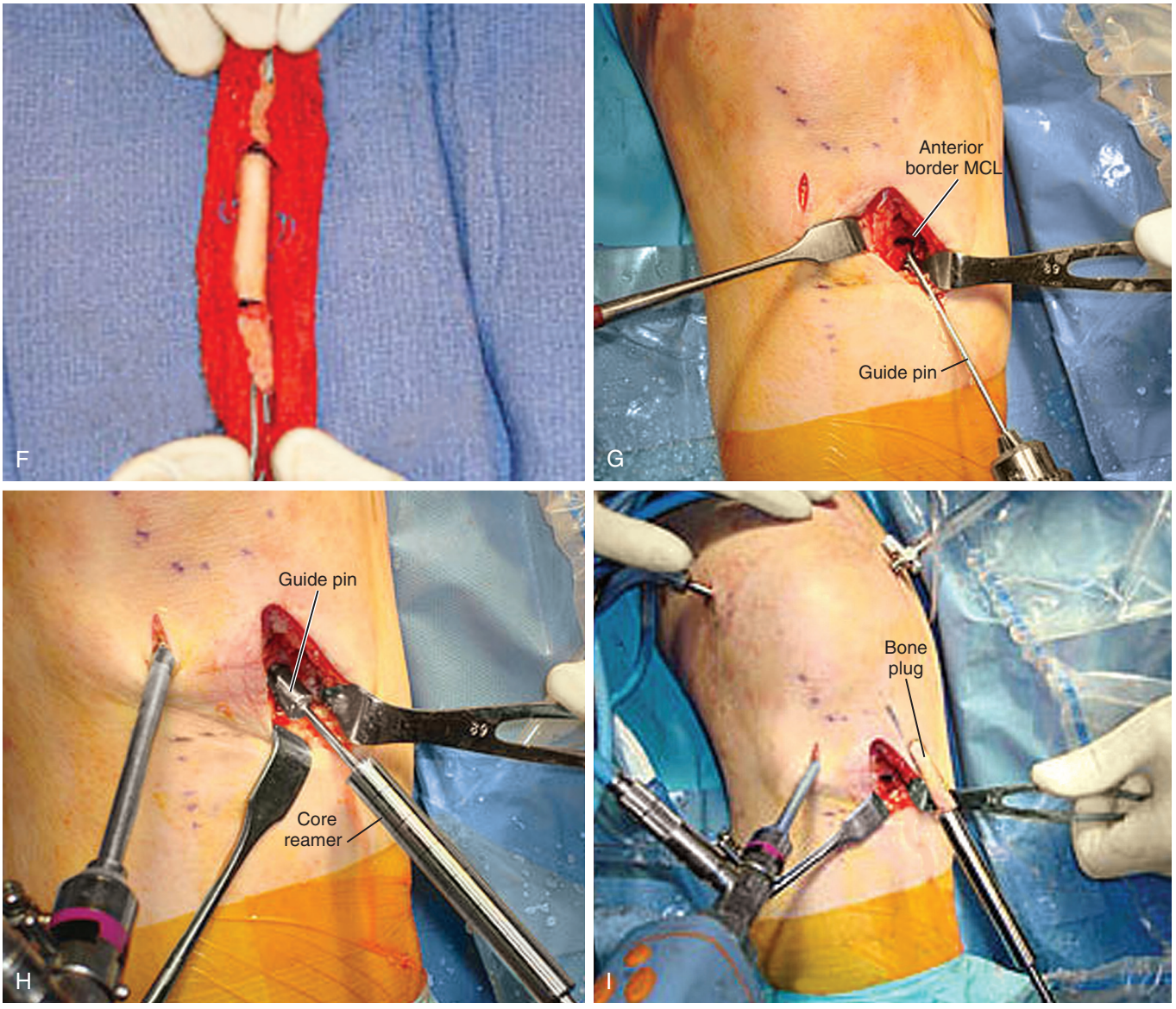


FIG 7-36, cont'd **F,** Preparation of the graft is shown. Two nonabsorbable No. 2 sutures are placed in a distal drill hole in each bone plug. The bone tendon junction is marked. The graft is wrapped in a blood-soaked sponge with the goal of maintaining viability of some tendon cells. **G,** The skin incision is displaced distally to reach the desired position for the coronal tibial tunnel, as described in the text. **H,** The core reamer is placed in the tibial tunnel for the graft harvest. **I,** The bone plug removed by the core reamer. *MCL,* Medial collateral ligament.

The retinaculum in the middle of the patellar tendon is incised and the dissection limited only to the midportion of the patellar tendon. The parapatellar tissues and blood supply to the tendon are not disturbed. The tendon should not be dissected to its edges because this damages the blood supply, particularly to the major vein and artery on the medial side of the tendon. In some knees, a branch of the infrapatellar nerve will cross the middle of the patellar tendon and should be preserved. In these knees, the nerve provides a large area of cutaneous sensation over the lateral aspect of the knee. It should be noted that up to one half of patients will have a 2-cm area of numbness just lateral to the patellar tendon from incision of small cutaneous nerve branches not visible during the procedure. Patients are warned of the potential loss of sensation preoperatively. The numbness may be avoided by use of a lateral incision adjacent to the patellar tendon; however, this requires a second tibial incision for the tibial tunnel that could be avoided if an all-inside ACL technique is performed. The patellar retinaculum is carefully incised and reflected medially and laterally only for the width of the graft to be removed. The retinaculum is protected to allow for closure over the bone-grafted patellar defect. A similar procedure is used at the tibial tuberosity.

It is useful to have a precut 10-mm and 22-mm paper ruler held on a hemostat to place over the tendon and bone harvest sites to allow fine marks to be placed on the tissues to define graft dimensions.

The patellar tendon is incised in the midportion to the appropriate size, 9 to 10 mm. The patella is displaced distally into the wound using

a forked retractor placed at the superior patellar margin. A powered handheld saw with a thin-width blade is marked with a Steri-Strip 9 to 10 mm from the tip to prevent too deep a cut, which would weaken the patella. A trapezoidal bone block graft from the patella is removed by angling the fine saw 15 degrees at each side of the cut. The bone cut extends to the inferior pole and care is taken to protect the insertion site of the patellar tendon. A 4-mm osteotome gently removes the patellar bone block without wedging the sidewalls, which could induce a fracture. A similar procedure is followed in the harvest of the tibial bone block.

The tourniquet is deflated, and a cotton sponge is placed in the wound. The graft is later wrapped in the blood-soaked sponge, which provides for protection of the graft, maintains a moist blood environment, and may allow cells to survive in the graft-remodeling process. It would be incorrect to have the graft openly exposed on the back table, which would allow drying, cell death, and possible air contamination. A first assistant prepares the graft to decrease operative time.

The bone blocks are prepared to easily pass through the selected diameter tunnels. The diameter of the tunnels will be configured 1 mm larger than the diameter of the bone block. The bone-tendon junction of each graft is marked for later identification. The graft preparation involves a 2-mm drill hole placed one third of the way from the end of each bone block for sutures. The end sutures allow the graft to be passed into the tunnel. A suture placed into the midportion of the graft would tilt the bone block, making passage into the tunnels difficult. The tibial portion of the graft is identified and will be later passed in a retrograde manner through the tibial tunnel into the femoral tunnel. The bone block tip is fashioned into a bullet tip configuration for tibial tunnel passage. Two No. 2 nonabsorbable FiberWire (Arthrex) sutures are passed into the distal one third tibial bone block. The graft is wrapped in a blood-soaked sponge.

At the conclusion of the ACL reconstruction, closure of the patellar tendon graft harvest site is performed. The patellar tendon is loosely approximated with 2-0 absorbable sutures. A coring reamer used for the tibial tunnel provides a large dowel of cancellous bone to completely fill the patella and tibia defects. The bone-grafted sites are smoothed to remove any pressure points. It is important to place two horizontal mattress sutures at the inferior pole of the patella and at the superior tendon attachment at the tibia to create a pocket to maintain the position of the core bone graft at each site. Otherwise, the bone graft may displace and be a source of pain because it is located in the tendon rather than the bony defect. The patella retinaculum is carefully closed to provide a soft tissue covering over the patella defect. The retinaculum over the tibial tuberosity is not as well defined; however, the soft tissues are closed using 2-0 absorbable horizontal mattress sutures.

The meticulous technique described for the B-PT-B graft procedure is an important part of the operative procedure. The skin incision is medial to any bone prominences and does not extend over the patella. The dissection is limited entirely to the central portion of the patellar tendon where the graft is removed, protecting nerves and the parapatellar vascular supply. The surgeon is seated, with the patient's foot in the surgeon's lap to directly visualize the wound and carefully control the saw blade. A headlight is always used to see the fine neural and vascular structures.

The use of the coring reamer at the tibial site provides ample bone graft to completely fill the tibia and patella bone defects. The use of shavings or small amounts of bone obtained in the procedure is insufficient to completely fill these defects and has led to complaints of kneeling pain in some studies.[87,157] If the tibial tuberosity defect is left partially unfilled, there will be ridges on either side of the defect that will prevent the patient from kneeling because of pain with pressure at this site. If the defects are closed as described, then kneeling with little to no discomfort is to be expected, equal to the opposite knee. In our opinion, this point has not been sufficiently stressed in the literature. A completely filled graft harvest site at the patella and tibial tubercle is required. Saving bone chips during the ACL tunnel preparation usually results in insufficient bone for both harvest sites. The added time to use the coring reamer bone-graft harvesting instruments provides the benefit of a quality bone graft for both the patellar and tibial sites. Commercially sold bone allografts are available; however, we prefer to use the patient's bone. The length of the bone block is 22 to 24 mm to facilitate passage.

In cases where a patella alta (and exceedingly long patellar tendon) is present, a problem arises when harvesting the patellar tendon, which is often 60 mm in length, to use for an ACL reconstruction. There are two techniques that may be used to prevent the bone portion of the graft from protruding at the tibial and femoral sites. The most ideal is to use a 2-incision technique in which the tibial and femoral tunnels are devised to be approximately 35 mm in length to accommodate the abnormally long B-PT-B graft. A second, less ideal option that may be selected when required, involves rotating the bone portion of the graft back onto the patellar tendon and suturing it to the tendon over a FiberLoop (Arthrex), which is usually placed at the femoral tunnel site.

Graft Harvest: Quadriceps Tendon-Patellar Bone Autograft

A 5- to 6-cm longitudinal incision is made from the superior pole of the patella that extends proximally. The prepatellar retinaculum is reflected and protected for later closure over the grafted patellar defect. The quadriceps tendon and its junction with the vastus medialis obliquus and vastus lateralis obliquus (VLO) are identified. The proximal portion of the quadriceps tendon is identified and the graft harvest is carried 10 mm distal to the rectus femoris muscle-tendon attachment in order not to weaken this site. A 10-mm wide tendon graft, through all three layers, is removed to a length of 60 to 70 cm (Fig. 7-37). In large patients, the 10-mm graft may prevent the deeper third layer from being removed. The tendon attachment to the anterior superior pole of the patella is carefully identified and the synovial attachment protected. A power saw with the cutting blade marked with paper tape to a depth of 10 mm is used to cut the anterior cortex. It is necessary to place the thin saw blade at the superior pole immediately posterior to the quadriceps tendon patella attachment to saw through the patellar bone at this location. The goal is to produce a patellar bone graft 22 to 24 mm long by 9 to 10 mm wide. The bone graft is sized to 9 to 10 mm in diameter. The quadriceps tendon defect is closed with interrupted 0-Ethibond suture (Ethicon). Two sutures of 0-nonabsorbable material are placed just proximal to the proximal patellar bone defect to create a pocket for the bone graft obtained from the coring tibial reamer. The core bone graft completely obliterates the patellar defect, and a meticulous closure of anterior tissues over the graft is performed, as already described. Even though techniques have been described for quadriceps tendon graft harvest without removing the patellar bone, the senior author believes this technique to be less desirable. The patellar bone fixation is superior to tendon fixation and adds length of the tendon portion of the graft within the tibial tunnel, which is advantageous for healing.

Graft Harvest: Semitendinosus-Gracilis Autograft

The STG graft harvest procedure is shown in Figure 7-38. A 3- to 4-cm oblique incision is made over the palpated pes tendons. The incision

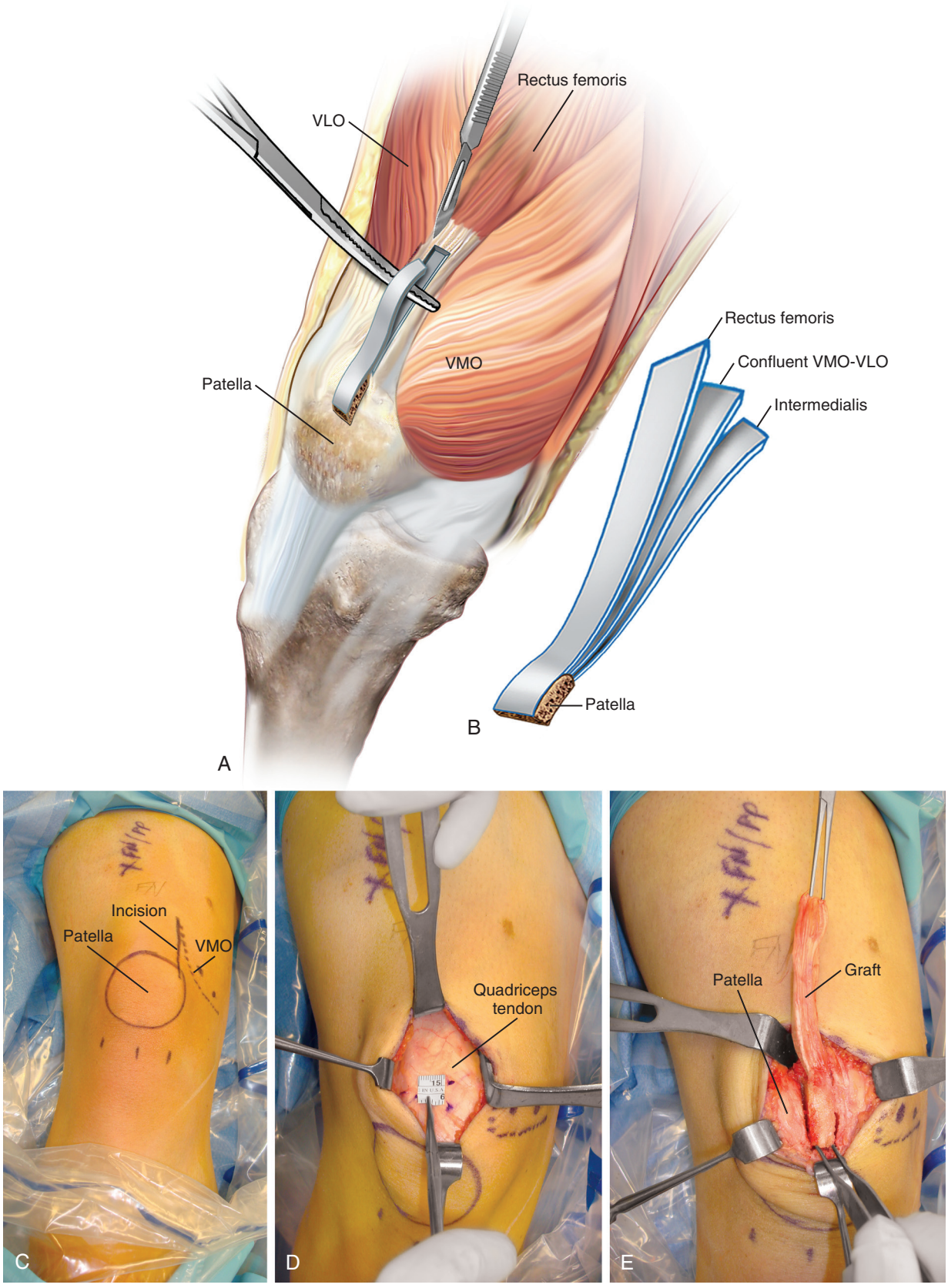


FIG 7-37 **A,** The quadriceps tendon and vastus medialis oblique and vastus lateralis oblique muscles are identified proximally. A 9- to 10-mm wide tendon graft, through all three layers, which has a length of 60 to 70 cm, is removed. The graft harvest does not extend to the muscle tendon junction. A patellar bone graft is fashioned to be approximately 22 to 24 mm long by 9 to 10 mm wide by 9 to 10 mm in diameter. **B,** Usually, all three layers are sutured together at the end of the graft (2-0 nonabsorbable suture) with a running suture on both sides of the graft. **C,** Surgical case, initial skin incision. **D,** Measurement of graft width. **E,** Final harvest. *VLO,* Vastus lateralis obliquus; *VMO,* vastus medialis obliquus.

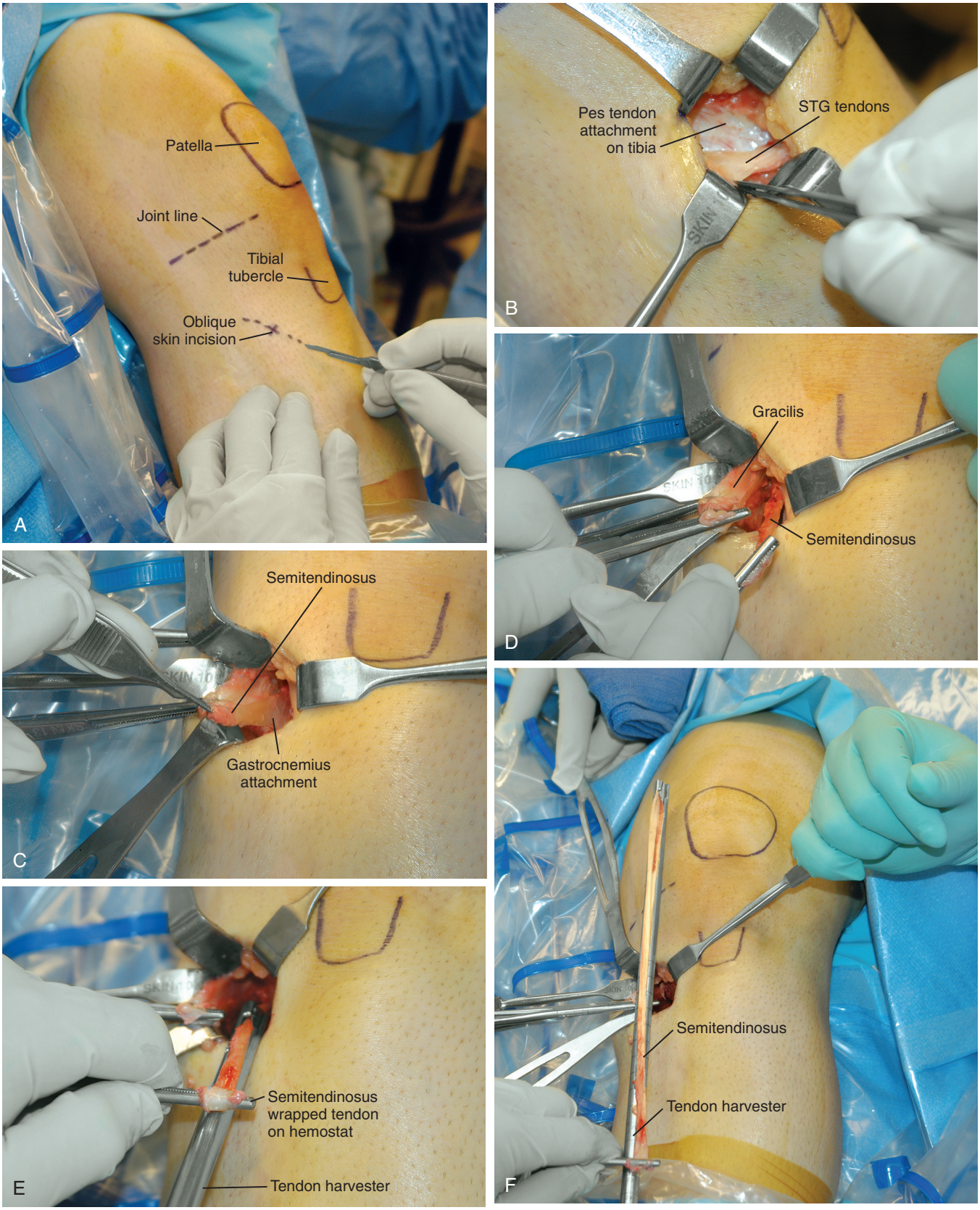


FIG 7-38 **A,** A 2-cm longitudinal or oblique incision at the anteromedial tibial region. **B,** An L-shaped incision at the pes tendon tibial attachment is performed and the tendon flap is reflected to identify the semitendinosus-gracilis (STG) tendons. **C,** Dissection of soft tissue to identify the STG and remove the gastrocnemius secondary attachment. **D,** "Push-pull" test to confirm that the STG tendons are free of attachments. **E,** Harvest of STG using closed-end harvester to prevent premature transection of STG. **F,** Appearance of long semitendinosus tendon obtained at harvest.

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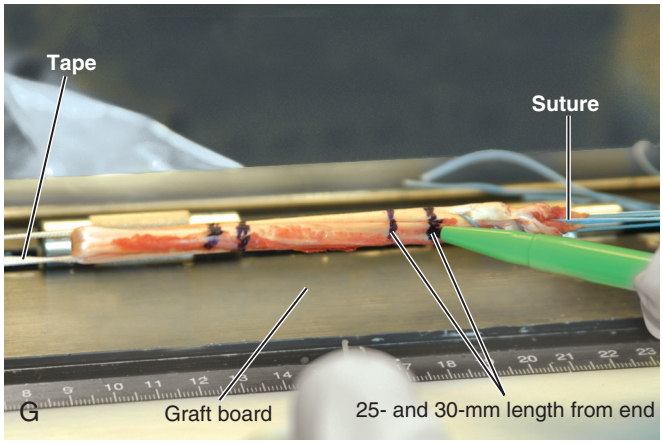


FIG 7-38, cont'd **G,** Graft preparation with graft board. Nonabsorbable 3-mm tape at the proximal end and three 2-0 FiberWire fixation at the distal end. (An alternative is a TightRope [Arthrex] fixation device.) Running suture is used on each side of the STG graft.

is cosmetic and the plane beneath the subcutaneous tissues is carefully dissected. The senior author prefers an AM incision over a popliteal-based incision to gain maximum length of the tendons at the tibial confluent attachment. The surgeon is seated, the bed is flexed 60 degrees, and a headlight is routinely used. The sartorius fascia is incised directly proximal to the semitendinosus and gracilis palpated tendons over the distal superficial medial collateral ligament (SMCL) attachment. This provides a window and opening to protect the SMCL. The overlying fascia is incised proximally in the same oblique plane of the STG tendons.

It is worthwhile in the initial dissection to identify the STG tendons to protect them and not inadvertently section the tendons. This is best performed by extending the fascia, incising just above the gracilis tendon over its tibial insertion, and then at a 90-degree angle, laying back the insertion site distally. This allows the STG tendons to be viewed throughout their distal course to their tibial attachment. In most knees, the STG tendons are confluent and blend to make one tendinosis structure. Each tendon is identified and incised through the confluent distal tendon region. Each tendon is grasped at a 90-degree angle at its distal end and rolled two to three times around a straight hemostat, which allows tension to be placed on the tendon without producing damage.

The proximal extent of each tendon is palpated and superficial tissues removed, protecting the overlying sartorius fascia. The dissection plane is never carried close to the inferior sartorius or posterior semitendinosus muscles to avoid injury to the saphenous nerve. The headlight provides excellent illumination in the proximal portion of the incision to protect any neurovascular structures. The proximal fascia about each tendon is bluntly dissected and the semitendinosus tendon attachment to the medial gastrocnemius fascia is incised. With tension on each tendon and a repetitive pulling motion, each tendon will freely displace 10 cm. It is important to determine that each tendon is completely free of tissues to allow the tendon harvester to pass freely. The anesthesiologist is asked to provide muscle relaxation sedation to facilitate this step. The closed-end graft harvester is passed along the trajectory of each tendon and each tendon is transected at 20 cm for a four-strand graft or 24 cm for a six-strand graft described later. There is a commercially available tendon harvester with a blunt tip that protects against inadvertent tendon transection that has a tendon cutter in its distal tip activated by the mechanism at the handle. The STG tendons are prepared (see Fig. 7-38). In the four-strand graft, each tendon is looped about a 3-mm tape and the tendon end sutured to itself with a No. 2 nonabsorbable suture. A third suture (FiberLoop) is added at both graft tendon ends. A running 0-nonabsorbable suture is used to produce a tubed structure running from proximal to distal and then back to the proximal starting point. A metal graft tensioning board (25- to 30-N tension) is used rather than a graft preparation board with plastic holders because the latter is difficult to sterilize to avoid a graft contamination problem. The graft is marked 25 mm from each end, wrapped in a blood-soaked sponge, and placed in a secure place on the back table. The overall length is approximately 80 to 85 mm.

The six-strand graft is used in women and patients of small stature in which the STG tendon diameter is decreased and to provide added tendon substance for a 9- to 10-mm graft diameter. This avoids a 6- to 7-mm graft, which has a known increased failure rate (see "Other Authors' Clinical Studies"). The six-strand graft technique is described in Table 7-9 and is shown in Figure 7-39.

Iliotibial Band Extraarticular Tenodesis

Two clinical studies (Noyes and Barber[185] and Ferretti and coworkers[66]) have shown significant improvements in knees with gross instability and loss of secondary lateral restraints that had an extraarticular tenodesis procedure for additional restraint of abnormal tibial internal rotation. The goal is to reconstruct the function of the anterolateral ligament and posterior femoral tibial ITB attachment, which restrains abnormal internal tibial rotation. The lateral capsule fibers (referred to as the anterolateral ligament) are plicated at surgery; however, it is not necessary to add a graft reconstruction for this structure. The procedure is described in detail in Chapter 8.

Anterior Cruciate Ligament Bone-Patellar Tendon-Bone Graft Anatomic Tibial and Femoral Technique

A single-graft procedure is described in which the graft is located into the central anatomic tibial and femoral attachment locations, as already discussed. The graft placement specifically avoids the proximal ACL femoral attachment site and the posterior ACL tibial attachment site to avoid a vertical graft and allow the graft to resist rotational motions in addition to anterior tibial translation (Fig. 7-40). This

TABLE 7-9 Preparation of Six-Strand Semitendinosus-Gracilis Autograft

Indications: Harvest of a semitendinosus-gracilis (STG) autograft of narrow diameter, where a final 6- to 7-mm diameter graft would be produced, which is less than ideal and associated with a high failure rate.

Surgical Steps:

1. Based on patient size, anterior cruciate ligament (ACL) length, and tunnel lengths, a final 75- to 85-mm length graft is prepared.
2. Place tibial and femoral ACL tunnels in center of attachment sites as already discussed.
3. Measure the length of the tibial and femoral tunnels and ACL graft distance to tunnels. To compute ideal final graft length, add tunnel lengths and intraarticular length, then subtract 10 mm for positioning and tensioning. For example:
   - 30-mm tibial and femoral tunnels (60 mm) + 35-mm intraarticular length = maximum graft length of 95 mm – 10 mm = maximum graft length of 85 mm.
   - In a smaller patient, a 25-mm femoral tunnel and a 35-mm tibial tunnel and an intraarticular length of 30 mm = maximum graft length of 80 mm – 10 mm = ideal graft length of 70 mm.
4. Harvest STG graft to 24 cm for 80 mm triple semitendinosus (ST) and gracilis (G) six-strand graft.
5. Place zero FiberWire at the end of both tendons and mark the graft into thirds. Lead the sutured tendon end around TightRope at both ends, ending up at the one-third graft length and tie the tendon end onto the looped tendon at this one third site.
6. Place the six-strand graft on a tensioning board, tension at 40 N, and tie each end suture onto the TightRope. Place a single FiberLoop at each end of six-strand graft and tie over TightRope. The final construct is FiberWire plus FiberLoop tied to TightRope at each end of the graft construct. Consider adding additional FiberLoop as necessary.
7. Use as a running suture zero FiberWire looped up one side and back the other side of the six-strand graft to approximate all six tendon loops into one single-graft strand.

CRITICAL POINTS Operative Techniques: ACL Bone-Patellar Tendon-Bone Graft Anatomic Tibial and Femoral Technique

Placement of Tibial Tunnel

- Define center ACL, usually 16 to 20 mm anterior to RER or interspinous ridge.
- Mark ACL center, usually adjacent and always anterior to posterior edge of lateral meniscus anterior horn attachment.
- Place guide pin eccentric and 2 to 3 mm anterior and medial to true ACL center.
- Determine graft length of patellar tendon on MRI.
- Two-incision technique allows graft length to be adjusted by proximal advancement of femoral tunnel.
- Place tibial tunnel in coronal manner, 55- to 60-degree angle, tunnel length 35 to 40 mm.
- Begin tunnel anterior and adjacent to superficial MCL, 15 mm medial to tibial tubercle medial border, 10 mm distal to proximal patellar tendon insertion.
- Use core reamer to obtain good-quality bone to fill bone defects.
- Drill tunnel, chamfer edges.

Placement of Femoral Tunnel

- Use either two-incision technique (open or flip drill) or AM portal with knee hyperflexed 120 degrees.
- Two-incision technique: Drill tunnel retrograde through lateral incision 2 to 3 cm at distal lateral femoral condyle.
- Perform femoral notchplasty to avoid graft impingement.
- Identify ACL attachment with knee in 20 to 30 degrees of flexion, scope in AM portal.
- Place guide pin within central ACL attachment. Always preserve 3 to 4 mm of posterior back wall of the tunnel so that the graft is not placed too far posteriorly. A guide pin placed 8 mm from the posterior articular cartilage at the central ACL attachment will have a 4-mm posterior back wall for an 8-mm graft.
- Drill tunnel, chamfer edges.

Graft Tunnel Passage, Conditioning, and Fixation

- Pass graft gently in retrograde arthroscopically assisted.
- Bring graft proximally until bone is flush with tibia.
- Femoral position of graft at or just proximal to inside femoral tunnel.
- Fix femoral bone graft plug with interference screw.
- Condition graft, 44-N tension, flex knee 0 to 135 degrees 40 cycles.
- Verify position arthroscopically, no impingement.
- Place knee in 20 degrees of flexion, reduce tension to 10 to 15 N.
- Place interference screw tibia. Use additional sutures tied over suture post if required.
- Perform Lachman test, ensure no overconstraint.
- For STG graft, femoral fixation: Post with sutures and absorbable interference screw if necessary. Tibial fixation: Interference screw plus suture post.

section describes using a single B-PT-B autograft that is preferred compared with an allograft procedure. Our clinical studies described later support the concept of a single-graft technique for primary ACL reconstruction.

Placement of Tibial Tunnel

As previously described, the ideal central ACL tibial attachment location is directly adjacent and anterior to the posterior edge of the lateral meniscus anterior horn attachment (see Fig. 7-29). The ACL attachment can be easily mapped at surgery based on the anatomic reference maps previously provided, with the ACL center location based on the anterior-to-posterior and medial-to-lateral attachments. The anterior extent of the ACL attachment may be obscured by soft tissues, and the RER or posterior interspinous ridge of the PCL fossa is an important landmark. The center of the ACL will be 16 to 20 mm anterior to the RER or interspinous ridge. No portion of the tibial tunnel is posterior to the posterior edge of the lateral meniscus attachment, which represents the posterior one third of the ACL attachment. The guide pin is placed eccentric and 2 to 3 mm anterior and medial to the true ACL center as the ACL graft displaces to the posterior and medial aspects of the tibial tunnel.[45] This eccentric tunnel places the majority of the graft within the ideal central tibial attachment.

It is important to determine the graft length of the autograft or allograft to ensure a mismatch does not occur between intraarticular length of the tunnel and the length of the graft. The most common problem is with a relative patella alta and a B-PT-B length greater than 90 mm based on the patient's body habitus. The length of the patellar

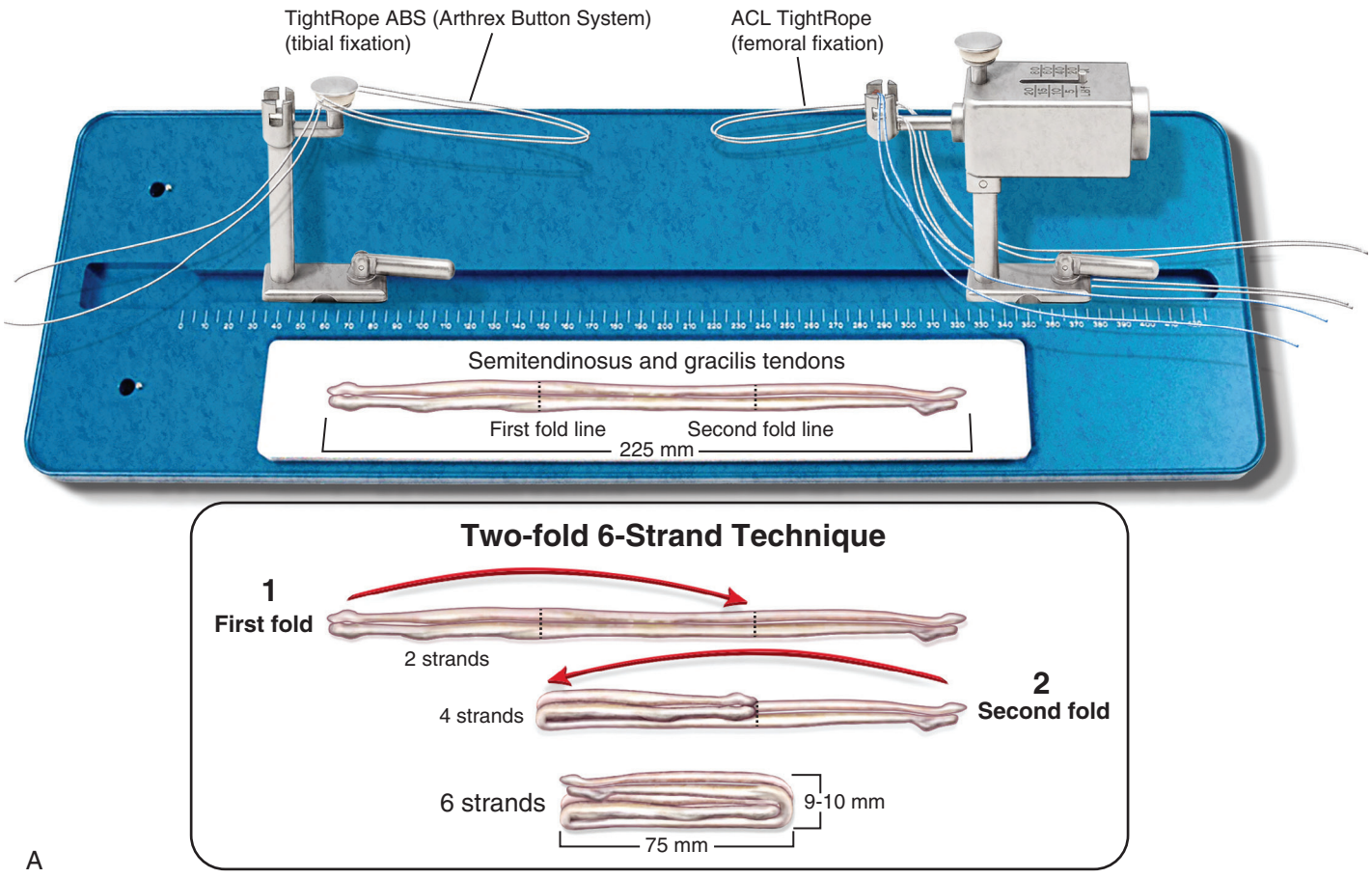
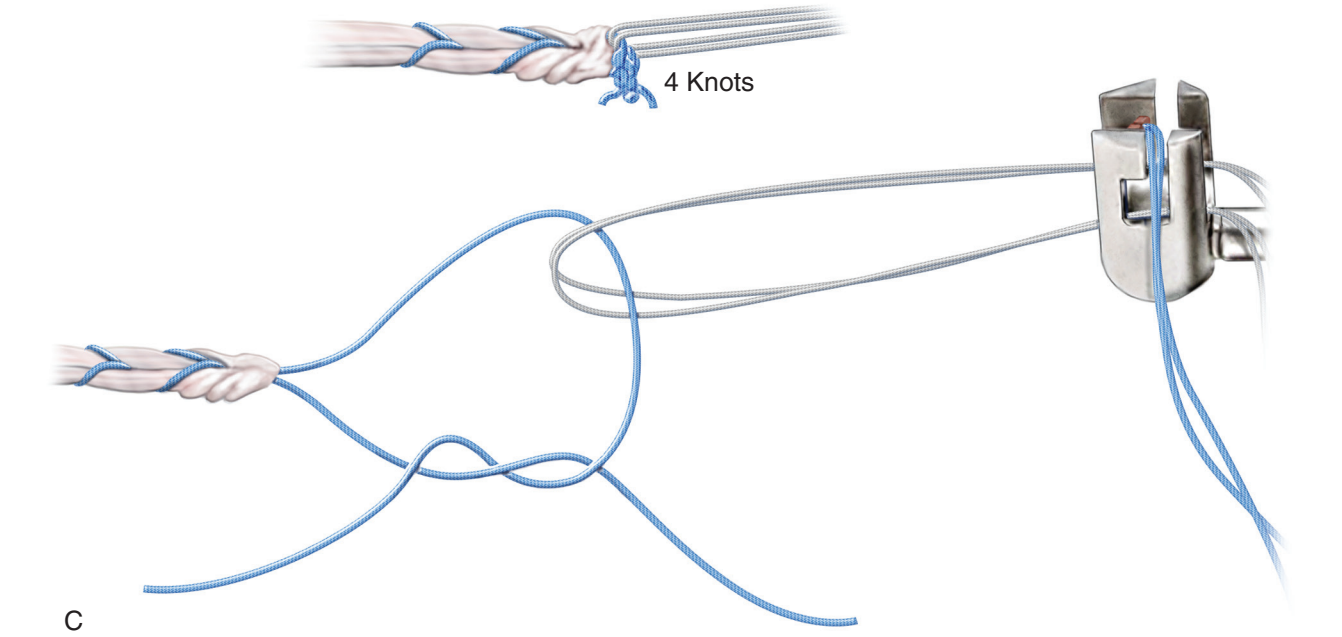
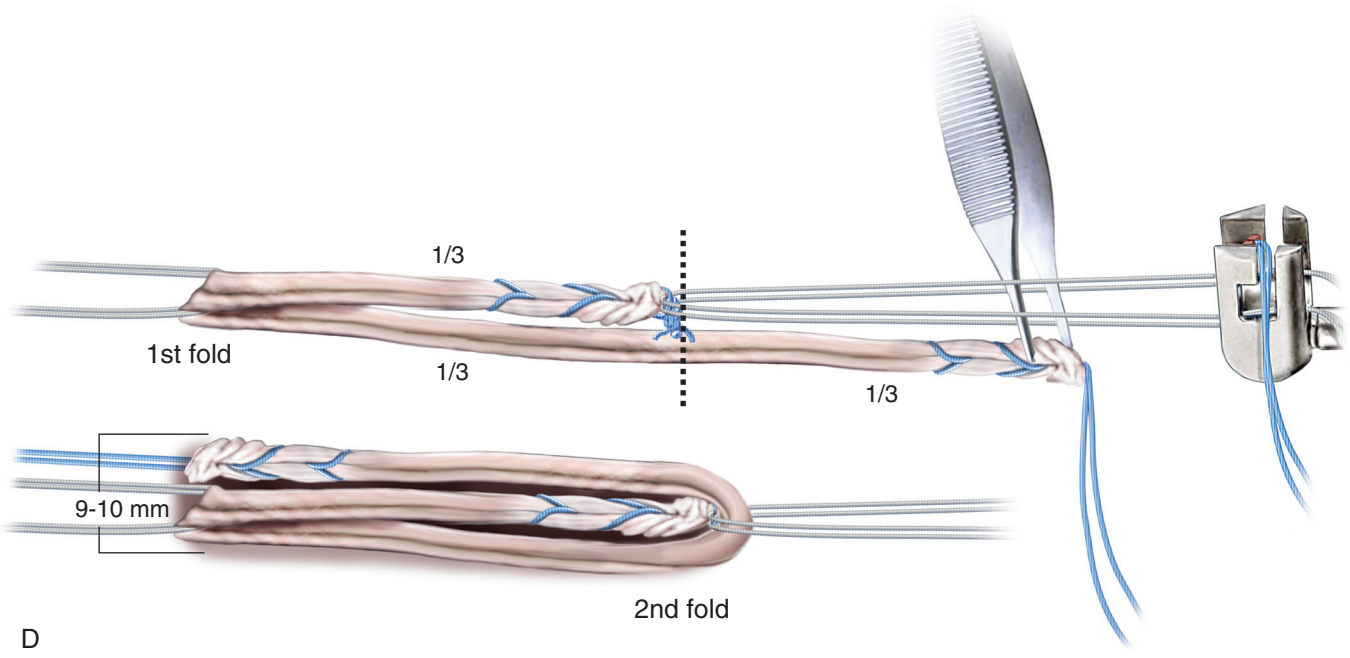


FIG 7-39 Anterior cruciate ligament six-strand semitendinosus-gracilis (STG) autograft technique. **A,** A 70- to 80-mm length graft is prepared. The STG tendons are folded two times to obtain a six-strand graft. **B,** The semitendinosus and gracilis tendons are sutured together at either end with two to three locking-type sutures (0 or No. 2 FiberWire) to stabilize the end.





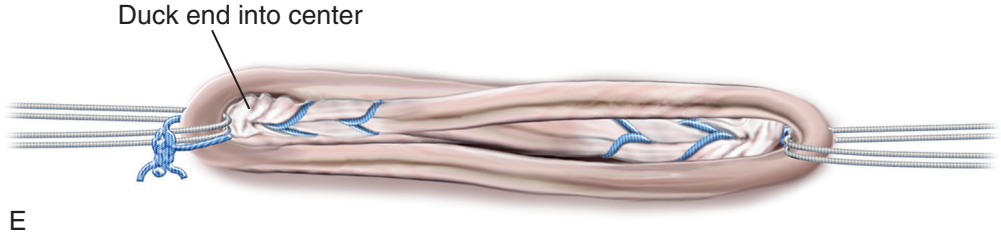


FIG 7-39, cont'd **C,** One end of the STG graft is tied to the TightRope. **D,** The other end of the STG graft is folded through one end of the TightRope loop and folded back to the second TightRope loop. **E,** The end of the STG is placed into the center of the folded graft and tied to the second TightRope loop.

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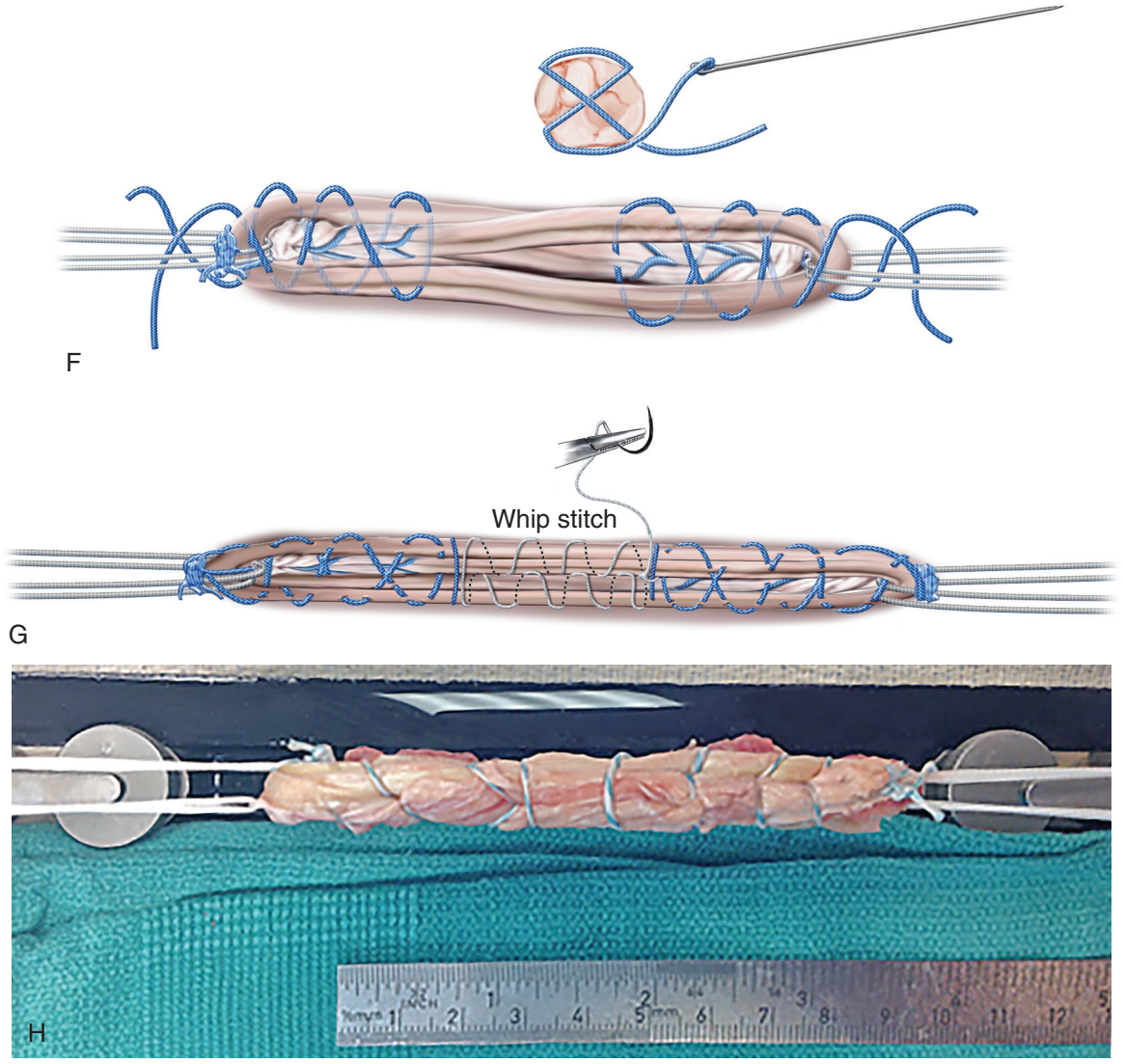


FIG 7-39, cont'd **F,** Two FiberLoop sutures (No. 2) are passed in a criss-cross fashion to secure each end of the six-strand graft. **G,** Place the construct under 40-N force to precondition the fibers. A whipstitch suture is placed along the top of the graft and then brought back on the bottom of the graft to secure the STG tendons together. **H,** Final six-strand graft construct.

tendon is determined on preoperative lateral radiographs. The normal patellar length based on the Linclau technique[152] (see Chapter 38) is a 1:1 ratio with the patellar tendon in the 35-mm range. The intraarticular ACL length is measured on the lateral MRI, and this length is matched with the autograft. It is possible to accommodate a shorter length patellar tendon by adjusting the proximity of the tibial tunnel. A total B-PT-B tendon length greater than 90 to 95 mm is usable with the bone portion of the graft adjusted in the tibial and femoral tunnels. A two-incision technique allows adjustment of graft length by proximal advancement in the femoral tunnel and is ideal when there is graft mismatch caused by an excessively long patellar tendon. There is a technique with a long B-PT-B graft in which the tibial bone plug may be rotated 180 degrees onto the tendon, sutured to the bone plug, and the tibial tunnel resized. However, the senior author recommends a two-incision technique to manage this problem. The bone plug sutures are tied to a tibial post. With a graft length mismatch, we do not recommend removal of the bone plug to shorten overall graft length or multiple twisting of the graft to shorten its length.

The ideal tibial tunnel is placed in a coronal manner, at a 55- to 60-degree angle, allowing a tunnel length of 35 to 40 mm. The tunnel is begun just anterior and adjacent to the SMCL and is usually 15 mm medial to the tibial tubercle medial border and 10 mm distal to the most proximal point of the patellar tendon tibial tubercle insertion.

A core reamer is placed over the guide pin to remove a tibial bone plug when a B-PT-B or QT-PB autograft is used to obtain a core of bone to fill the bone defects. As already described, the core reamer provides a more suitable graft material than drill reamings, and the bone defects are filled in an anatomic manner that results in the patient able to kneel on the tibial bone harvest site.

The tunnel is drilled to the desired graft diameter and the joint tunnel edges chamfered to prevent graft abrasion.

Placement of Femoral Tunnel

As previously described, a two-incision technique (open or FlipCutter [Arthrex]), an AM portal femoral tunnel placement with knee hyperflexion technique, or a flexible reamer is used. Baer and associates[17]

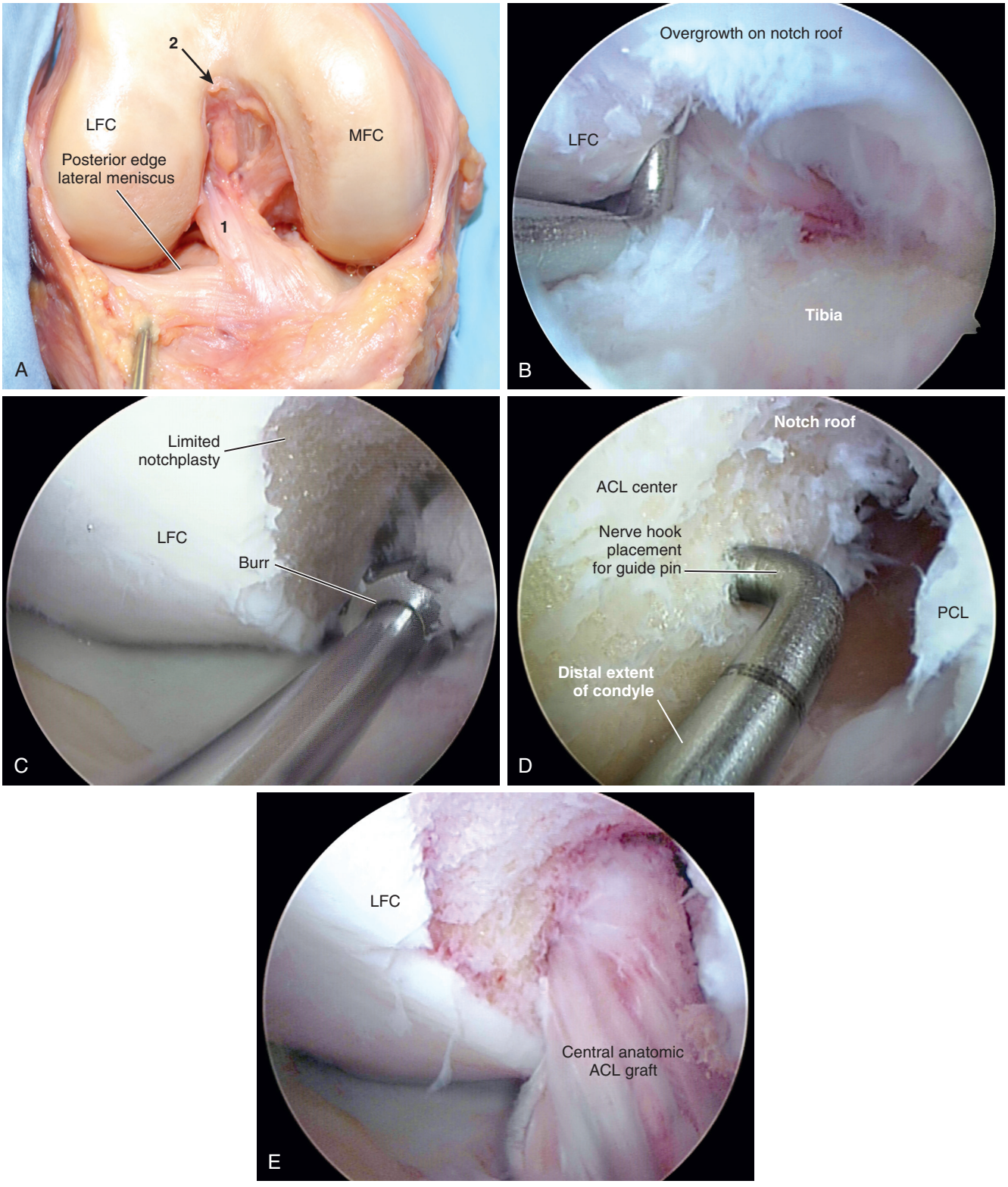


FIG 7-40 **A,** A normal femoral notch, which is viewed at arthroscopy by using the anteromedial portal. Label *1* shows the normal space between the medial femoral condyle and the posterior cruciate ligament (PCL), which is occupied by the anterior cruciate ligament (ACL). Label *2* shows the normal anterior notch that should not impinge on the graft. **B,** Revision ACL with failed ACL graft shows overgrowth of the lateral notch and notch roof, requiring a limited notchplasty. **C,** The lateral notch wall is visualized entirely posteriorly to the articular cartilage of the femoral condyle. **D,** The ACL femoral attachment is mapped out and a central small hole is made for placement of the guide pin. The resident's ridge has been removed. The anterior notch region has not been disturbed. **E,** Final placement of a single-bundle graft within a central anatomic tibial and femoral placement that occupies over 75% of the attachment site. *LFC*, Lateral femoral condyle; *MFC*, medial femoral condyle.

reported in a cadaver study that at least 110 degrees of knee flexion is required for femoral tunnel drilling through the AM portal to avoid potential injury to the peroneal nerve, the lateral condylar articular surface, the FCL, and the popliteus tendon. The use of the AM portal or more medial accessory portal to place the femoral tunnel has the problems in some knees of difficulty with visualization at 100 to 120 degrees of flexion, the potential for the drill to damage the medial femoral condyle, and a shorter femoral socket. As with any of the ACL techniques, surgeon experience is necessary to achieve a successful result. There is an advantage of using the flexible guide pin and reamers in larger patients where 110 degrees of knee flexion is easily achieved, avoiding greater knee hyperflexion.

The two-incision technique retrograde-drilling procedure (Fig. 7-41) involves a lateral incision of 2 to 3 cm in length at the distal lateral femoral condyle. The posterior one third of the ITB is incised for 4 to 6 cm to allow exposure. The interval posterior to the vastus lateralis is entered and the muscle protected. An S retractor is placed beneath the VLO to gently lift the muscle anteriorly, avoiding entering the proximal joint capsule. The proximal edge of the lateral femoral condyle is bluntly palpated with an instrument (over-the-top location), with the goal of locating the tunnel entrance just anterior and not distal to this point. A 15-mm periosteal incision is made and an elevator used to remove soft tissues from the site for the tunnel proximal entrance. With a B-PT-B graft length of 80 to 85 mm, a FlipCutter procedure may be selected to create a femoral socket rather than a tunnel.

As already described, the placement of the tibial tunnel in the central tibial ACL attachment in almost all cases requires a femoral notchplasty to avoid graft impingement with knee hyperextension. In most chronic ACL-deficient knees, there is an overgrowth of cartilage and spur formation in the femoral notch, requiring a notchplasty. The notchplasty rules taught by the senior author and used in all the clinical studies reported are described in Table 7-10. A lateral notchplasty is performed as required when there is insufficient width (9-10 mm) between the PCL and the lateral femoral notch wall to accommodate the ACL graft.

The ACL femoral attachment is mapped based on the bony landmarks already described. The location of the guide pin for an ACL central femoral tunnel is shown in Figures 7-31, 7-34, 7-40, and 7-42, *C* to *E*. The guide pin is placed within the central ACL attachment, which is midway between the lateral notch roof and the distal articular cartilage edge, 8 mm from the posterior articular cartilage edge. Clock locations are actually an inaccurate description of the tunnel location.[59,60] With the central femoral tunnel, the posterior back wall is 3 to 4 mm thick and the graft occupies approximately two thirds to three fourths of the ACL footprint. Always preserve 3 to 4 mm of the posterior back wall of the tunnel so that the graft is not placed too far posteriorly. Grafts placed too far posteriorly will have increased tension with knee extension and may potentially block full extension. In these cases, the graft will be observed to shorten with knee hyperextension and piston into the tibial tunnel. A guide pin placed 8 mm from the posterior articular cartilage at the central ACL attachment will have a 4-mm posterior back wall for an 8-mm graft and 3-mm wall for a 10-mm graft. One key to define the ACL attachment is to place the knee in 20 to 30 degrees of flexion viewed through the AM portal and map out the oval attachment and center point, measuring the distance to the posterior articular cartilage. It is often easier to mark out the ACL femoral attachment when it is viewed in a vertical plane rather than the horizontal attachment plane with knee flexion. The tunnel is drilled to the appropriate diameter, which is usually 1 mm greater than the bone portion that allows a snug graft fit in the tunnel. The edges of the tunnel are chamfered to prevent graft abrasion. The technique with a rear-entry guide drill is shown in Figure 7-42.

Graft Tunnel Passage, Conditioning, and Fixation

The graft is passed in a retrograde manner either with a Beath pin in the arthroscopic technique (placed through the accessory AM portal) or in the two-incision technique with a 20-gauge looped wire passed from the femur to the tibial tunnel. The graft is gently lifted up through the tibia and guided into the femoral tunnels with a nerve hook. The graft is marked at the bone-tendon junction to adjust its length in each tunnel. The graft is brought proximally until the bone is flush with the tibia. In most knees, the femoral portion of the graft is at or just proximal to the inside femoral tunnel. The femoral bone-graft plug is fixed with an interference screw of a metallic or absorbable type. Graft conditioning is performed by placing approximately 44-N tension on the distal graft sutures and flexing the knee from 0 to 135 degrees for 30 to 40 flexion-extension cycles. The arthroscope is placed to verify that the graft position is ideal and there is no impingement against the lateral femoral condyle or notch with full hyperextension. Appropriate notchplasty is performed when necessary.

The knee is placed at 20 degrees of flexion, and the tension on the graft is reduced to approximately 10 to 15 N to avoid overconstraining AP tibial translation. A finger is placed on the anterior tibia to maintain the posterior gravity position of the tibia. An alternative procedure is to fixate the graft with a larger graft tension at 0 degrees; however, the senior author believes there is more control of graft tension at the partially flexed position. An interference screw is placed. In cases where the interference screw fixation is not ideal or the screw resistance on placement is not acceptable, the sutures are tied over a suture post. The arthroscope is placed into the joint and final graft inspection performed. A Lachman test is performed and there should be total AP translation motion of 3 mm, indicating that the graft has not been over tightened. If the graft has a "bowstring," tight appearance with little to no anterior tibial translation on testing, the distal tensioning and fixation procedure is repeated with less tension placed on the graft.

Li and associates[145] reported the ACL 3-dimensional morphological changes in humans during weight-bearing flexion using a fluoroscopic and MRI-based system. The ACL tibial insertion twisted internally relative to the femoral insertion. The ACL internal twist amounted to approximately 10 degrees at full extension to 44 degrees at 90 degrees of flexion. The data were based on insertion site measurements and not actual ACL fiber microgeometry. Even though some authors[8] have recommended an ACL graft orientation to reproduce an internal twist of the ACL fibers, this effect on clinical outcomes is unknown. The B-PT-B orientation is usually placed in the sagittal plane on the femur and tibia with the cancellous surface lateral in the femoral tunnel to lessen abrasion of the tendon against the femoral condyle.

Techniques Using Other Grafts

With all other grafts, the same procedure is used with the following exception. In the two-incision technique with a STG graft, a femoral post is used with the sutures tied first at the femoral site about the post (35-mm, 4.0-mm cancellous self-cutting screw with washer). An absorbable interference screw is added. At the tibia, the interference screw is first placed, followed by the suture post fixation. Using the combined interference screw and suture post provides sufficient graft strength fixation for rehabilitation to proceed equal to the B-PT-B graft. An alternative technique for a four-strand STG graft using a FlipCutter and EndoButton (Smith & Nephew) or TightRope (Arthrex) technique is shown later in this chapter. The bone portion of the QT-PB is usually placed into the femoral tunnel; however, the graft can be reversed with the bone plug placed into the tibial tunnel and located appropriately to make up for an enlarged tibial tunnel that requires the bone portion of the graft.

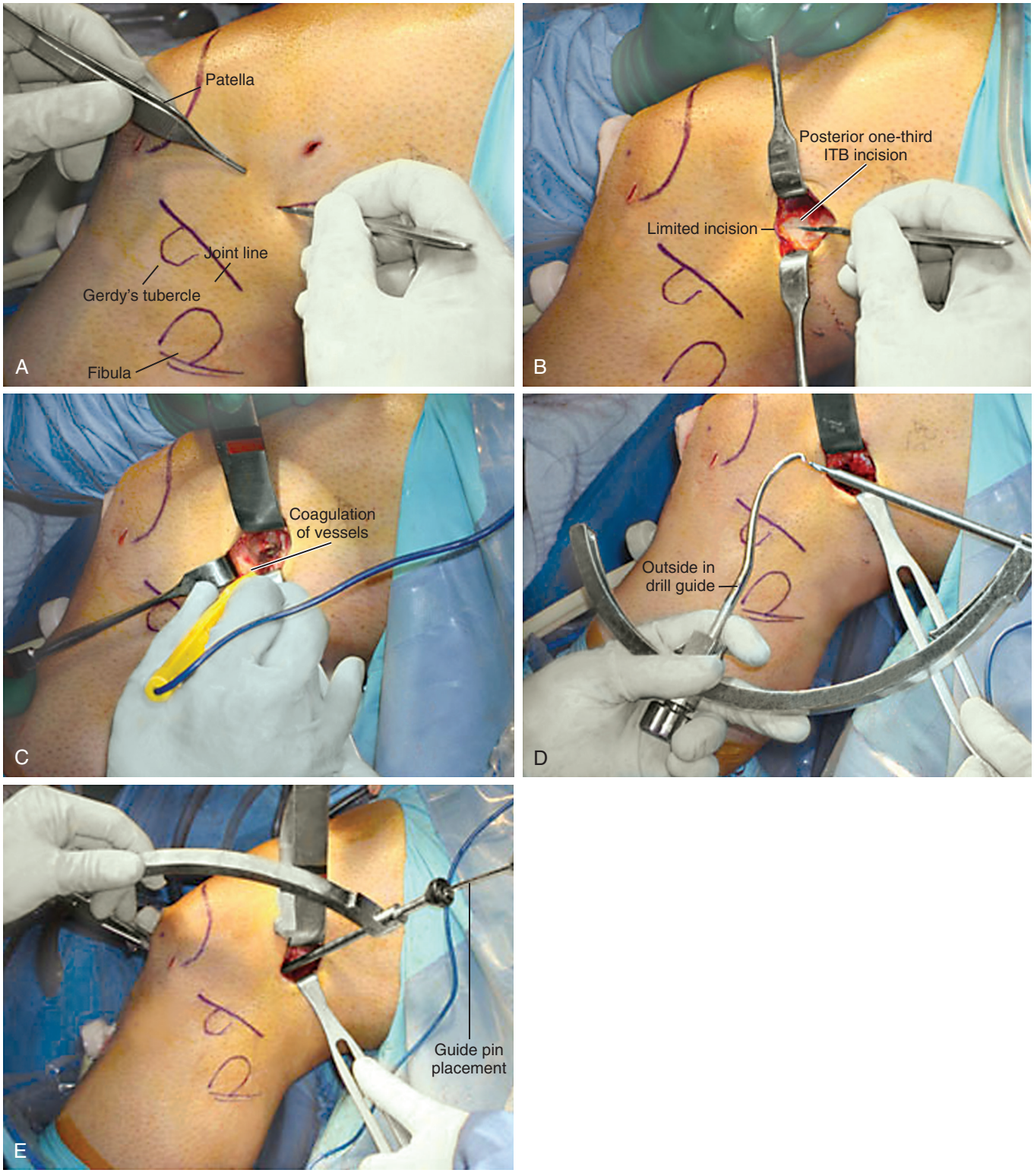


FIG 7-41 The anterior cruciate ligament procedure for a two-incision technique is shown. **A,** The anatomic landmarks are shown. The joint line, tibial tubercle, and fibula are marked. **B,** The 2-cm incision is made in the posterior one third of the iliotibial band (ITB), as described in the text. **C,** Electrocoagulation of vessels. **D,** Commercially available drill guide. **E,** Placement of guide pin. Antegrade drilling is viewed arthroscopically.

TABLE 7-10 Notchplasty Techniques and Rules

1. The arthroscope is placed in the anteromedial (AM) portal with instruments passed through a central portal (patellar tendon graft site or central patellar tendon portal). Place the knee at 20 to 30 degrees of flexion to view the anterior cruciate ligament (ACL) attachment, not a high flexion angle where the ACL is in a horizontal plane. A mistake is to view the lateral wall of the notch through an anterolateral (AL) portal, which provides suboptimal visualization. In the presence of a prominent lateral resident's ridge, it is often difficult if not impossible to view or identify with accuracy the ACL femoral attachment though the AL portal.
2. Measure the clearance of the lateral notch wall to the posterior cruciate ligament (PCL) to ensure there is 9- to 10-mm clearance for the graft. Remove the shallow notch to obtain this clearance, starting distally and progressing proximally up to the top of the notch entrance. This ensures an adequate lateral graft notch clearance throughout knee flexion, preventing graft abrasion from a stenotic lateral notch wall. Usually only 2 to 3 mm of the lateral notch is removed; aggressive resection of the lateral wall beyond this should be avoided.
3. To ensure that the height of the notch is sufficient and will not impinge, place the notchplasty burr at the central ACL tibial attachment and gently bring the knee into full hyperextension. The burr should not impinge into the anterior notch. This defines the millimeters of the anterior and lateral aspect of the notch that are removed to prevent graft impingement. Normally, this is 4 to 6 mm; more is removed when there is excessive hyperextension.
4. The anterior notch is gently curved, removing an A-shaped notch if present. Before graft passage, the arthroscope is placed within the tibial tunnel "worm's-eye view" and the knee taken to full hyperextension, observing whether any portion of the anterior notch comes into view which would require removal. This provides for direct arthroscopic confirmation that there is no ACL graft impingement and intraoperative fluoroscopy is not required.
5. Avoid use of a commercially available "tunnel smoother" because this is too aggressive. When placed in an intraarticular location within both femoral and tibial tunnels and moved proximally and distally, this instrument may remove the anterior aspect of the femoral tunnel and posterior aspect of the tibial tunnel, producing a vertical graft.
6. Once the anterior and lateral aspects of the femoral notch (shallow portion) are prepared, it is possible to completely view the deep portion of the notch, identify the appropriate place for the ACL graft on the lateral wall, and remove an anterior bone buttress in front of the ACL attachment (resident's ridge). Maintain the knee at 20 to 30 degrees of flexion rather than 90 degrees of flexion.
7. The deep roof portion of the notch represents the Blumenstaat line, and it is important not to elevate the notch because this would change the anatomic reference points for the native femoral ACL attachment. In addition, the lateral deep wall of the notch is not changed or removed to maintain the native ACL attachment location for the ACL graft. Remaining ACL fibers are helpful to define the femoral footprint. Only in rare instances is there overgrowth in this region and insufficient clearance between the lateral notch and the PCL. The tissue in this region is gently removed and the PCL synovium is protected. A sharp curette is used to remove soft tissues on the lateral wall to the femoral condyle articular cartilage edge, which is the required reference for ACL graft placement. The mistake is made not to go deep enough in the notch on the lateral wall to view "around the corner" because sometimes the notch wall will have a gentle deep lateral slope of a few degrees.

A variety of techniques for femoral fixation (Fig. 7-43) and tibial fixation (Fig. 7-44) are available, based on the preference of the surgeon. Interference screw fixation alone of an STG or soft tissue allograft is not recommended either. A suture post is commonly required to achieve higher strength graft fixation.

Alternative Procedures

FlipCutter for Femoral Tunnel

An alternative approach to the two-incision technique is the FlipCutter technique that may be used to locate and drill the tunnel from inside out (Fig. 7-45). This procedure provides a long femoral tunnel for graft healing and incorporation. It also allows control of the guide pin for the femoral tunnel to be oriented into the most ideal position to achieve good-quality bone for interference screw fixation. This technique avoids the necessity for tunnel drilling in a hyperflexed knee position.

The steps for this technique are shown in Figure 7-45. The steps already described for locating the central femoral ACL guide pin placement are performed. A 10-mm incision is made at the posterior one third of the thigh and at the proximal margin of the lateral femoral condyle. The drill guide is placed and the blunt proximal guide sleeve bluntly advanced to the femur. The guide pin FlipCutter is advanced and the position and entrance determined with the arthroscope in the AM portal. The drill socket is created. The tunnel joint entrance is chamfered to prevent graft abrasion. The graft is passed in a retrograde manner and fixed by an EndoButton, the TightRope technique, or with an interference screw (B-PT-B) using the AM portal in a retrograde manner. In rare cases where the bone quality on the femur is not ideal and a femoral suture post is desired, it is easy to enlarge the incision for visualization, extend the femoral tunnel to exit proximally, and provide a graft suture post.

CRITICAL POINTS Operative Techniques: Alternative Procedures

FlipCutter for Femoral Tunnel

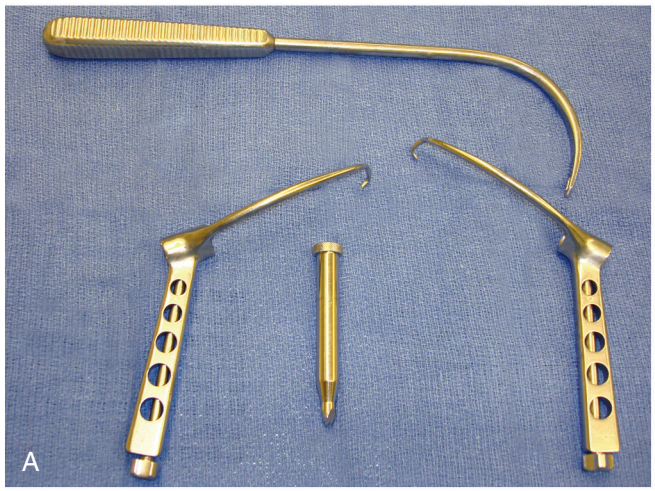
- Used to locate and drill tunnel from inside out.
- Provides long femoral tunnel.
- Guide pin control to orient tunnel in best position to achieve good-quality bone for fixation.
- Avoids necessity for drilling tunnel in hyperflexed knee position.

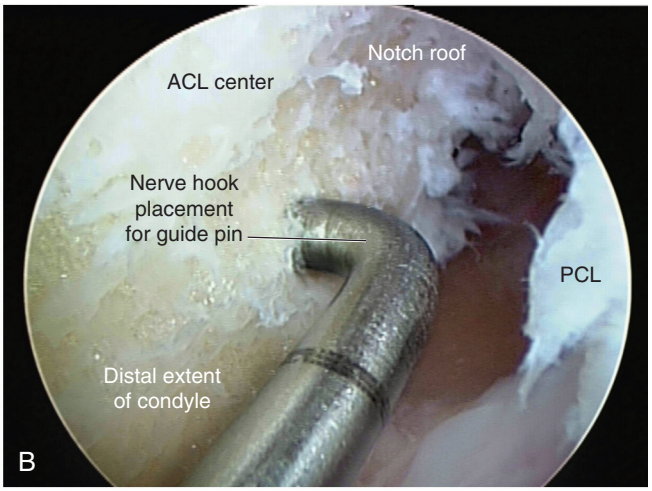
All-Inside ACL Graft-Link Technique Using Second-Generation FlipCutter and TightRope Devices

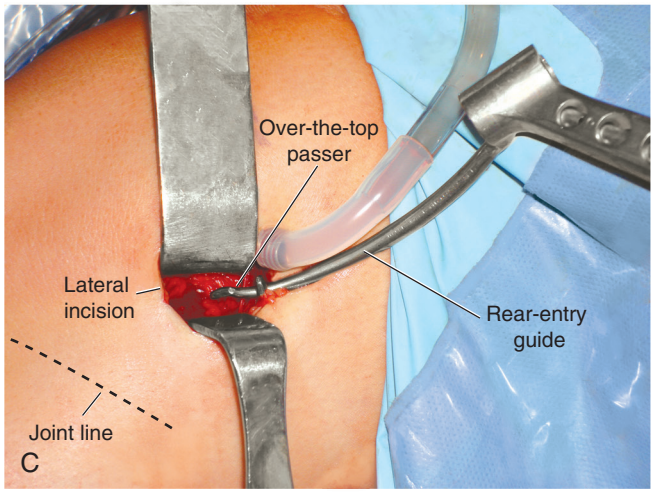
- Advantages include the ability to measure femoral and tibial tunnel length, preparation of the graft to match the sum of tunnel length and intraarticular length (usually 75 mm), and a suture-based graft tensioning that allows the graft to fill the tunnels.

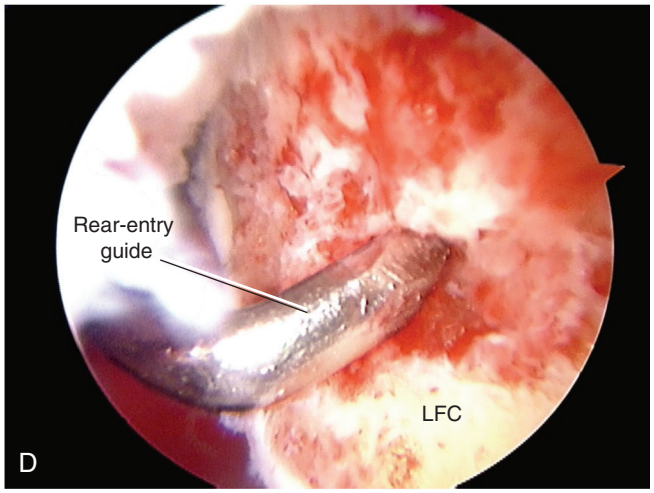
Management of Graft Malposition

- Excessive anterior femoral tunnel: two-incision reorientation of the femoral tunnel is indicated, and a femoral suture post is added to provide a combined interference screw and suture post fixation.
- Excessive posterior femoral tunnel: requires an anterior adjustment in the tunnel.
- Tibial tunnel malposition: small adjustments may be made in medial or lateral graft position by placing the interference screw in a medial or lateral direction.
- Fracture of the bone portion of the graft: place two additional sutures in the tendon portion of the graft and two sutures in the bone portion.
- B-PT-B fixation problems with interference screws are usually solvable by upsizing the screw diameter and adding a suture fixation post.
- Enlarged tibial or femoral tunnel: place absorbable interference screw to compress one side of the graft into the tunnel.









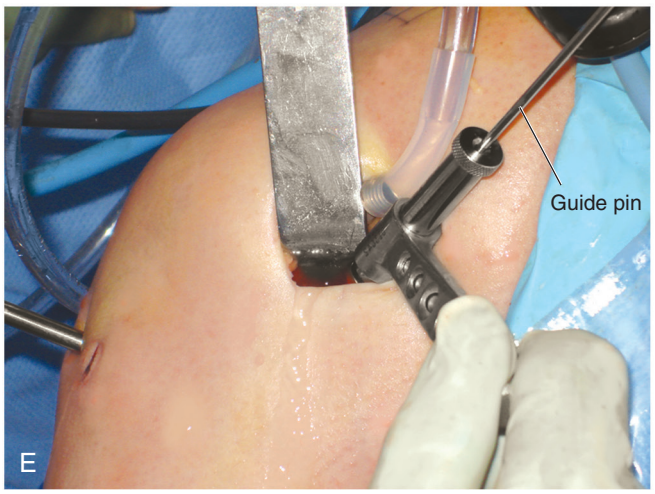


FIG 7-42 **A,** The rear-entry drill guide system is shown (Acufex, Smith & Nephew Endoscopy). **B,** Central anterior cruciate ligament (ACL) femoral attachment location. **C,** Passage of guide through the second incision. **D,** Guide pin location on the lateral femoral wall. **E,** Drilling of the femoral tunnel from outside in. *LFC,* Lateral femoral condyle; *PCL,* posterior collateral ligament.

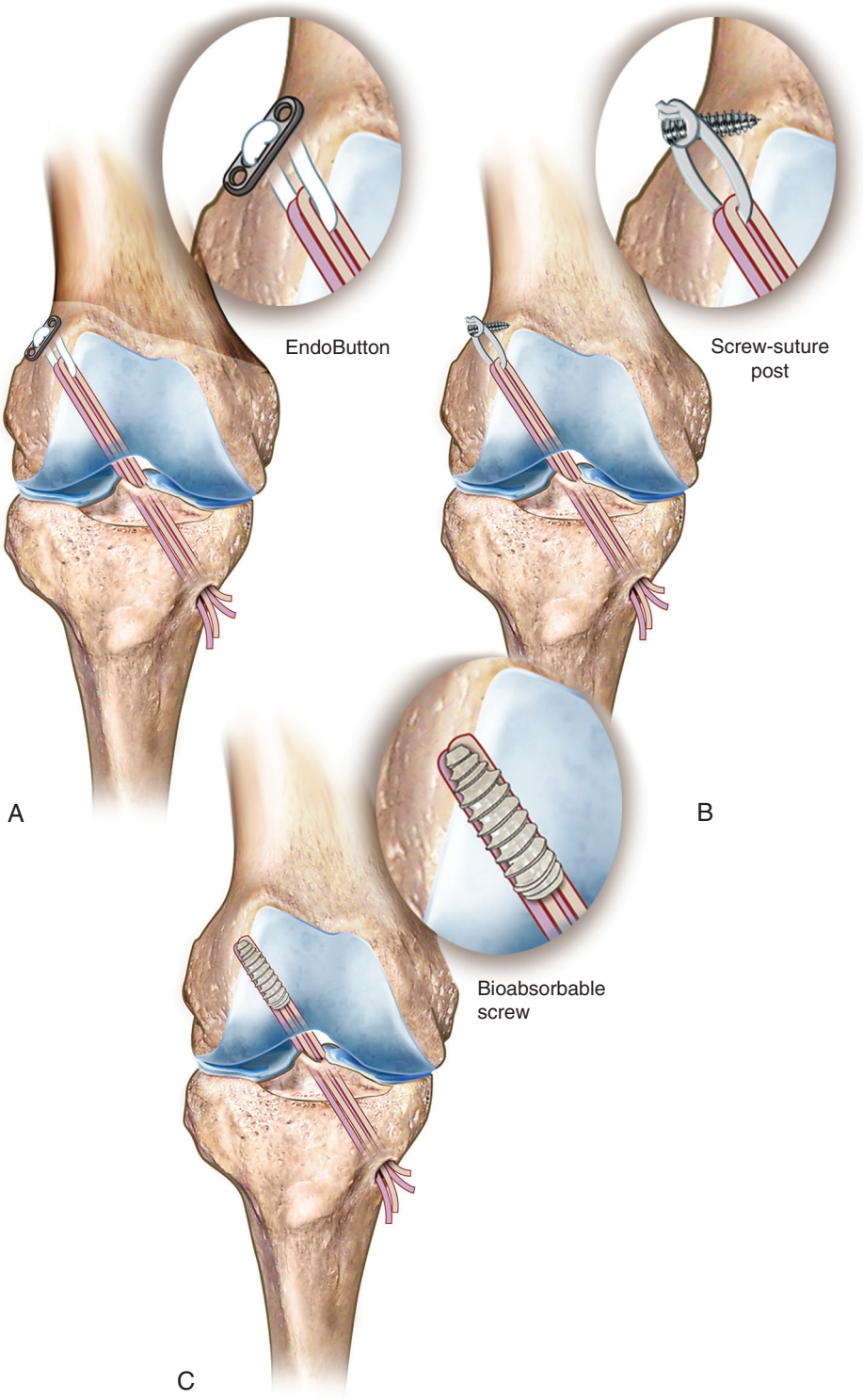


FIG 7-43 A variety of anterior cruciate ligament femoral fixation techniques for semitendinosus-gracilis grafts. The interference screw alone **(C)** is not recommended because it produces the lowest graft tensile strength to pullout.

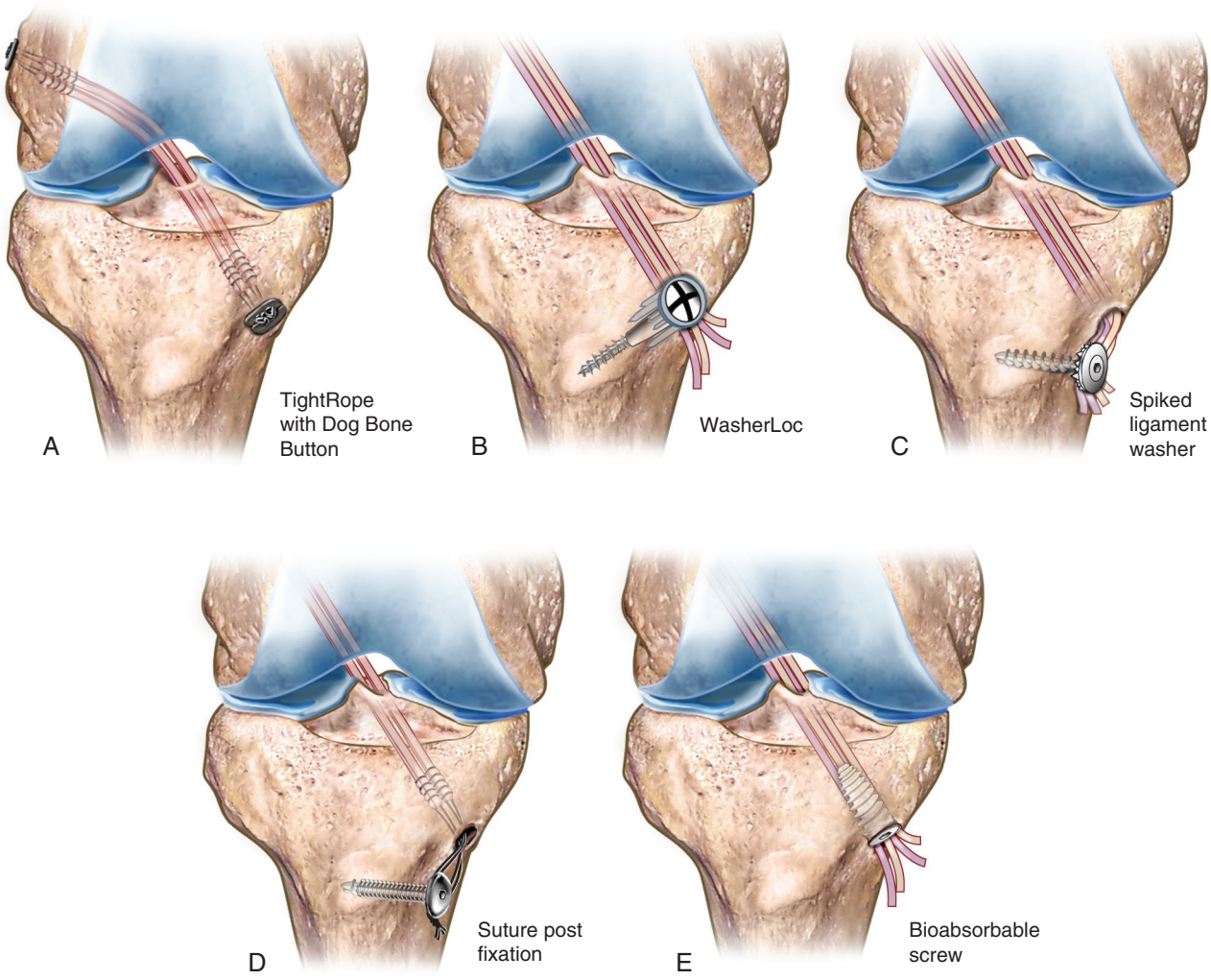


FIG 7-44 Various tibial fixation techniques for semitendinosus-gracilis grafts. An interference screw alone **(D)** is not recommended.

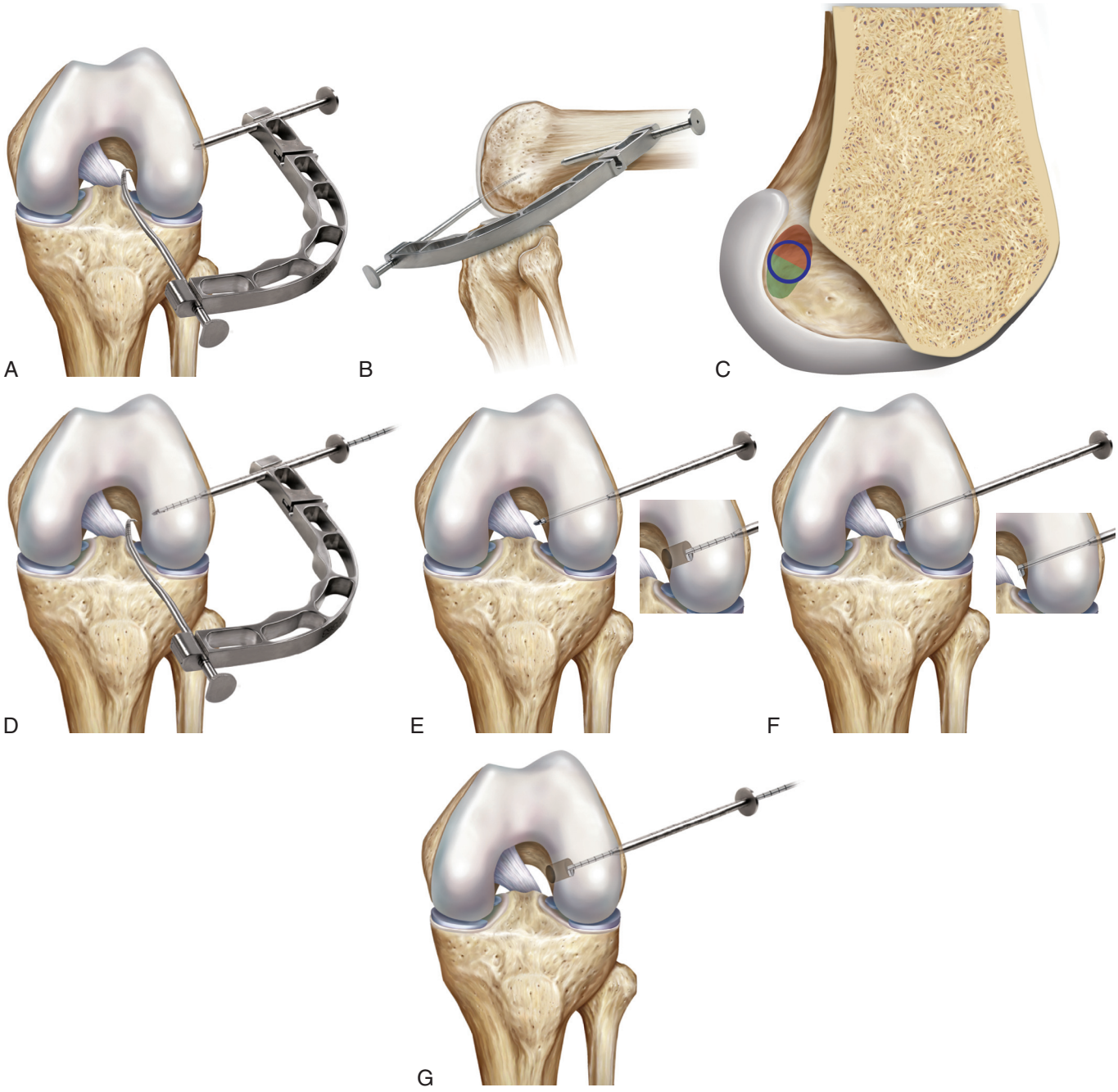


FIG 7-45 Demonstration of FlipCutter technique for femoral socket or tunnel. **A** and **B,** Placement and location of drill guide. **C,** Central anterior cruciate ligament anatomic tunnel placement. **D,** Placement of the FlipCutter. **E,** The FlipCutter is advanced at the femoral attachment. **F,** The drill end is "flipped" at a right angle to the pin. **G,** Creation of a femoral socket that can extend completely as a tunnel if desired. (Courtesy Arthrex, Inc., Naples, FL.)

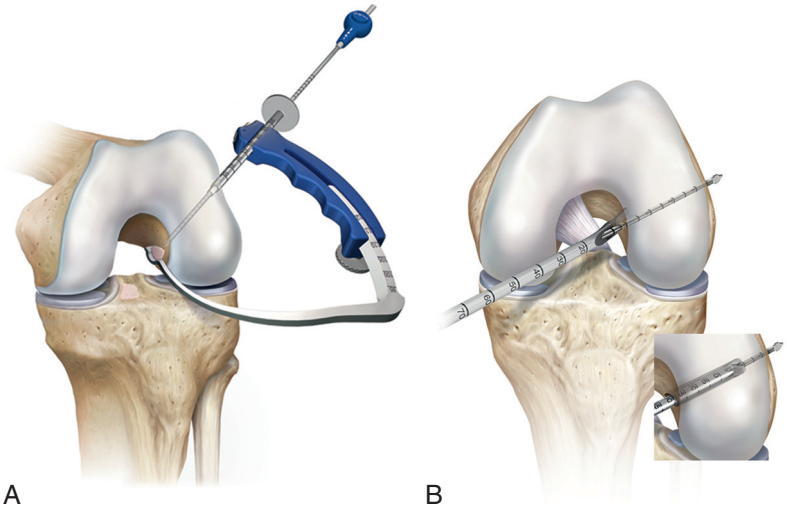


FIG 7-46 The femoral socket can also be prepared in a retrograde fashion using the FlipCutter and the RetroConstruction Drill Guide System **(A)** or an antegrade fashion with a RetroButton Pin II and Low Profile Reamers **(B)**. Note intraosseous length during tunnel preparation and mark that distance on the anterior cruciate ligament TightRope RT implant. (Courtesy Arthrex, Inc., Naples, FL.)

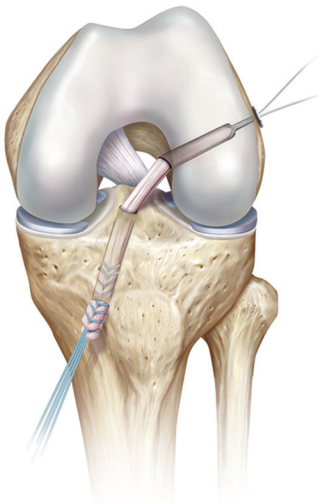


FIG 7-47 Hold slight tension on the tibial tails of the graft during graft advancement. To advance the graft, pull on the tensioning strands one at a time, alternating approximately 1 cm on each side. A mark on the graft made at a distance of the femoral socket is helpful in signaling that the graft is fully seated. Once the graft is fully seated, pull firmly back on the graft to check fixation. If desired, advance the graft just shy of the full length of the socket. This will allow retensioning of the graft after tibial fixation has been completed. (Courtesy Arthrex, Inc., Naples, FL.)

All-Inside Anterior Cruciate Ligament Graft-Link Technique Using Second-Generation FlipCutter and TightRope Devices

Lubowitz and colleagues[155] described the surgical technique in detail for an all-inside ACL reconstruction using a hamstring graft, second-generation FlipCutter guide pins (Arthrex) to create femoral and tibial sockets, and TightRope (Arthrex) for fixation (Figs. 7-46 to 7-52). The advantages of this technique include the ability to measure femoral and tibial tunnel length, preparation of the graft to match the sum of tunnel length and intraarticular length (usually 75 mm), and a suture-based graft tensioning that allows the graft to fill the tunnels. The central femoral and tibial native insertion sites are carefully marked as previously described. Placement of the femoral FlipCutter guide pin is accomplished through a small stab wound 25 mm above the lateral femoral epicondyle in the mid lateral plane. The guide sleeve is advanced 7 mm in the femur (also tibial cortex) to avoid the FlipCutter breaching the cortex. The FlipCutter guide pin is placed at an approximate 45-degree angle at the AM tibial cortex adjacent to the tibial tubercle. A flexible silicone cannula in the AM arthroscopic portal aids in intraarticular graft passage. A recent modification of this technique for tibial fixation of the graft is shown in Figure 7-51.

Flexible Guide Pin and Drill for Femoral Tunnel

The VersiTomic Flexible Reaming System (Stryker), composed of flexible reamers and guide pins, may be used for creating independent bone tunnels during ACL reconstruction (Fig. 7-53).

Management of Graft Malposition

In the operative technique it is important to recognize whether or not an improper graft position has occurred so that steps may be taken to address the problem. An excessive anterior femoral tunnel results when all of the soft tissues have not been removed from the lateral femoral wall and the "around-the-corner" view posteriorly of the femoral condyle has not been achieved. It is important that the AM portal be used to view the entire lateral sidewall in selecting the ideal femoral tunnel position. Excessive posterior placement of a femoral tunnel with a back-wall blow-out would provide a compromise to interference screw fixation. In these cases, a two-incision reorientation of the femoral tunnel is indicated, and a femoral suture post is added to provide a combined interference screw and suture post fixation.

An excessively placed posterior femoral tunnel results in shortening of the graft in extension; this requires an anterior adjustment in the tunnel. When the guide pin is placed in the femoral ACL attachment from either an inside-out or outside-in approach, it is possible to start with a 6-mm acorn-shaped reamer to readjust the tunnel and subsequent tunnel entrance with a stepwise progression in the reamers. In this manner, the most ideal placement of the femoral tunnel may be achieved. A distal femoral tunnel past the 9 o'clock position may result

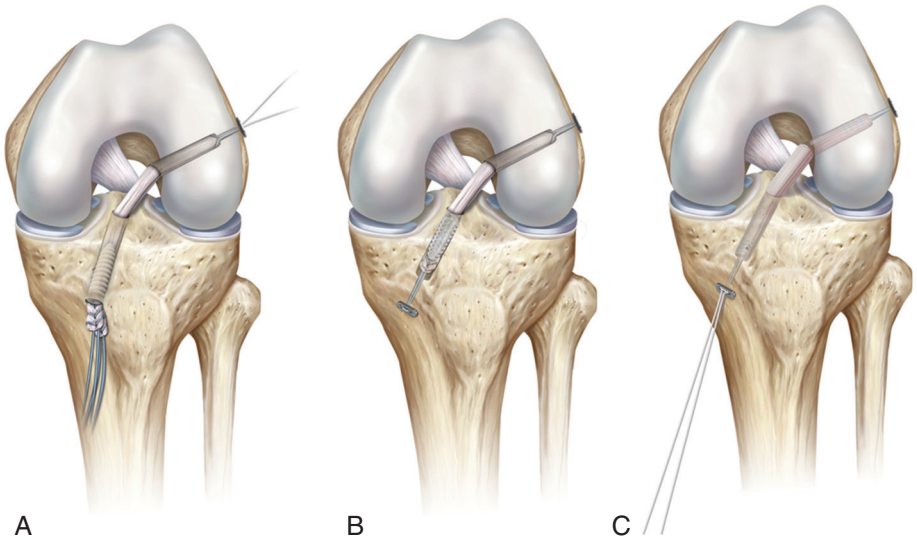


FIG 7-48 **A,** Fix the tibial side of the graft. If desired, and space has been left on the femoral side, retention shortening strands on the femur. Cut shortening strands with a closed-end TightRope Suture Cutter. **B,** Anterior cruciate ligament (ACL) TightRope RT is also ideal for all-inside ACL reconstruction because it facilitates incremental graft advancement and tensioning after tibial fixation has been completed. **C,** ACL TightRope RT may also be used on the tibial side with the GraftLink procedure. See Arthrex technique guide LT0157 for details. (Courtesy Arthrex, Inc., Naples, FL.)

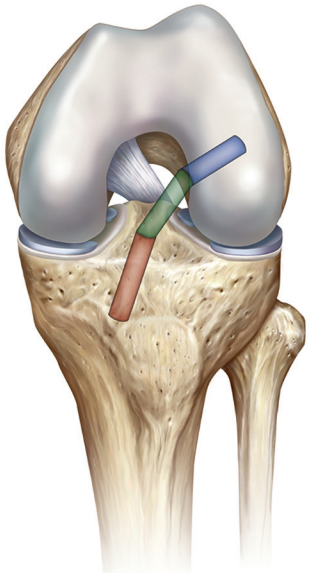


FIG 7-49 GraftLink all-inside anterior cruciate ligament reconstruction with TightRope: Socket creation. The length from the end of the femoral socket to the end of the tibial socket should be at least 10 mm longer than the graft to ensure that the graft can be tensioned fully. For example, with a 70-mm graft length and assuming a maximum intraarticular length of 30 mm (green shading), there will be approximately 20 mm of graft in the femoral and tibial socket. Drill the femoral 20 to 25 mm deep (blue shading) and the tibia approximately 30 mm deep (red shading) to allow an extra 10 mm for tensioning. (Courtesy Arthrex, Inc., Naples, FL.)

in a graft impinging on the lateral femoral condyle, requiring excessive notchplasty. The final graft length is short and not ideal.

A tibial tunnel malposition posteriorly produces a vertical graft. A tibial tunnel placed too far anteriorly may result in anterior graft impingement or loss of the anterior tibial cortex for adequate interference screw fixation. A tibial tunnel placed too far medially or laterally may impinge on the PCL or lateral femoral condyle, respectively. Small adjustments may be made in medial or lateral graft position by placing the interference screw in a medial or lateral direction. The principle is never to accept a misplaced tibial or femoral tunnel and risk of a graft failure and revision knee problem.

A fracture of the bone portion of the graft, in which 15 mm of bone remains, may be managed by placing two additional sutures in the tendon portion of the graft and two sutures in the bone portion. An interference screw is used along with a suture post. In the rare instance of disruption of a B-PT-B graft at the bone-tendon junction, the senior author prefers to harvest an STG autograft instead of adding sutures to the tendon portion because the diameter of the patellar tendon is not ideal in the absence of the bone portion.

In cases of Osgood-Schlatter disease or an accessory ossification of the patellar tendon at the patella attachment (that is not appreciated until the graft is harvested), it is possible to remove the excess bone that will not affect the length or integrity of the graft. However, it is best to avoid a graft from these locations in these disease states and inform the patient that an alternative graft source will be used. The problem is that it may be necessary in a large Osgood-Schlatter lesion to dissect intact tendon adjacent to the graft harvest site to remove the bony lesion entirely, which results in weakening of the tendon attachment site. This problem requires added postoperative protection and modification of the immediate rehabilitation program. B-PT-B fixation problems with interference screws are usually solvable by upsizing the screw diameter and adding a suture fixation post. Never compromise the final graft fixation strength and accept a less than ideal

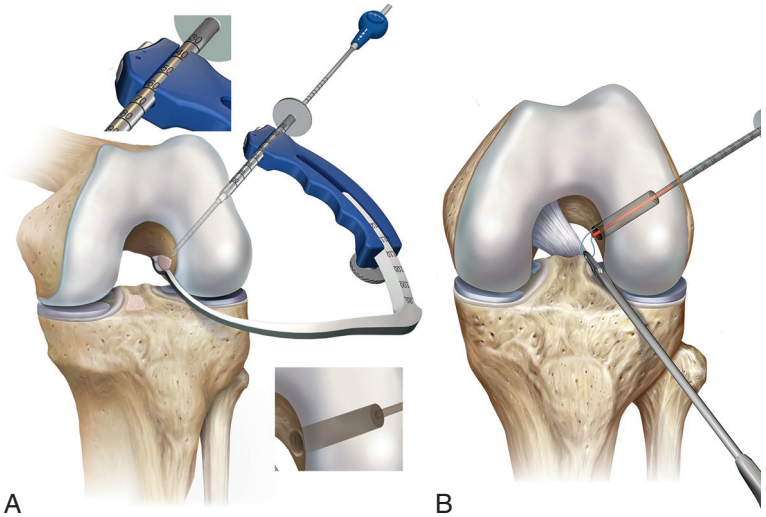


FIG 7-50 **A,** The FlipCutter may be used to create the femoral socket. Note the intraosseous length on the drill sleeve when pushed down to bone (inset). **B,** After "flipcutting," pass a FiberStick suture through the stepped drill sleeve and dock for later graft passing. (Courtesy Arthrex, Inc., Naples, FL.)

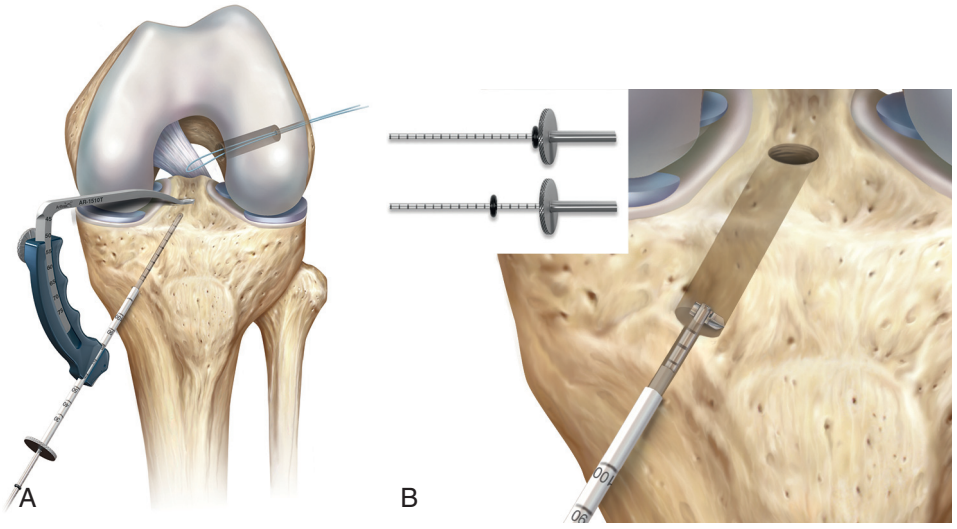


FIG 7-51 Tibial socket creation. **A,** Drill the FlipCutter into the joint. Remove the marking hook. **B,** Flip the blade and lock into cutting position. Drill forward, with distal traction, to cut the socket. Use the rubber ring and 5-mm markings on the FlipCutter to measure socket depth (inset). (Courtesy Arthrex, Inc., Naples, FL.)

fixation because this would potentially result in graft loosening in the early postoperative period.

It is more difficult to manage an enlarged tibial or femoral tunnel with an STG graft because the technique requires that a snug-diameter tunnel be placed to achieve a graft-tunnel interface to allow graft incorporation and avoid excessive tunnel widening. An absorbable interference screw may be necessary to compress one side of the graft into the tunnel, which would require modification of the postoperative rehabilitation to protect the graft during the initial healing stages. EndoButton or TightRope techniques are frequently used with STG grafts, and problems may be encountered with inadvertent reaming of the femoral cortex and loss of fixation strength. Fixation with an interference screw provides a weaker graft fixation, and consideration of a two-incision technique with a suture post is warranted. There is a concern regarding STG tendons looped over a 3-mm loop in the Endobutton or TightRope fixation.

OUR ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION CLINICAL STUDIES

We have published a series of prospective clinical studies on ACL primary reconstruction in over 650 knees with acute, subacute, and chronic ruptures.* The data from these investigations provide information regarding the following variables on clinical outcome: (1) type of graft, (2) sterilization of allografts, (3) gender, (4) chronicity of injury, (5) concomitant operative procedures, (6) preexisting joint arthritis, (7) varus osseous malalignment, (8) the rehabilitation program, and (9) type of insurance (workers' compensation versus private). This chapter provides summaries of these investigations and the reader is encouraged to refer to the original publications for further

*References 11, 18, 20, 21, 37, 185-188, 190, 191, 193-198, 202, 210.

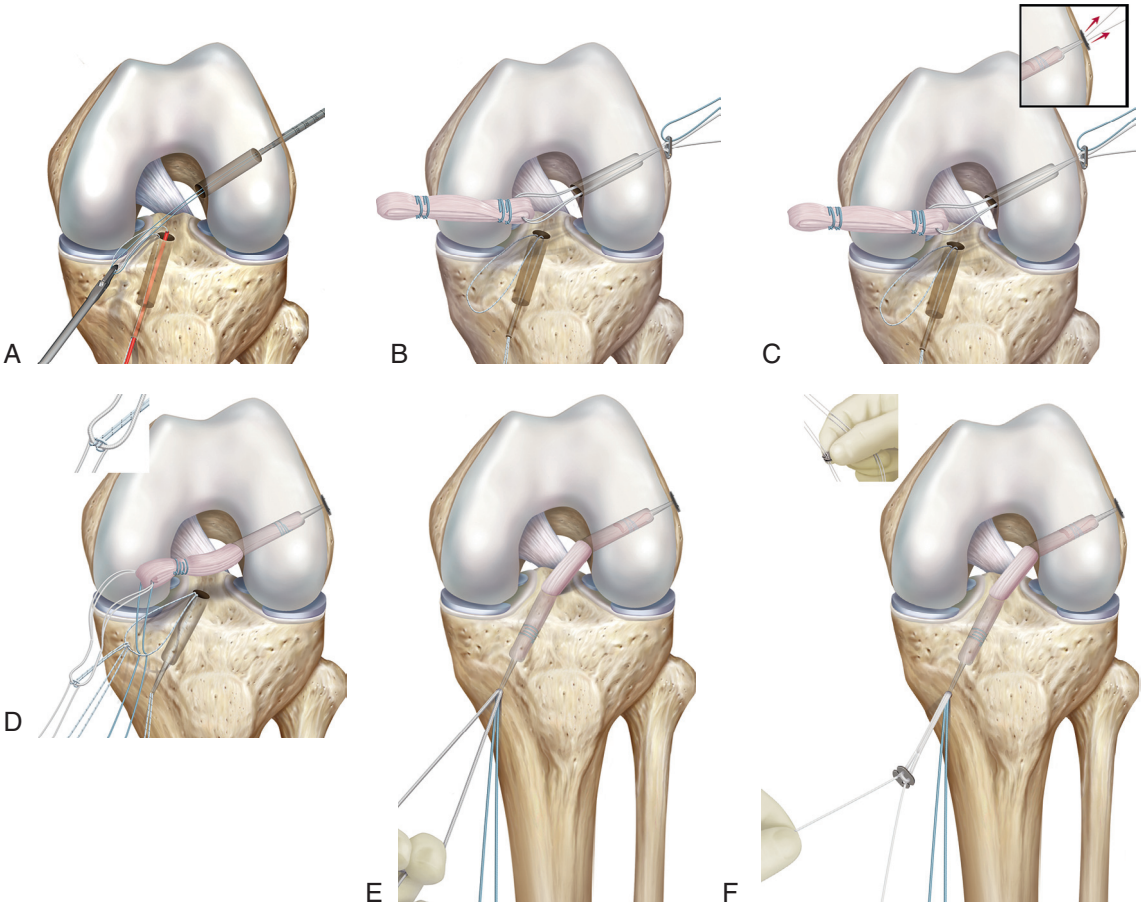


FIG 7-52 Graft passing. **A,** Straighten the FlipCutter blade and remove from the joint. Pass a TigerStick into the joint and retrieve both the tibial TigerStick and the femoral FiberStick out the medial portal together with an open suture retriever. Retrieving both sutures at the same time will help avoid tissue interposition that can complicate graft passing. **B,** Pass the blue button suture and the white shortening strands through the femur. Remove slack from sutures and ensure equal tension. Clamp or hold both blue and white sutures together and pull them together to advance the button out of the femur. Use markings on the loop and arthroscopic visualization of the button to confirm exit from the femoral cortex. Pull back on the graft to confirm the button is seated. **C,** While holding slight tension on the graft, pull the shortening strands proximally, one at a time to advance the graft. Pull on each strand in 1-cm increments. **D,** Cinch a suture around the end of the TightRope ABS loop to use for passing (inset). Load the cinch suture and the whipstitch tails from the graft into the tibial passing suture. Pull distally on the tibial passing suture to deliver both the TightRope ABS loop and the whipstitch sutures out of the tibia distally. **E,** Advance the graft into the tibia by pulling on the inside of the ABS loop and whipstitch sutures. **F,** Load the TightRope ABS button onto the loop. Pull on the white shortening strands to advance the button to bone and tension graft. Ensure the button has a clear path to bone, as to not entrap soft tissue under the button. (Courtesy Arthrex, Inc., Naples, FL.)

detail. The grafts studied included freeze-dried fascia lata and fresh-frozen or irradiated (2.5 mrad) B-PT-B allografts and B-PT-B autografts. An ACL reconstruction was considered failed if more than 5 mm of increased AP tibial displacement was measured on knee arthrometer testing or if a grade II or III pivot shift was elicited on clinical examination (International Knee Documentation Committee [IKDC] knee categories of abnormal and severely abnormal combined).

Type of Graft

A higher rate of ACL graft failure was noted in knees with chronic ACL ruptures that received fresh-frozen or irradiated allografts (16%-30%)[185,186] compared with those that received autografts (3%-8%[195]; Table 7-11). Accordingly, the senior author advised against the use of allografts in 1997[195] because of these differences. The only exception was in a group of knees that underwent a combined allograft and ITB extraarticular procedure in which a failure rate of only 3% was found.[185]

In knees that underwent ACL reconstruction for acute or subacute ruptures, there was no difference in the overall failure rate among B-PT-B allografts (7%)[191] and autografts (3%).[195] However, a greater percentage of knees that received allografts had 3 to 5 mm of increased AP displacement, indicating partial graft function, compared to autografts (Fig. 7-54). The knees in this category typically demonstrate a grade I pivot shift and may be at increased risk for progression to a fully positive pivot shift in the future. As a result of these findings, we recommended in 1997 to use arthroscopically assisted B-PT-B autogenous grafts as the first choice for acute and chronic ACL ruptures.[195]

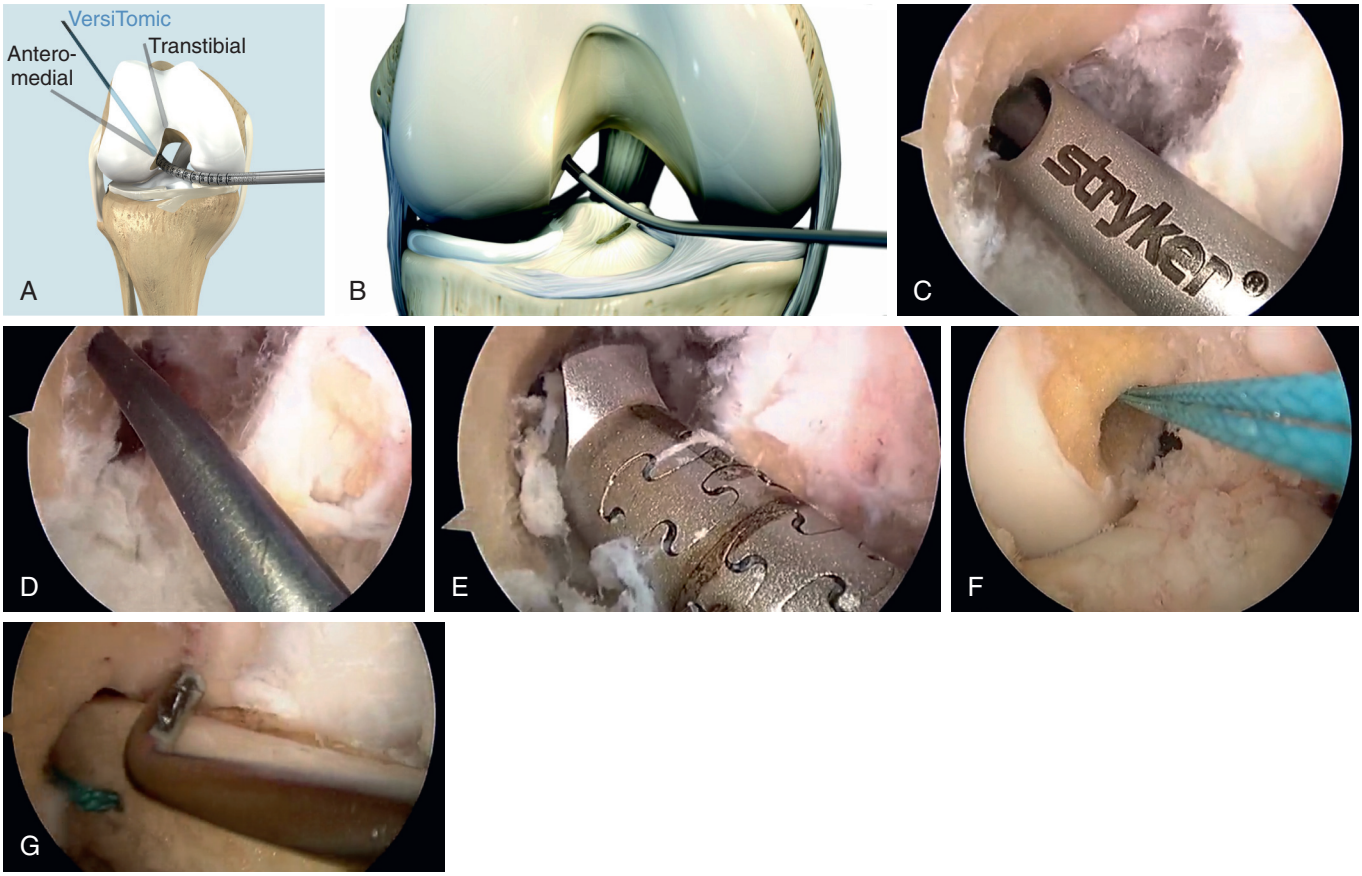


FIG 7-53 The VersiTomic Flexible reaming system. **A,** The flexible reamer angle provides a deep femoral tunnel compared with the anteromedial portal drill placement. The tunnel is located in the proximal two thirds or central two thirds of the femoral anterior cruciate ligament attachment. **B** to **D,** Femoral tunnel location for guide pin with knee flexion of 100 to 110 degrees of flexion. Guide pin exits lateral thigh 3 cm above lateral femoral epicondyle at metaphyseal junction femoral cortex. **E,** Flexible reamer entrance into desired femoral tunnel location. **F** and **G,** Femoral tunnel and bone-patellar tendon-bone graft placement. (Courtesy Stryker, Kalamazoo, MI.)

Augmentation Procedures for Allografts (Iliotibial Band Extraarticular, Ligament Augmentation Device)

We conducted a prospective study (Level II) on the use of an extraarticular ITB tenodesis procedure combined with a B-PT-B allograft for chronic ACL ruptures.[185] This was the first study that compared the outcomes of this combined procedure (64 patients) with those of an allograft alone (40 patients). The knees in this study had a high grade of instability before surgery because 50% or more had a grade III pivot shift, indicating deficiency of the extraarticular lateral restraints.

At follow-up, a mean of 2.9 years postoperatively, the rate of graft failure was 16% in the allograft-alone subgroup compared with 3% in the combined allograft-ITB subgroup ($P < .05$, see Table 7-11). The difference in AP displacements measured on KT-1000 testing was also statistically significant (Fig. 7-55, $P < .01$). The difference in the rate of failure was not caused by an irradiation effect because only 10 patients in the allograft-alone group and 2 patients in the combined allograft-ITB group received irradiated grafts. The combined subgroup returned to significantly higher levels of sports activity ($P < .05$) and had higher overall rating scores on the Cincinnati Knee Rating System (CKRS) ($P < .01$). There were no differences among the subgroups in isokinetic muscle test scores, functional limitations, symptoms, or patellofemoral crepitus.

We hypothesized that the ITB tenodesis provided support to the intraarticular allograft by restoring the secondary lateral restraints to anterior translation and internal rotation. Therefore, the procedure may be useful in knees with a grade III pivot shift. However, the study cohort is not large enough to provide definitive recommendations and further study is indicated. The results of this study may have implications in the treatment of ACL revision knees in which an allograft approach is selected (see Chapter 8).

From a historical perspective, we conducted a prospective, randomized clinical trial (Level I) on the effect of a ligament augmentation device (LAD) combined with an irradiated B-PT-B allograft for chronic ACL ruptures.[186] The results of the combined procedure in 49 knees were compared with those of a fresh-frozen B-PT-B allograft used alone in 66 knees. At an average of 2.8 years postoperatively, there was no difference in overall graft failure rates (20% and 16%, respectively; see Table 7-11) or in the individual symptom, functional limitation, or overall rating scores. The LAD did not improve the efficacy of the reconstruction and was therefore not recommended for use with an allograft for ACL reconstruction.

Secondary Sterilization Process Used for Allografts

Based on the two studies in the chronic ACL groups shown in Table 7-11, a higher rate of ACL graft failure was measured in knees that

TABLE 7-11 Summary of Our Primary Anterior Cruciate Ligament Reconstruction Clinical Studies: Knee Arthrometer Data and Final Failure Rates

Study	Stage (n)	Follow-up (yr)	Graft Type	Allograft Sterilization	Preoperative Total AP Displacement (mm) (Mean, Range)	Follow-up Total AP Displacement (mm) (Mean, Range)	FOLLOW-UP TOTAL AP DISPLACEMENT CATEGORIES (I-N) (%)			Final Failure Rate* (%)
							<3 mm	3-5 mm	>5 mm	
Noyes et al.[187] (1990)	Acute (68)	5-9	Fascia lata allograft	Fresh-frozen (n = 28)	—	1.0 ± 3.1 (–2.5 to +6.5)	77	20	3	7
				Freeze-dried (n = 40) + ETO in 32	—	1.0 ± 2.9 (–7.0 to +5.0)	75	20	5	5
Noyes, Barber-Westin[185] (1991)	Chronic (64)	2-4.5	B-PT-B allograft	All combined	9.2 ± 3.0 (3.0-16.0)	2.6 ± 2.5 (–2.8 to +8.0)	54	34	12	16
				Fresh-frozen (n = 54)	9.0 ± 3.0 (3.0-16.0)	2.5 ± 2.3 (–2.0 to +7.5)	53	31	16	16
				Irradiated (n = 10)	10.0 ± 2.0 (7.0-13.5)	2.8 ± 3.2 (–2.0 to +8.0)	60	10	30	30
Noyes, Barber-Westin[185] (1991)	Chronic (40)	2-4.5	B-PT-B allograft + ITB EA	Fresh-frozen	8.3 ± 3.3 (3.0-15.5)	1.1 ± 2.5 (–4.0 to +6.5)	74	23	3	3
Noyes, Barber-Westin[186] (1992)	Chronic (49)	2-3.4	B-PT-B allograft + LAD	Irradiated	9.5 ± 3.5 (5.0-18.0)	2.7 ± 3.5 (–3.0 to +12.0)	53	30	17	20
Noyes, Barber-Westin[195] (1997)	Chronic (57)	2-3	B-PT-B autograft		11.4 ± 4.5 (4.0-22.0)	0.4 ± 2.7 (–3.5 to +10.0)	84	12	4	8
	Acute (30)				9.0 ± 2.9 (3.5-14.0)	–0.3 ± 2.6 (–5.5 to +7.0)	92	4	4	3
Barber-Westin et al.[20] (1997)	Acute and chronic (47 male)	2-3	B-PT-B autograft		10.3 ± 4.0 (3.5-22.0)	0.2 ± 2.9 (–5.5 to +8.0)	80	16	4	4
	Acute and chronic (47 female)				12.9 ± 4.5 (4.5-22.5)	0.7 ± 2.8 (–3.5 to +10.0)	87	8	5	6
Noyes, Barber-Westin[196] (1997)	Acute and chronic (19 WC)	2-3.4	B-PT-B autograft		11.2 ± 3.7 (6.5-15.0)	0.6 ± 3.1 (–3.0 to +10.0)	87	13	0	0
	Acute and chronic (19 PI)				10.4 ± 2.3 (4.0-16.5)	0.5 ± 2.2 (–4.5 to +4.0)	80	13	7	5

*Failed was defined as >5-mm increase total AP displacement or grade II or III pivot shift.

AP, Anteroposterior; *B-PT-B*, bone-patellar tendon-bone; *ETO*, ethylene oxide; *I-N*, involved knee–noninvolved knee; *ITB*, iliotibial band; *LAD*, ligament augmentation device; *PI*, private insurance; *WC*, Workers' compensation.

received allografts sterilized with 2.5 mrad of gamma irradiation (23%; 14 of 61 knees) compared with those that were fresh frozen (11%; 10 of 92 knees, $P < .05$).[185,186] We prefer and recommend other methods of secondary sterilization that have been discussed in detail by others elsewhere.[171,292,293]

Gender

We conducted a prospective study (Level II) on 94 patients (47 males, 47 females) who received B-PT-B autografts to determine whether or not a difference existed in outcome between men and women.[20] This was the first study of its kind to conduct this type of comparison. The patient groups were stratified according to chronicity of the injury to determine whether this factor affected the results. Patients in the acute subgroup received the operation within 14 weeks of the original injury; all others were placed in the chronic subgroup. The patients were matched for age, preoperative sports activity levels, condition of the articular cartilage, and months of follow-up.

At a mean of 2.2 years postoperatively, there were no significant differences in outcome between the men and the women. Although the women demonstrated greater mean AP displacements before surgery than the men (14.3 ± 5 mm and 11.2 ± 4 mm, respectively; $P = .05$), these data were similar at follow-up (0.90 ± 2.69 mm for men, 0.70 ± 3.49 mm for women), as were the percentages of patients with less than 3 mm, 3 to 5.5 mm, and 6 mm or more of increased AP displacement (Fig. 7-56). The overall failure rate was 4% for men and 6% for women. There was no difference between genders for range of knee motion, patellofemoral crepitus, anterior knee pain, muscle strength deficits (Table 7-12), or complications. In addition, there was no significant difference between men and women for symptoms, functional limitations with daily or sports activities, or the overall rating scores. The conclusion was reached that equal consideration should be given to active patients for ACL reconstruction regardless of gender. Subsequently, other authors conducted similar analysis and reached the same conclusions for men and women receiving B-PT-B autografts[65] and STG autografts.[252]

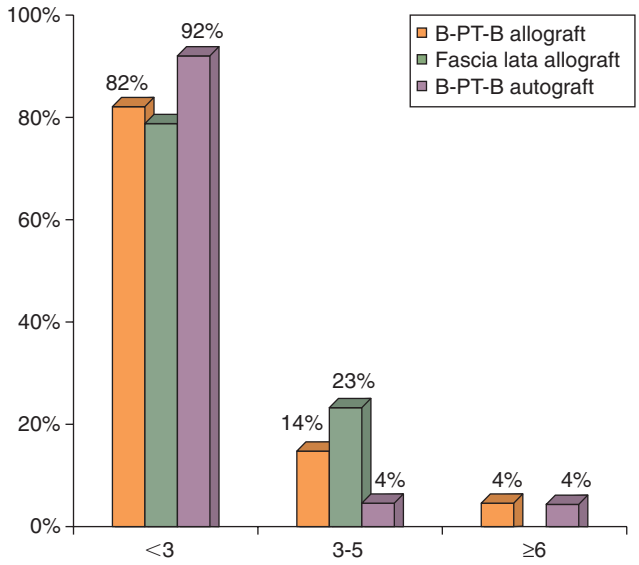


FIG 7-54 Knee arthrometer results from our clinical studies in patients who received ACL reconstruction for acute or subacute ruptures with either bone-patellar tendon-bone (B-PT-B) allograft, fascia lata allograft, or B-PT-B autograft tissue.

Chronicity of Injury

We prospectively followed 94 consecutive patients who received B-PT-B autografts to determine whether a difference existed in objective or subjective outcome between acute and chronic ACL ruptures.[195] Eighty-seven patients (93%) returned for follow-up evaluations from 2 to 3.7 years postoperatively. The acute subgroup comprised 30 patients who underwent reconstruction, a mean of 6 weeks (range, 2-14 weeks) after the injury. The chronic subgroup comprised 57 patients who underwent reconstruction, a mean of 4.5 years (range, 3 months to 29 years) after the original knee injury. All of these patients had symptoms or functional limitations that failed to improve with rehabilitation or activity modification. A total of 94 operative procedures had been done in 34 of these patients before the ACL reconstruction, including 20 medial meniscectomies and 9 lateral meniscectomies (partial or total).

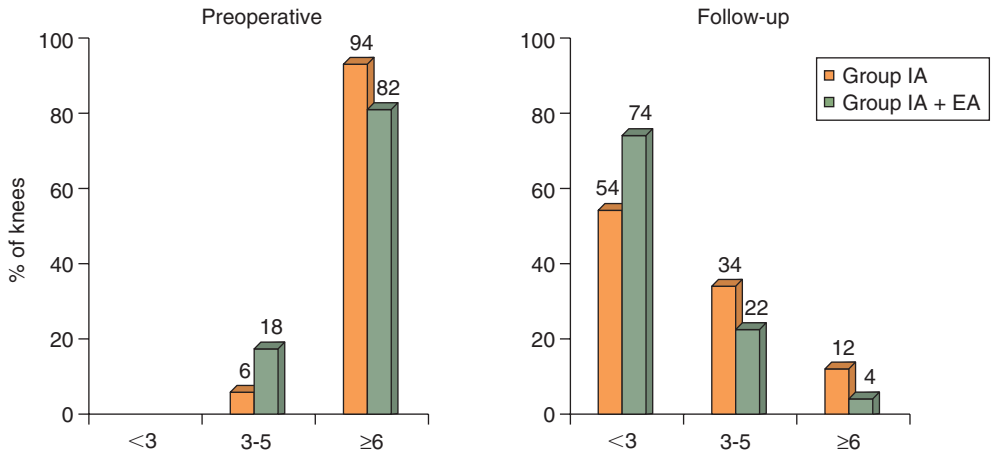


FIG 7-55 Preoperative and follow-up results of testing with the KT-1000 arthrometer for anterior-posterior displacement at 89 N of total force for group IA (allograft alone) and group IA + EA (allograft and extraarticular procedure). At the latest follow-up evaluation, the difference in the displacement between the two groups was statistically significant ($P < .01$). (From Noyes FR, Barber SD. The effect of an extra-articular procedure on allograft reconstructions for chronic ruptures of the anterior cruciate ligament. *J Bone Joint Surg Am.* 1991;73:882-892.)

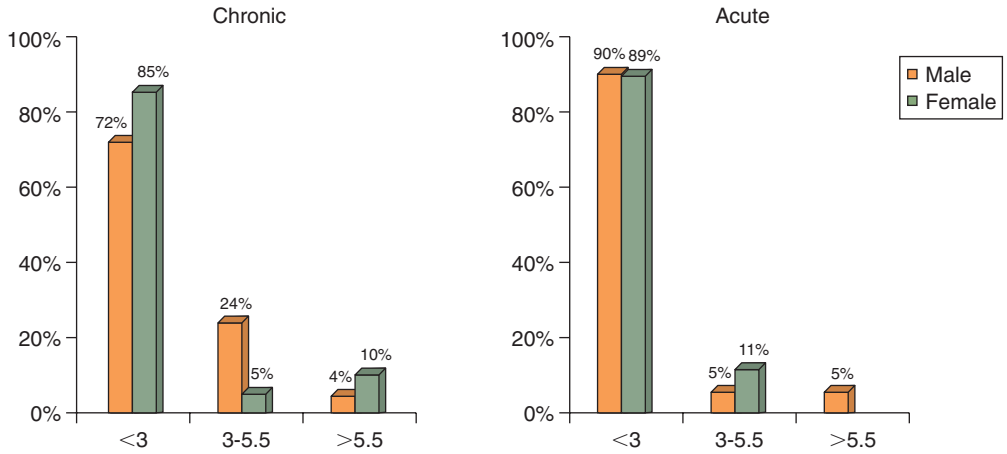


FIG 7-56 The results of KT-2000 arthrometer testing at 134-N (involved vs. noninvolved limb) at follow-up. There was no statistically significant difference found between men and women in the percentage of patients in the three anterior-posterior displacement categories. (From Barber-Westin SD, Noyes FR, Andrews MA. A rigorous comparison between the sexes of results and complications after anterior cruciate ligament reconstruction. *Am J Sports Med.* 1997;25:514-526.)

TABLE 7-12 Results of Isometric Muscle Testing Between Men and Women After ACL B-PT-B Autograft Reconstruction

Deficit of Reconstructed Limb Compared With Opposite Limb (%)	KNEE EXTENSORS (%)		KNEE FLEXORS (%)	
	Men	Women	Men	Women
0-10	67	62	74	69
11-20	24	24	11	24
21-40	9	7	15	7
>40	0	7	0	0

ACL, Anterior cruciate ligament; *B-PT-B,* bone-patellar tendon-bone.

TABLE 7-13 Summary of Data Comparison Between Acute and Chronic ACL B-PT-B Autogenous Reconstructions

Outcome Factor	Acute vs. Chronic Result	Method
Postoperative stability	NS	KT-2000 arthrometer
Patellofemoral crepitus	NS	Knee examination
Patellofemoral pain	NS	Knee examination
Range of knee motion	NS	Goniometer
Knee motion complications	NS	Knee examination
Meniscal repair	NS	Knee examination
Tibial tunnel width	NS	Radiographs
Femoral tunnel width	NS	Radiographs
Patellar tendon height	NS	Radiographs
Articular cartilage	NS	Arthroscopy
Functional analysis	S: squatting, running, jumping, twisting NS: walking, stairs	Cincinnati Knee Rating System
Symptoms	S: pain NS: swelling, giving-way	Cincinnati Knee Rating System
Overall rating score	S	Cincinnati Knee Rating System
Patient rating outcome	S	Cincinnati Knee Rating System

For all significant values, the acute subgroup had better results than the chronic subgroup.
ACL, Anterior cruciate ligament; *B-PT-B,* bone-patellar tendon-bone; *NS,* difference not statistically significant; *S,* difference statistically significant.

The results of the comparisons are shown in Table 7-13. There was no difference among the subgroups in mean AP displacements (chronic group, 0.4 ± 2.7 mm; acute group, –0.3 ± 2.6 mm), pivot shift testing, knee motion complications, or overall rate of graft failure (chronic group, 8%; acute subgroup, 3%). A total of 46 menisci had been repaired during the ACL reconstruction. At follow-up, there was no evidence of retears in 41 of these knees, indicating the importance of meniscus repairs in acute and chronic knees.

There were significant differences among the subgroups for pain ($P = .04$), squatting/kneeling ($P = .03$), running ($P = .02$), jumping ($P = .04$), twisting/turning ($P = .01$), the patient rating of the overall condition of the knee ($P = .007$), and sports activity levels ($P = .05$). Patients in the acute subgroup had less pain and limitations with sports functions and returned to more strenuous activities than those with chronic deficiency. The conclusion was reached that joint stabilization should be performed early in active patients before reinjuries and loss of meniscus tissue. In addition, investigations that assess the results of ACL reconstruction should separately assess the outcome of acute/subacute and chronic ruptures with rigorous knee rating systems.

Concomitant Operative Procedures

We conducted several studies on patients who received concomitant procedures with an ACL reconstruction, including complex meniscus repair for tears that extended into the central third region,[37,198,199,205,247] HTO,[188,202] PL reconstructions,[189,190,192,197,200,201] MCL repairs,[190] and multiligament procedures.[197]

In a series of 177 patients who underwent repair of 198 meniscus tears that extended into the central third region, the ACL was also

TABLE 7-14 Reoperation Rates of Meniscus Repairs According to ACL Function

ACL Function	Repaired Menisci That Required Follow-up Arthroscopy for Tibiofemoral Joint Symptoms
Functional ($n = 166$)	32 (19%)
Not functional ($n = 32$)	7 (22%)
Total ($n = 198$)	39

Functional = <5 mm of increased anteroposterior displacement on arthrometer testing or pivot shift grade 0 or I; not functional = >5 mm of increased anteroposterior displacement on arthrometer testing or pivot shift grade II or III.
ACL, Anterior cruciate ligament.

reconstructed in 126 (71%) knees with either irradiated allografts (72 knees) or B-PT-B autografts (54 knees).[247] At a mean of 3.5 years postoperatively, the failure rates were 4% for the autografts and 15% for the allografts. The increased failure rate for the allografts may have been related to the irradiation sterilization process. The study found that 159 of the meniscus repairs (80%) were successful, with no tibiofemoral joint symptoms. Thirty-nine patients (20%) required repeat arthroscopy for symptoms. No statistical relationship was found between ACL function at follow-up and the reoperation rate for a symptomatic meniscus repair (Table 7-14).

A separate investigation was performed for 28 complex meniscus repairs for tears that extended into the central third region in 27 patients aged 40 to 58 years.[198] The ACL was reconstructed in 21 patients with B-PT-B autografts in all but five knees. At a mean of 2.8 years postoperatively, none of the ACL grafts had failed. Twenty-six of the meniscus repairs (87%) were asymptomatic and considered successful. Concomitant ACL reconstruction appeared to increase the healing rate of meniscus repairs. This older group of patients was physically active and w believed it was important to stabilize the knee and preserve the meniscus, as all desired to return to athletics.

A third investigation followed 61 knees in 58 patients under the age of 20, who underwent a total of 71 complex meniscus repairs that extended into the central third region.[199] Forty-seven knees had a concurrent ACL reconstruction with either irradiated B-PT-B allografts (20 knees) or B-PT-B autografts (27 knees).[199] At a mean of 4.2 years postoperatively, none of the autografts had failed, whereas five of the allografts (25%) had failed, which was most likely related to the irradiation sterilization process. As a footnote, irradiated allografts were used from a historical perspective when tissue banking was still undergoing certification procedures. We abandoned irradiated allografts in the late 1990s after publishing in vitro and in vivo studies on the deleterious effects of high-dose irradiation on allografts.

Fifty-three of the meniscus repairs (75%) were asymptomatic and had not required further surgery. None of the patients in whom the allografts failed had tibiofemoral symptoms. A long-term investigation was conducted on a subgroup of 31 of these patients who had a single longitudinal meniscus tear.[205] The study included 18 patients who underwent ACL reconstruction (8 allografts and 10 autografts) and who were evaluated a mean of 17.3 years postoperative (range, 10.1-22.9 years). All of these knees had an IKDC ACL rating of either A or B, indicating normal or nearly normal graft function. The success rates of these three investigations warrants repair of complex meniscus tears that extend into the central third region in active individuals, along with stabilization of ACL deficiency (see Chapter 23).



FIG 7-57 An example of a two-incision anterior cruciate ligament bone-patellar tendon-bone autograft technique combined with a proximal advancement of the posterolateral (PL) complex for abnormal lateral tibiofemoral joint opening. The PL insufficiency represented an interstitial stretching and not a traumatic rupture, which was an ideal indication for the proximal advancement, avoiding a more complex posterolateral graft reconstruction.

In our experience, the majority of patients who require PL reconstructions also require ACL or PCL reconstruction. Four investigations determined the outcome of PL reconstructions that consisted of a proximal advancement of the PLS,[192] a femoral-fibular allograft reconstruction,[189,201] and an anatomic B-PT-B FCL reconstruction,[200] all of which are described in detail in Chapter 17. In one study, 21 patients were followed who received a proximal advancement of the PLS; 12 patients also had an ACL B-PT-B reconstruction (allograft in 10, autograft in 2).[192] These patients all had a definitive FCL, although lax, which did not require graft reconstruction (Fig. 7-57). At follow-up, a mean of 3.5 years postoperatively, only one of the ACL reconstructions had failed. The PL procedure was successful in restoring function or partial function in all but two knees.

In another study, we followed 21 patients who received an allograft femoral-fibular PL reconstruction, of whom 13 also had a B-PT-B ACL reconstruction (11 allografts, 2 autografts).[189] All of the allograft tissues were irradiated. At follow-up a mean of 3.5 years postoperatively, only one ACL reconstruction had failed. The PL procedure restored function or partial function in all but five knees. The patients in whom the PL procedure was rated as functional were followed in a long-term investigation (mean, 14 years); the study included 10 patients who had received ACL allografts. The IKDC ACL ratings were A to B in seven knees, C in one knee, and D in one knee. All of the PL reconstructions were rated as A or B.

In another investigation, 13 patients who underwent 14 anatomic FCL B-PT-B reconstructions were followed 2 to 13.7 years postoperatively.[200] In this group, 12 patients underwent concomitant ACL reconstruction with irradiated B-PT-B allografts, B-PT-B autografts, or quadriceps tendon-PT autografts. At follow-up, all but two of the ACL

reconstructions were rated as IKDC normal or nearly normal, and all but one of the posterolateral reconstructions were rated normal or nearly normal. These studies emphasize the importance of surgically restoring all deficient knee ligamentous structures concomitantly. The selection criteria for the appropriate posterolateral procedure are described in Chapter 17.

We followed a series of 46 patients who had combined ACL and MCL deficiency to determine the appropriate treatment (operative or conservative) for MCL ruptures, described in detail in Chapter 19.[190] All patients underwent ACL allograft reconstruction. In 34 patients in whom all of the medial structures were ruptured, an MCL repair was performed. In 12 patients, only the superficial MCL fibers were torn and these did not undergo surgery. At follow-up, a mean of 5.3 years postoperatively, seven of the ACL allografts (15%) had failed. All of the knees had less than 3 mm of increased medial joint opening at 5 degrees and 25 degrees of flexion. The study found that knee motion problems and patellofemoral symptoms were more common in patients who received the MCL repair. Therefore, the recommendation was made for knees with combined ACL-MCL ruptures to treat the MCL injury with appropriate conservative measures first, followed by a staged ACL reconstruction (see Chapter 20). An exception is a displaced medial meniscus tear, which requires early operative intervention.

Preexisting Joint Arthritis and Prior Meniscectomy

We studied the effect of preexisting advanced articular cartilage damage in knees undergoing ACL reconstruction for giving-way symptoms to determine whether the operation was effective in improving the overall quality of life. In one investigation,[193] 53 patients received autogenous B-PT-B ACL reconstructions an average of 7.5 years after the original injury. A total of 90 prior operative procedures had been performed in these knees, including 10 ACL reconstructions that had failed, 27 medial meniscectomies, and 10 lateral meniscectomies (partial or total). During the reconstruction, a total of 84 advanced lesions were found; subchondral bone exposure was noted in 20 knees and extensive fissuring and fragmentation (extending greater than half of the depth of the surface) was found in 33 knees. Eighty-seven percent of the knees that had lesions in the tibiofemoral compartment had undergone prior meniscectomy. At follow-up a mean of 27 months postoperatively, 40 ACL reconstructions (75%) were rated as normal; 10 (19%), as nearly normal; and 3 (6%), as failed. Statistically significant improvements were found for pain, swelling, giving-way (Table 7-15), functional limitations with daily and sports activities, the patient perception of the overall knee condition (Fig. 7-58), and the overall CKRS score. The conclusion of the study is that ACL reconstruction, even in cases of moderate arthrosis, may provide a benefit to select patients.

In a second study, 40 patients with advanced articular cartilage deterioration underwent ACL B-PT-B allograft reconstruction an average of 7 years after the original knee injury. Thirty-two of the allografts (80%) had received 2.5 mrad of gamma irradiation before implantation. A total of 102 prior operative procedures had been done, including 16 prior failed ACL procedures in 12 patients, 24 medial meniscectomies, and 18 lateral meniscectomies. A total of 64 noteworthy articular cartilage lesions were identified at surgery, including subchondral bone exposure in 15 knees (38%) and extensive fissuring and fragmentation in 25 knees (62%). Seventy-nine percent of knees with damage in a tibiofemoral compartment had undergone a prior meniscectomy. At follow-up, a mean of 3.1 years postoperatively, 70% of the ACL reconstructions were rated as normal or nearly normal and 30% as failed. The failure rate was most likely related to the irradiation of the grafts. Statistically significant improvements were found for pain, partial giving-way, and full giving-way ($P < .01$). Significant improvements were also found for squatting, running, jumping, twisting/turning, and the overall rating score. In the patient rating of the overall knee condition, 42% rated the knee as normal or very good, 24% as good, 21% as fair, and 13% as poor.

These investigations demonstrated that ACL reconstruction is effective in reducing symptoms and functional limitations and increasing activity levels in approximately two thirds of patients with advanced articular cartilage damage. Many patients return to low-impact activities based on the advice to avoid sports involving jumping, cutting, twisting, and pivoting. This is especially true in those in whom prior meniscectomy has been performed. It is important to note that these patients suffered giving-way symptoms and, therefore, the requirement for stabilization was justified. A trial of function is frequently attempted in patients who have advanced arthritis, pain, and giving-way that includes muscle strengthening and a functional knee brace. If this trial is unsuccessful in resolving these symptoms, ACL surgery is warranted. These studies do not answer the question of the ability of an ACL reconstruction to prevent or delay worsening of the preexisting articular cartilage damage.

TABLE 7-15 Change in Symptom Scores From the Preoperative to the Follow-up Evaluation in 53 Patients With Advanced Joint Arthrosis After ACL B-PT-B Autograft Reconstruction

Symptom	Improved	Same	Worse
Pain	37 (70%)	14 (26%)	2 (4%)
Swelling	38 (72%)	14 (26%)	1 (2%)
Partial giving-way	47 (89%)	6 (11%)	0
Full giving-way	42 (79%)	8 (15%)	3 (6%)

All values are *n* (%).
ACL, Anterior cruciate ligament; *B-PT-B,* bone-patellar tendon-bone.

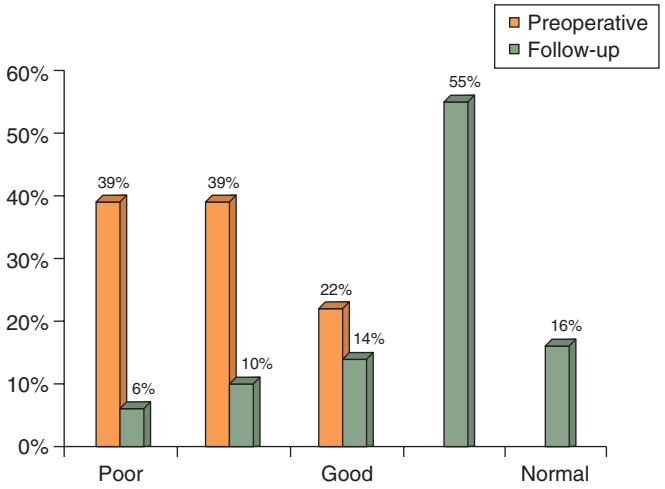


FIG 7-58 The patients' own ratings of the overall knee condition showed significant improvement from the preoperative condition to that recorded at the follow-up evaluation ($P = .0001$). (From Noyes FR, Barber-Westin SD. Anterior cruciate ligament reconstruction with autogenous patellar tendon graft in patients with articular cartilage damage. *Am J Sports Med.* 1997;25:626-634.)

Varus Osseous Malalignment

Two investigations assessed the outcome of treatment of varus-angulated, ACL-deficient knees[188,202]; both are described in detail in Chapter 26. In one study[202] 41 patients were treated with HTO and an ACL reconstruction with a B-PT-B allograft or autograft, which was staged after the HTO in the majority a mean of 6 months later. In addition, PL reconstructions were done in 18 triple varus knees along with the ACL reconstruction, which were all staged after the HTO. At follow-up, a mean of 49 months after the ACL reconstruction, a decrease was noted in the mean AP displacement measurement of the autografts compared with the allografts (autograft mean preoperative, 12.8 ± 5.5 mm and mean follow-up, 1.4 ± 5.4 mm; allograft mean preoperative, 12.2 ± 3.9 mm and mean follow-up, 4.1 ± 5.8 mm; P = not significant). From a historical standpoint, irradiated allografts were no longer used because of this trend. The failure rates were 43% for the allografts and 23% for the autografts. Owing to the small numbers in each graft subgroup (21 allografts [73% irradiated], and 20 autografts), no conclusion could be reached regarding the effect of each type of graft on the failure rate. However, before referral to our center, 15 of these patients had undergone ACL reconstructions that had failed, and there was a significant difference in the failure rate between the revision and primary cases (67% and 33%, respectively, $P < .05$).

In a second investigation, 41 patients underwent HTO, 16 of whom also had a staged ACL allograft reconstruction.[188] This investigation demonstrated that not all varus-angulated, ACL-deficient knees require both procedures, but that ACL reconstruction is warranted when giving-way symptoms continue after osteotomy. Patients who do not experience such symptoms and who have advanced arthritis may avoid ACL surgery by activity modification. Staging these two operative procedures allows the patient and clinician to determine whether joint stabilization is required. Indications for concurrent ACL reconstruction or staged after HTO are discussed in detail in Chapter 26.

Rehabilitation Program

Our rehabilitation protocols are described in detail in Chapter 11. Several investigations assessed the effects of these programs on knee motion complications and graft failure rates.[18,21,204,210,211] The use of immediate knee motion after both ACL allograft and autograft reconstruction was proven to be effective in reducing the risk of arthrofibrosis and was not deleterious to the healing graft (see Chapter 10). In a series of 207 patients who received ACL allograft reconstruction, 189 (91%) achieved a full range of motion without additional treatment measures.[211] The remaining 19 patients were placed into a phased program that included serial extension casting (six knees), early gentle manipulation under anesthesia (nine knees), and arthroscopic lysis of adhesions and scar tissue (three knees). At follow-up, two patients had a loss of 5 degrees of full extension and two others had a permanent and significant limitation of motion. The incidence of knee motion problems was 4% in patients who had only an ACL reconstruction, 10% in knees in which an ITB extraarticular procedure had also been done, and 12% in knees in which a meniscus repair had been performed, and 23% in knees that also had a MCL repair.

In a second investigation, we followed 443 patients who had a B-PT-B autogenous reconstruction for either an isolated rupture (219 knees) or combined with other procedures (224 knees).[204] At follow-up, a normal range of motion was detected in 436 knees (98%) and a mild loss of extension (≤5 degrees) was found in 7 knees. Twenty-three knees required a treatment intervention for an early postoperative limitation of knee motion, including extension casting (9 knees), gentle manipulation under anesthesia (9 knees), arthroscopic debridement (3 knees), and continuous epidural anesthetic and inpatient physical therapy (2 knees). At follow-up, 87% had less than 3 mm of increased AP displacement on arthrometer testing, 9% had 3 to 5.5 mm, and 4% had 6 mm or greater. There was no effect of gender, injury chronicity, articular cartilage condition, location of physical therapy, prior surgery performed, or prior ACL reconstruction performed on the risk of a motion problem (Table 7-16). Although not statistically significant owing to the small number present, a concurrent MCL repair was believed to be a clinically significant risk factor for a knee motion problem.

TABLE 7-16 Assessment of Possible Risk Factors for Knee Motion Limitation After ACL B-PT-B Autogenous Reconstruction in 443 Knees

Risk Factor	No. in Study	Motion Limitations, n (%)
Sex		
Male	293	15 (5%)
Female	150	15 (10%)
Injury chronicity		
Acute, subacute	161	10 (6%)
Chronic	282	20 (7%)
Articular cartilage condition at reconstruction		
Normal	236	21 (9%)
Damaged*	207	9 (4%)
Location of physical therapy		
Our center	259	20 (8%)
Other authors' center	184	10 (5%)
Prior surgery performed		
Yes	193	13 (7%)
No	250	17 (7%)
Prior ACL reconstruction performed		
Yes	60	6 (10%)
No	383	24 (6%)

ACL, Anterior cruciate ligament; *B-PT-B,* bone-patellar tendon-bone.
*Fissuring and fragmentation greater than half depth of the surface or subchondral bone exposed.

Two investigations were performed in which serial knee arthrometer measurements were done postoperatively to determine whether any phase of the rehabilitation program or the amount of time that elapsed after surgery was associated with increased AP displacement (> 3 mm) or graft failure.[18,21] In the first study, 84 patients who received a fresh-frozen B-PT-B ACL allograft reconstruction were followed a mean of 3.1 years postoperatively.[18] The clinical outcome of these patients had been described in another report on the effectiveness of an ITB extraarticular procedure with allograft tissue.[185] This study included 52 patients who had the allograft alone and 32 who also had the ITB extraarticular procedure. Knee arthrometer measurements were taken at postoperative weeks 4, 8, 12, 16, 24, 52, and 128 for the majority of patients. The rehabilitation program was divided into four phases: assisted ambulatory, early strength training, intensive strength training, and return to sports activities.

There were a total of 28 patients in the allograft-alone group and 9 patients in the allograft-ITB procedure group with abnormal displacements detected postoperatively. The abnormal displacements were first identified a mean of 83 weeks following surgery in both groups. The majority of abnormal displacements (86%) were detected during the intensive strength training or return to sports activities

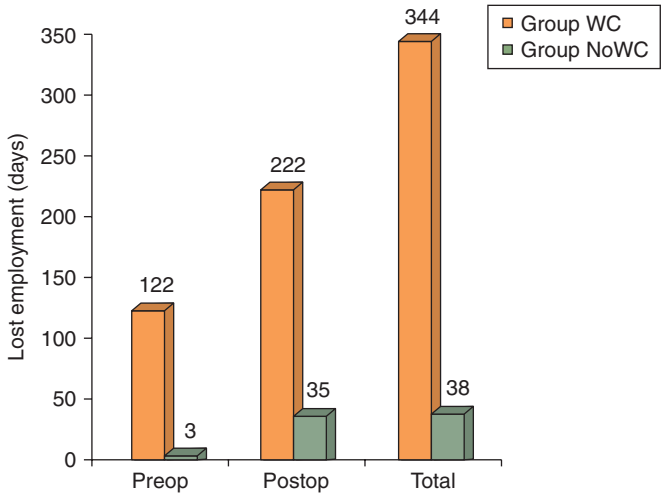


FIG 7-59 The mean number of days of lost employment for patients who did (WC) and did not (NoWC) receive workers' compensation benefits before and after anterior cruciate ligament reconstruction. The difference between the groups was statistically significant for all time periods analyzed ($P < .001$). (From Noyes FR, Barber-Westin SD. A comparison of results of arthroscopic-assisted anterior cruciate ligament reconstruction between workers' compensation and noncompensation patients. *Arthroscopy.* 1997;13:474-484.)

phases. The rehabilitation program did not result in early stretching or failure of the allografts in this cohort.

A similar investigation was done in a group of 142 patients who underwent ACL B-PT-B autograft reconstruction.[21] A total of 938 serial KT-2000 measurements were collected the first 2 years postoperative. Twenty-one knees had abnormal displacements detected after surgery. No association was found between the initial onset of the abnormal displacements and either the amount of time after surgery or the rehabilitation program. The failure rate was an acceptable 5%.

Insurance (Workers' Compensation)

A study was conducted to determine if differences existed after B-PT-B autograft ACL reconstruction between patients who received workers' compensation (WC) benefits and patients who received private insurance benefits (NoWC).[196] Nineteen patients from each group were matched for age, injury chronicity, number of prior operations, and months of follow-up. The only significant difference in outcome was the mean days of lost employment (Fig. 7-59) before surgery (WC, 122 days; NoWC, 3 days; $P < .0001$) and after surgery (WC, 222 days; NoWC, 37 days; $P < .001$). At a mean of 2.2 years postoperatively, 17 patients in the WC group had returned to work (6 with symptoms) and 2 were disabled. In the NoWC group, all patients had returned to work, 2 with symptoms. There were no differences between the groups in AP displacements, functional limitations with sports or daily activities, patient perception of the knee condition, the overall rating score, or complications. None of the autografts failed in the WC group, and only 1 graft failed in the NoWC group. In the WC group, 13 patients rated their knee condition as normal or very good, 3 as good, and 3 as fair. In the NoWC group, 15 rated their knee condition as normal or very good, 4 as good, and 1 as poor. The hypothesis proposed was that the difference in the days of lost employment was caused by wage systems that support WC injuries for long periods of time, the lack of a case-management system that closely follows injured workers, the inability of workers to modify existing job requirements, and/or improper early diagnosis and treatment of the injury. After this study, Wexler and coworkers[294] conducted an investigation on 22 WC patients who underwent ACL B-PT-B reconstruction. All patients returned to work and none of the grafts failed. We concluded that the outcomes were similar to historical controls and that WC did not compromise the results of ACL reconstruction.

A summary of the outcomes from our primary ACL reconstruction investigations is shown in Table 7-17.

OTHER AUTHORS' CLINICAL STUDIES

It is not the purpose of this chapter to conduct an exhaustive review of the outcome of ACL primary reconstructions reported in the English literature. Rather, the reader is encouraged to review recent metaanalysis and systematic reviews on this topic.* A summary of some of the most relevant and current topics is provided below. A recent review of the incidence and trends of ACL reconstruction in the United States between 1994 and 2006 found a significant increase in the number of procedures performed (from 32.9/100,000 in 1994 to 43.5/100,000 in 2006; $P = .01$). The increase was especially noted in women, patients younger than 20 years of age, and patients older than 40 years of age.[161] The investigators concluded that this is one of the most common orthopedic procedures performed and prevention strategies are justified in these groups.

Allografts Versus Autografts

Many studies have compared the outcomes of ACL allografts with ACL autografts and the results and conclusions have varied widely (Table 7-18). Problems related to study design, surgeon bias in graft selection, length of follow-up, failure to account for the factors of patient age and activity level, and failure to account for allograft sterilization processing account for some of the discrepancies among investigations. Importantly, recent studies have shown significant and deleterious effects of high levels (2.0-2.5 mrad) of irradiation, patient age younger than 25 years, and high activity levels on outcomes of ACL allograft reconstructions.

In 2013, the largest metaanalysis of ACL B-PT-B allograft and autograft reconstruction studies to date was published by Kraeutler and associates.[137] Encompassing 76 studies (4276 B-PT-B autografts and 906 B-PT-B allografts) that followed patients 4.3 years postoperatively or more, the authors found that allografts had a threefold increase in rerupture rates compared with autografts (12.7% and 4.3%, respectively). Autografts had significantly better outcomes for subjective IKDC, Lysholm, Tegner, single-leg hop, and KT-1000 scores.

Prodromos and coworkers[235] analyzed data from 20 allograft studies and compared stability findings with previously published data of B-PT-B and STG autografts. Allografts had a significantly greater percent of knees with abnormal stability, defined as more than 5 mm of increased AP displacement, compared with all autografts (14% vs. 5.3%, $P < .001$). In addition, a significantly greater abnormal stability rate was found in irradiated allografts compared with nonirradiated allografts (31% vs. 12%; $P < .001$). Sun and associates[276] also reported significantly higher failure rates in irradiated B-PT-B allografts compared with B-PT-B autografts (34.4% vs. 6.1%) in 102 patients followed 2 to 4 years postoperatively. In this investigation, nonirradiated allografts had a failure rate that was comparable to autografts (8.8%).

Pallis and associates[224] analyzed the survival of ACL reconstructions that had been performed in 120 cadets aged 18 to 23 years before

*References 9, 10, 25, 29, 34, 39, 40, 42, 49, 53, 63, 72, 136, 137, 139, 147, 163, 221, 236, 243, 249, 254, 283.

TABLE 7-17 Summary of Conclusions From Our Primary Anterior Cruciate Ligament Reconstruction Clinical Studies

Factor	Conclusions
Type of graft	B-PT-B autografts preferred whenever possible, decreased failure rate in chronic knees, more rapid graft healing. Autografts provide higher success rate in subjective, objective, and functional parameters. Allografts reserved for multiligament surgery, knee dislocations, and special situations.
Augmentation procedures for allografts	ITB extraarticular procedure decreases allograft failure rate in chronic knees, recommended in grossly unstable knees (grade III pivot shift).
Secondary sterilization of allografts	Irradiation most likely deleterious, increase in failure rate; not recommended.
Gender	No difference in outcomes between males and females. No scientific basis to use gender as selection criteria for reconstruction.
Chronicity of injury	No difference between acute and chronic knee injuries in objective stability after B-PT-B autograft reconstruction. Significantly poorer results in chronic knees for symptoms, limitations with sports and daily activities, and patient rating of knee condition owing to loss of meniscus tissue, preexisting joint damage. Reconstruct ACL early after injury in active patients.
Concomitant operative procedures	Meniscus repairs frequent, results may be improved by concomitant ACL reconstruction. High success rates, even in complex tears extending into central third region, regardless of patient age. Posterolateral injuries frequently accompanied by ACL ruptures; reconstruct all ligamentous ruptures concurrently. MCL injuries usually do not require surgical treatment unless gross instability exists.
Preexisting joint arthrosis	Symptomatic unstable knees can be improved by ACL reconstruction. Advise return to low-impact activities.
Varus osseous malalignment	ACL reconstruction usually staged after osteotomy in symptomatic unstable knees. ACL reconstruction not required after osteotomy in knees that are asymptomatic, patient willing to modify activities.
Rehabilitation program	Immediate motion and rehabilitation safe, not deleterious to healing graft, low incidence (<1%) of arthrofibrosis. Identify and immediately treat limitation of knee motion with overpressure program. Full motion regained within weeks of surgery (with exception of PCL reconstructions in which hyperflexion is delayed).
Insurance	No difference in outcome between workers' compensation and privately insured patients except days of lost employment. Reconstruct knees of workers' compensation patients earlier after injury.

ACL, Anterior cruciate ligament; *B-PT-B,* bone-patellar tendon-bone; *ITB*, iliotibial band; *MCL*, medial collateral ligament; *PCL*, posterior cruciate ligament.

entering the U.S. Military Academy. All participated in intramural, club, or intercollegiate athletics, as well as military training. Those who had received an allograft were 7.7 times more likely to experience a subsequent graft failure compared with those who had received a bone-to-bone autograft.

Kaeding and associates[122] found that patients who received allografts were more likely to experience graft failure than those who received autografts (8.9% and 3.5%, respectively; $P < .01$), and that age influenced the odds. The differences in absolute failure rates between autografts ($n = 691$) and allografts ($n = 234$) according to age were as follows: 14 years, 15%; 18 years, 13%; 22 years, 9%; 30 years, 4%; and 40 years, 2%.

Carey and associates[39] analyzed data from nine studies (746 patients) that followed patients a mean of 4.1 years postoperatively who had received either allografts or autografts. The majority of grafts were B-PT-B and both irradiated and fresh-frozen allografts were included. No significant differences were found in any of the outcome measures among graft types. The authors stressed that none of the studies stratified outcomes according to age or activity level, which (in addition to the irradiation factor) limited the investigation's conclusions.

Bone-Patellar Tendon-Bone Versus Semitendinosus-Gracilis Tendon Autograft

Many studies have reported few differences in the outcomes of B-PT-B and STG autografts.* However, a recent registry study from Scandinavia reported a significantly greater revision rate in patients who underwent STG reconstruction (1042 of 38,666 patients) compared with B-PT-B procedures (156 of 6736 patients; hazard rate ratio, 0.63).[82] Another study reported a higher percentage of STG knees with grade II pivot shift test results compared with B-PT-B knees at 2 years postoperatively (24% vs. 10%; $P = .02$).[94] Two studies that pooled data from previously published trials also found significantly poorer results in STG knees for pivot shift test results.[25,147] An investigation that assessed 13,647 ACL reconstructions a mean of 3 years postoperatively reported a higher relative risk of revision surgery (1.41) after STG compared with B-PT-B.[241] Increased anterior knee pain and kneeling pain has been reported following B-PT-B reconstruction compared with STG reconstruction in several studies,[23,57,94,131,144,147,160,232,299] although others have refuted these findings.[83,104,141,250,283]

Leys and associates[144] followed 94 patients (43 B-PT-B and 51 STG) for 15 years postoperatively and found better outcomes in STG recipients in several parameters. These authors specifically noted a decline in outcomes in the B-PT-B knees from 10 to 15 years postoperative, including loss of knee extension, decreased performance in the single-leg hop test, and higher rate of radiologic OA. There was a high rate of reinjury to either knee in both groups (29% STG and 32% B-PT-B).

Effects of Age and Anterior Cruciate Ligament Graft Size

Authors have performed subset analysis comparing failure rates of B-PT-B and STG autografts according to age. Kamien and associates[123] followed 98 patients who received STG reconstructions for 2 years postoperatively and found a significantly higher percentage of patients 25 years of age or younger had failed (12 of 48, 25%) compared with patients older than 25 years (3 of 50, 6%; $P = .009$). Magnussen and

*References 3, 12, 23, 83, 104, 131, 147, 150, 168, 250, 254, 283, 299.

TABLE 7-18 ACL Allograft vs. Autograft Studies

Study	Knees (n)	Follow-up (yr)	ACL GRAFTS (n)		Failure Rates	Factors Affecting Outcome
			Autografts	Allografts/ Processing		
Kraeutler et al.[137] (2013); meta-analysis	5182	≥4.3	B-PT-B (4276)	B-PT-B (906)/NA	12.7% allografts 4.3% autografts	Allograft tissue
Ellis et al.[62] (2012)	76 (≤18 yr)	NA	B-PT-B (59)	B-PT-B (20)/ BioClens or 1.0- to 1.3-mrad irradiation	35% allografts, 3% autografts ($P = .001$) All failures occurred within 1 yr of surgery	Allograft tissue
Pallis et al.[224] (2012)	120 (18-23 yr)*	During tenure at Academy	B-PT-B (61) STG (45)	NA (16)/NA	Allografts 6.7 times more likely to fail compared with autografts ($P < .001$).	Allograft tissue
Prodromos et al.[235] (2007); meta-analysis	NA	≥2	STG (NA)	B-PT-B/irradiated (158), all types nonirradiated (1014)	14% allografts, 5.3% autografts ($P < .001$) 31% irradiated allografts, 12% nonirradiated allografts ($P < .001$)	Allograft tissue Irradiation of allograft tissue
Sun et al.[277] (2009)	99	2-4	B-PT-B (33)	B-PT-B/irradiated (32) or nonirradiated (34)	34.4% irradiated allografts, 8.8% nonirradiated allografts, 6.1% autografts ($P = .01$)	Irradiation of allograft tissue
Mehta et al.[173] (2010)	173	>4	B-PT-B (142)	B-PT-B/irradiated (14) or fresh-frozen (17)	9.7% irradiated allografts, 0.7% autografts, 0% fresh-frozen allografts ($P = .02$)	Irradiation of allograft tissue
Kaeding et al.[122] (2011)	925	2	All types (691)	All types (234)/ fresh-frozen	8.9% allografts, 3.5% autografts ($P < .01$) Younger age increased odds of allograft failure	Allograft tissue Patient's age
Barrett et al.[24] (2011)	417	2	B-PT-B (218) STG (98)	B-PT-B or posterior tibialis (101)/NA	16.5% patients ≤25 yr, 8.3% >25 yr ($P = .01$) for all grafts combined Patients ≤25 yr: 29% allograft, 25% STG, 12% B-PT-B ($P < 0.05$) Patients >25 yr: 13% allografts, 5% B-PT-B, 6% STG	Patient age ≤25 yr all graft types combined Allografts and STG autografts in patients ≤25 yr
Borchers et al.[30] (2009); case-control	63	2	STG (15) 5 failures, 10 controls	Tibialis tendon/ irradiated (48) 16 failures, 32 controls	Allograft 5.56 greater odds failure than autografts Higher activity level (Marx score ≥13) 5.53 greater odds of ACL graft failure	Allograft tissue High activity level
Lamblin et al.[139] (2013); meta-analysis	1002	≥2	"Mostly B-PT-B" (469)	"Mostly B-PT-B" (533)/fresh-frozen	3.6% allograft, 2.8% autograft ($P = NS$)	None
Sun et al.[278] (2011)	197	7.8	STG (91)	STG (95)/ fresh-frozen	8.4% allograft, 7.7% autograft ($P = NS$)	None
Mascarenhas et al.[167] (2010); case-control	28	8-9	B-PT-B (19)	B-PT-B (19)/ fresh-frozen	5% allograft, 0% autograft ($P = NS$)	None
Edgar et al.[58] (2008)	84	≥4	STG (37)	STG (47)/ cryopreserved or fresh-frozen	8% allograft, 2% autograft ($P = NS$)	None

*U.S. Military Academy.

ACL, Anterior cruciate ligament; *B-PT-B*, bone-patellar tendon-bone; *NA*, not available; *NS*, not significant; *STG*, semitendinosus-gracilis.

colleagues[159] followed 136 men and 120 women who underwent ACL STG autograft reconstruction a mean of 14 months (range, 6-47 months) postoperatively and noted a significant difference in the rate of revisions between patients aged 20 years or older and those younger than 20 years (0.7% vs. 14.3%; $P < .0001$). Bourke and associates[31] in a 15 year follow-up study of 186 patients found that those aged 18 years or younger had a threefold increase in the risk of rupturing the STG graft ($P = .002$). Shelbourne and coworkers[263] reported, at a minimum 5-year postoperative follow-up in 1415 patients, a higher risk of reinjury to either the BTB autograft-reconstructed knee or contralateral knee in patients younger than 18 years of age (17%) compared with those aged 18 to 25 years (7%) and those older than 25 years (4%).

Krych and associates[138] reported that age and body mass index (BMI) were associated with superior 6-month isokinetic muscle strength and single-leg hop test results in a cohort of 224 patients who underwent primary isolated transtibial ACL reconstruction. Multivariate analysis demonstrated that younger age (odds ratio [OR] 0.95 per 1-year increase, $P = .02$) and lower BMI (OR 0.90 per 1-unit increase, $P = .01$) were associated with superior outcomes. Graft selection was not associated with superior outcomes in the entire cohort; however, the use of allografts correlated with improved functional testing in patients over 30 years of age.

In Magnussen and colleagues' series[159] previously described, STG graft size was related to failure and subsequent ACL revision. Revision ACL reconstruction was required in just 1 of 58 patients (1.7%) whose grafts were greater than 8 mm in diameter. However, revision was done in 9 of 139 patients (6.5%) whose grafts were 7.5 to 8 mm, and in 8 of 59 patients (13.5%) whose grafts were 7 mm or less in diameter. In combining the factors of age and graft size, the authors reported that 16 of the 18 revisions were done in patients who were less than 20 years old and whose ACL grafts were 8 mm or smaller in diameter. This high revision rate represents a major problem to be addressed in the future in this younger athletic population. Limitations of this study addressed by the authors were the potential effect of an "accelerated rehabilitation" program that was done to return patients to sports at 6 months after surgery, unknown mechanisms for the repeat injury episode (such as noncontact versus contact), and the inability to examine the effect of gender on noncontact repeat ACL injuries. In our opinion, before accepting the conclusions of this study it would be necessary to determine if an ACL STG graft larger than 8 mm in diameter, or a B-PT-B graft would decrease the high revision rate in this younger athletic population that returned to sports at 6 months after surgery. In general, the data is concerning for grafts diameters smaller than 8 mm and attention is directed to the techniques described in this chapter to prepare a six-strand STG graft when necessary to achieve larger STG graft diameters.

Mariscalco and associates[162] studied the effect of STG autograft size on patient outcomes and revision in a Multicenter Orthopaedic Outcomes Network (MOON) study on 263 of 320 consecutive primary ACL reconstructions (82%). The authors concluded that hamstring grafts greater than 8 mm in diameter had a statistically significant higher Knee Injury and Osteoarthritis Outcome Score (KOOS) function score and lower revision rate. For patients aged 18 years or younger, grafts greater than 8 mm in diameter had 0 revisions (0 of 14 patients), although grafts 8 mm in diameter or less had a 7% revision rate (14 of 199 patients). The authors reported an ACL revision rate of 15.3% in patients younger than 19 years who had grafts that were 8 mm or smaller in diameter. The study had significant limitations, including using the revision rate rather than the actual failure rate, no data regarding return to sports or type of sports participation, no information on the type of repeat injury (contact versus noncontact), and a small sample size.

Park and colleagues[227] followed 296 patients who underwent ACL STG reconstruction a mean of 4.5 years (range, 2-5.9 years) postoperatively and reported a statistically significant difference in failure rates between those with grafts that were less than 8 mm compared with those whose grafts were 8 mm or greater in diameter (5.2% and 0%, respectively; $P < .05$).

These results point to the need to do everything possible in younger athletic populations undergoing ACL reconstruction to avoid an ACL graft failure and need for revision. Although all variables to lessen revision are still not known at present, possible potential effects of maximizing STG graft diameter, using objective criteria to allow athletes to return to sports,[19] conducting neuromuscular retraining in female athletes before return to sports, and critically examining all other risk factors (including gender and associated instabilities) have most likely have beneficial effects in reducing the need for ACL revision surgery.

Single- Versus Double-Bundle Anterior Cruciate Ligament Reconstruction

Multiple studies have compared outcomes of single- and double-bundle ACL reconstructions; in fact, more than 30 have been published since 2009.* It should be noted that, in many studies that compared outcomes of these ACL reconstruction techniques, the single graft represented a vertical ACL graft orientation as described previously in this chapter (posterior tibial attachment, high femoral attachment). A vertical graft placement has been shown in a number of in vivo and in vitro studies previously discussed to result in an inferior control of rotatory loading of the knee joint and the pivot shift phenomena.

Five metaanalyses published from 2012 to 2014 are summarized in Table 7-19.[136,148,149,284,300] There are limitations to these studies. First, the investigators did not take the potential problem of the single-graft being in a vertical position into account when conducting their reviews (although it is acknowledged that this may not always be possible to ascertain). Second, the follow-up of the studies analyzed was short, with most providing data 2 to 3 years postoperatively. Overall, the results favored double-bundle reconstructions in regard to the presence of a negative pivot shift and a higher IKDC objective score. However, there are limitations in the pivot shift test because the manner in which it is performed may affect the results,[208] the outcome is graded in qualitative terms, and the forces or torques applied do not replicate those that occur during athletic or strenuous activities. Therefore, caution is warranted in using these data to definitely determine "rotational" knee stability. Finally, results were either mixed or showed no significant difference among procedures for all other variables including KT-2000, IKDC subjective score, Lysholm score, Tegner score, and complications. The ability of either individual comparative studies or metaanalyses to provide a definitive conclusion regarding which procedure is superior is limited at best.

Three studies conducted a different type of analysis of single- and double-bundle ACL reconstructions that may have more meaningful application to actual knee function under high loading conditions. Misonoo and colleagues,[176] Claes and associates,[43] and Tsarouhas and coworkers[286] evaluated in vivo tibial rotation that occurred during pivoting and cutting tasks in healthy controls and knees that had undergone single- or double-bundle reconstruction 6 to 12 months previously. None of these studies found a significant difference between the two types of ACL reconstructive procedures in the amount of tibial

*References 2, 4, 13, 32, 43, 73, 85, 96, 101, 109, 110, 113, 125, 129, 130, 135, 140, 143, 176, 184, 217, 225, 255, 265, 269, 273, 279, 286, 287, 302, 306, 310.

TABLE 7-19 Metaanalysis of Results of Anterior Cruciate Ligament Single- Versus Double-Bundle Graft Reconstructions

			GRAFT (n)		PIVOT SHIFT		KT-2000			
Study	No. Studies Included	Follow-up, yr (Range)	Single Bundle	Double Bundle	Graft Favored	Factor	Graft Favored	Factor	Graft Favored	Other Results
Li et al.[149] (2014)	19	2.8 (2-8.6)	STG: 779 B-PT-B: 101	STG: 806	DB	Grade 0	No difference	Mean involved-noninvolved value	NA	IKDC objective score favored DB; no difference in IKDC subjective, Lysholm, and Tegner scores or complications
Xu et al.[301] (2013)	19	2.7 (1-8.6)	STG: 832 B-PT-B: 59	STG: 746	DB	IKDC grade A	No difference	NA	NA	IKDC subjective score favored DB; no difference in Lysholm, Tegner scores
Li et al.[148] (2013)	17	2.3 (0.4-8.6)	STG: 684 B-PT-B: 39	STG: 659	DB	Grade 0	DB	Mean involved-noninvolved value	DB	IKDC subjective score favored DB; no difference in IKDC objective and Lysholm scores, knee flexion deficit, knee flexor and extensor isokinetic strength
Kongtharvonskul et al.[136] (2013)	13	1.9 (1-2.6)	STG: 555	STG: 440	DB	Grade 0	DB	<3 mm involved-noninvolved	NA	IKDC objective score favored DB; no difference in IKDC subjective and Tegner scores or complications
Tiamklang et al.[284] (2012)	17	2.2 (1-8.6)	STG: 586 B-PT-B: 59 Tibialis anterior allograft: 20	STG: 534 Tibialis anterior allograft: 20	DB	IKDC grades A-B	DB	Mean involved-noninvolved value	No difference	IKDC objective score and return to preinjury activity levels favored DB; no difference in subjective IKDC, Lysholm, and Tegner scores, and adverse effects and complications

DB, Double-bundle; *IKDC,* International Knee Documentations Committee; *NA,* not available; *SB,* single-bundle.

rotation that occurred during the tasks. The investigators agreed that the results do not support the more complex double-bundle reconstruction. A note of caution is warranted in the interpretation of these studies because the ACL is not a primary restraint for controlling internal tibial rotation; rather, the lateral extraarticular structures (ITB, lateral capsule, anterolateral ligament) resist rotation.

Osteoarthritis Rates in Long-Term Studies

Published rates of radiographically documented OA following ACL reconstruction vary tremendously (Table 7-20). Investigators typically used weight-bearing AP and PA radiographs, as well as lateral and Merchant views, to determine the presence and severity of OA, although a few investigators also used MRI[89,102] or CT.[92] The two most commonly used rating systems to classify OA in recent studies were the Kellgren-Lawrence and IKDC. One conclusive association with future joint OA is loss of meniscus tissue. Nearly every long-term study reported a statistically significant correlation between meniscectomy performed either concurrently or after the ACL reconstruction and radiographic OA. Preexisting chondral damage was the second most frequently cited factor.

Determining the risk of developing future OA after ACL reconstruction is difficult for many reasons. There are several factors that may influence the development of articular cartilage deterioration, including the effects of the initial impact injury on the subchondral bone (bone bruising),[48,103] loss of meniscus tissue (either before, during, or after the ACL reconstruction), patient age, time from injury to reconstruction, number of reinjuries before reconstruction, failure of the reconstruction to restore normal AP displacement and knee kinematics, the rehabilitation program, complications (such as infection, arthrofibrosis), final knee motion achieved, and the activity level the patient resumes after surgery. In many studies, these variables are not controlled for, making reaching conclusions on this topic difficult. In addition, most long-term studies have an unfortunate high rate of transfer bias (patients lost to follow-up) and do not compare the radiographic findings of the reconstructed knee with the contralateral normal knee.

PREVENTION AND MANAGEMENT OF COMPLICATIONS

Arthrofibrosis and Limitation of Knee Motion

The postoperative complication of arthrofibrosis (either primary or secondary) or a limitation of knee flexion and extension resulting from other factors such as a cyclops lesion are frequently reported problems after ACL reconstruction. The causes, risk factors, preventative measures, and effective treatment strategies for knee motion complications are discussed in detail in Chapter 38. In addition, the reader is referred to our postoperative rehabilitation protocols provided in Chapter 11 for comprehensive exercises and modalities used after ACL reconstruction.

Infection

Deep joint infection after ACL reconstruction is a rare problem, occurring in approximately 0.8 to 1.70% of patients.[33,36,70,114,121,258]

Matava and colleagues[169] conducted a survey in which 61 orthopedic surgeons participated to determine the preferred treatment recommendations for postoperative infection. The infecting organism and systemic signs of sepsis were viewed as the most important factors in determining the initial treatment. Arthroscopic debridement and irrigation as early as possible were recommended and this protocol is also supported by other studies.[36,172,256,291,296] The majority of surgeons in Matava and colleagues' survey (85%) used culture-specific intravenous antibiotics and attempted to retain the ACL graft when possible. Graft excision and hardware removal were reserved for resistant infections that require further debridement procedures. Immediate graft removal was recommended by only 6% of surgeons treating infected autografts and 33% of those treating infected allografts. Only one half of the surgeons surveyed routinely used a drain after ACL reconstruction. The infection rate was twice as high for these surgeons compared with those who did not use a drain (0.27% and 0.10%, respectively; $P = .04$). The authors stressed that although obtaining a stable knee is the primary goal of ACL reconstruction, eradication of infection supersedes graft preservation to avoid the deleterious consequences of a chronic infection.

CRITICAL POINTS Prevention and Management of Complications

- Rules to prevent and treat infection summarized in Table 7-21.
- Graft contamination: Prefer to harvest second autograft. In allograft procedure, discard and use second allograft.
- Fluid extravasation: Be constantly aware of joint pressure, fluid inflow and outflow, increased thigh tension, any lack of joint distention during arthroscopic procedures. Palpate popliteal and calf region during procedure.

Brophy and associates (representing the MOON Knee Group)[33] reviewed incidence rates and potential risk factors of infection after ACL reconstruction. Of 2198 patients who underwent surgery from 2002 to 2005, 17 (0.8%) developed a postoperative infection. Diabetes was found to be a significant risk factor (OR, 18.8; $P < .001$). Use of a hamstring autograft (OR, 4.6; $P = .03$) and other graft choices (allografts, OR, 4.3; $P < .05$) were also associated with an increased odds of infection compared with B-PT-B autografts. Patient age, BMI, and smoking status were not associated with an increased infection risk.

Schulz and coworkers[256] treated 24 patients who developed postoperative septic arthritis after ACL reconstruction. The treatment protocol was based on the classification of the grade of infection proposed by Gachter[75] and included arthroscopic debridement, irrigation, partial to total synovectomy, and placement of intraarticular gentamicin-containing polymethylmethacrylate (PMMA) beads. The mean time from the ACL reconstruction to the first arthroscopic debridement was 62 days (range, 5-196 days). The ACL grafts had autodigested in 8 knees and were removed in 9 others. The infection resolved in all cases. Van Tongel and associates[291] described a series of 15 patients who underwent arthroscopic management of this complication, followed by intravenous antibiotics and then oral antibiotics. The infection resolved in all patients and the ACL grafts were retained in all but one knee.

Burks and colleagues[36] described a small series of 4 knees in whom graft removal was required during arthroscopic debridement and irrigation for septic arthritis. The patients developed the infection an average of 24 days postoperatively. The autografts had a fibrinous coating that led the authors to be concerned about the potentially deleterious effects of persistent infection or a delay in resolving the joint infection. All four patients had a revision ACL reconstruction between 1 and 6 weeks following completion of 6 weeks of antibiotics. At an average of 21 months postrevision, the patients had a normal range of knee motion and a mean of 3.0 mm (range, 1.9-4.0 mm) of increased anterior tibial displacement on KT-1000 testing.

The senior author has followed a series of operative rules over many years to prevent and treat operative infections; these are summarized in Table 7-21.

Table 7-20 Rates of Radiographic Osteoarthritis After ACL Reconstructions in Mid- and Long-Term Clinical Studies

Study	Graft†	Knees (n)	Follow-up, yr (Mean ± SD)	MODERATE OA (%)*					SEVERE OA (%)*					Factors Associated With Development of OA
				All	TF	MTF	LTF	PF	All	TF	MTF	LTF	PF	
Gerhard et al.[80] (2013)	B-PT-B	63	16 + 1	16					7					Meniscectomy
Oiestad et al.[223] (2013)	B-PT-B	181	12.3 ± 1.2		21			4		5			0	Age, poor quadriceps strength
Holm et al.[105] (2012)	B-PT-B	53	11.8 ± 0.5	26					9					Meniscectomy, chronicity of injury
Ahn et al.[5] (2012)	B-PT-B	117	10.3 ± 1	46	38	27	10	8	15	13	10	2.5	2.5	Partial meniscectomy and sagittal tibial tunnel position in medial compartment, BMI in lateral compartment
Murray et al.[183] (2012)	B-PT-B	83	13		17	11	6	10		13	11	2	1	Meniscectomy, preexisting chondral damage
Shelbourne & Gray[262] (2009)	B-PT-B	502	14.1			4-21	1-23		NA					Meniscectomy, chondral damage
Cohen et al.[46] (2007)	B-PT-B	62	11.2			16	18	22			6	0	0	Meniscectomy
Salmon et al.[253] (2006)	B-PT-B	43	13	19					2					Meniscectomy, increased displacement, loss extension
Hart et al.[92] (2005)	B-PT-B	31	10	26 CT: 39					3 CT: 19					Meniscectomy
Pernin et al.[228] (2010)	B-PT-B + ITB EA	100	24.5	27					27					Medial meniscectomy, preexisting chondral damage, age at surgery
Ait Si Selmi et al.[6] (2006)	B-PT-B + ITB EA	107	17.4	23					5					Medial meniscectomy, residual laxity, preexisting chondral damage
Janssen et al.[119] (2013)	STG	88	10 ± 0.7	48					6					Medial meniscectomy, age ≥30 yr, preexisting ICRS grade 2 or 3
Inderhaug et al.[115] (2013)	STG	83	10.2	8					0					Meniscectomy
Struewer et al.[275] (2013)	STG	52	10.2	19.2					5.7					Increased anterior tibial displacement
Streich et al.[274] (2013)	STG	40	10	5					2.5					Positive pivot shift, high BMI
Hoffelner et al.[102] (2012)	B-PT-B or STG	28	10	4 MRI: 7					0 MRI: 14					All isolated ACL tears, no increased risk OA compared with contralateral knees
Keays et al.[128] (2010)	B-PT-B or STG	27	6		12			0		0			0	Meniscectomy, chondral damage, B-PT-B graft, weak quadriceps, low quadriceps/hamstrings ratio
Hanypsiak et al.[89] (2008)	B-PT-B or STG	44	12.7	32 MRI: 34					NA					Meniscectomy
Pinczewski et al.[232] (2007)	B-PT-B or STG	128	10	1-3					0					Poor performance single-leg hop test, B-PT-B graft
Li et al.[146] (2011)	B-PT-B, STG, or allograft	249	7.9			5	3	1			2	1	0	BMI >30, medial meniscectomy, preexisting grade ≥2 Outerbridge medial chondrosis, length of follow-up

ACL, Anterior cruciate ligament; *BMI*, body mass index; *B-PT-B*, bone-tendon-bone; *CT*, computed tomography; *ICRS*, International Cartilage Repair Society grading system; *IKDC*, International Knee Documentation Committee; *ITB EA*, iliotibial band extraarticular; *LTF*: lateral tibiofemoral; *MRI*, magnetic resonance imaging; *MTF*, medial tibiofemoral; *NA*, not available; *OA*, osteoarthritis; *PF*, patellofemoral; *SD*, standard deviation; *STG*, semitendinosus-gracilis; *TF*, tibiofemoral.

*Rates are from radiographs unless otherwise indicated. Moderate OA, IKDC grade C (abnormal), Kellgren-Lawrence grade 3, or Ahlback grade 2; severe OA, IKDC grade D (severely abnormal), Kellgren-Lawrence grade 4, or Ahlback grade 3.

†All autografts unless otherwise indicated.

TABLE 7-21 Rules to Prevent and Treat Postoperative Infection

1. Obtain a preoperative history of the patient's health and diet, perform a general assessment of nutritional status and the need for vitamin supplementation (including vitamin C). A history of prior infections, methicillin-resistant *Staphylococcus aureus* requires infectious disease consultation (e.g., preoperative nasal swab).
2. Preoperative preparation to avoid postoperative anemia with low hemoglobin values, menstruation issues. Consider appropriate serum iron, iron-binding capacity studies, and others.
3. Conduct a skin evaluation, avoid skin rashes or sores. Patient uses a chlorhexidine body wash 3 days before surgery and a preoperative antibacterial wash from the toes to groin the evening before and the morning of surgery. Use hair clippers (instead of a razor) in preanesthetic room.
4. Administer antibiotics 1 hour before surgery, confirm at "time-out" (when the limb to be reconstructed is signed by the surgeon), repeat antibiotics for longer cases based on half-life (usually 4 hours for most cephalosporins). Repeat intravenous antibiotics in recovery room and over 24 hours if admitted.
5. Skin preparation agent of choice in meticulous manner following manufacturer's recommendations, occlusive skin dressing.
6. Careful planning of skin incision in knees with prior incisions to avoid flap necrosis or delayed healing. Perform a meticulous dissection of skin flaps beneath the fascial plane and not directly in the subcutaneous plane to protect the blood supply. Avoid undue skin tension and retraction, avoid grasping the skin with forceps, use blunt retractors instead of sharp rakes, and observe skin viability after the tourniquet has been deflated. Use tourniquet only as required. Perform a meticulous closure, do not place tension on skin Steri-Strips to prevent blister formation with postoperative edema.
7. Operative technique issues: Perform sharp dissection and a meticulous gentle handling of soft tissues, avoid a "blunt finger" or "sponge" dissection. Limit the number of times that fingers are "poked" into the wound by using instruments instead of fingers. Debride devitalized soft tissues, limit the dissection to only the operative site. Use meticulous hemostasis, maintain the blood supply to tissues, and limit electrocoagulation to direct operative site. Use the least number of nonabsorbable sutures possible, limit suture load to that which is required, and close all dead spaces. Deflate the tourniquet before closure, and limit operative time with trained staff.
8. Operating room staff issues: Staff double-checks operative instrument pack sterility markers, avoid operating rooms used for general surgery and infectious cases (even though assured clean room reestablished in the "perfect world"). Conduct a monthly check of the incidence of infections or undue occurrence of infections within operating room. Document hospital procedures to detect remote infections, share information with surgeons and hospital infectious committee. Limit traffic in and out of the operating room. Cover all hair on head, use long operative gowns when the knee is flexed over bed, closely monitor for any break in sterility.
9. Postoperative dressing: Double cotton-double elastic bandage (Robert Jones dressing) to provide firm uniform compression, avoid rewrap unless a problem occurs. If the dressing becomes loose, rewrap, maintain for 48 to 72 hours, and then replace with elastic stocking and supplemental elastic bandage for added compression. The goal is to prevent hematoma and soft tissue swelling without compromise of skin circulation. Use commercial ice delivery systems, maintain limb elevation, and avoid limb-dependent conditions. Avoid use of drains unless specifically indicated. Recheck for calf tenderness, perform deep venous thrombosis assessment.
10. Intraoperative meticulous coagulation of any intraarticular bleeding sites during procedure. Aspirate knee joint hematoma first postoperative day, or subsequently if tense, painful, or over approximately 50 mL.
11. First postoperative day: Patient performs active quadriceps cocontraction with hamstrings, must show active muscle contraction, which is repeated every hour. The patient places a hand on the thigh to monitor quadriceps firmness and turgor. Ankle pumps are performed every hour while awake.
12. Patient takes oral temperature during day and importantly at night and records results. The surgeon is notified immediately if temperature reaches 101° F. The surgeon is also notified if the patient maintains a low-grade temperature or experiences persistent joint pain, redness, warmth, and increased swelling.
13. Conduct a careful weekly assessment of the wound for redness, swelling, or any other signs of infection. Maintain a low tolerance for knee joint aspiration and fluid analysis (cells, Gram stain, sugar, cultures) for any abnormal signs suggesting infection such as low-grade temperature, persistent joint swelling, redness or warmth; failure to achieve dry knee within first 2 to 3 weeks of surgery. Repeat blood studies as necessary (use sedimentation rate, C-reactive protein studies, although often not helpful 4 to 6 weeks postoperative owing to elevation from surgery). Clinical findings alone are sufficient to proceed with emergent arthroscopic washout and soft tissue cultures as described below.
14. Occurrence of postoperative infection:
    a. Immediate emergent arthroscopic washout and arthroscopic debridement of devitalized tissues, intravenous antibiotics switched to culture-specific antibiotics when tissue cultures and Gram stain are available. Obtain tissue specimens for culture and fluid aspirate. Magnetic resonance imaging (MRI) obtained before washout to assess soft tissue abscess, sinus tracks, and Baker's cysts, which may represent a closed abscess.
    b. First time washout and debridement: Grafts and hardware left in place, consider removal if subsequent arthroscopic washout is required or highly virulent organism cultured.
    c. Recognize frequent need to repeat washout after 48 hours.
    d. Do not stop gentle flexion and extension overpressure program, including patellar mobilization, to maintain knee motion; otherwise, a joint fibrosis will rapidly develop.
    e. Open graft harvest wound or meniscus repair wound: If any local signs of infection are noted, opening of these wounds is not required in majority of cases.
    f. Recognize that cause of recurrent infection may be presence of Baker's cyst or other soft tissue abscess requiring open drainage. Repeat MRI is beneficial in resistant cases.
    g. When major concurrent medial or lateral reconstructive procedure is involved, determine the need to open the wounds and perform debridement if any signs of infection. Proceed with secondary closure rules, allow granulation tissue formation, consider skin tension sutures (to prevent abnormal skin contracture) and wound drainage systems.
    h. Closely inspect any soft tissues areas that are involved that would allow open drainage into joint. These require urgent treatment and soft tissue joint closure, including necessary muscle flaps in severe cases.
    i. Close follow-up of infectious disease team to monitor progress, use appropriate blood studies, repeat aspiration as necessary, and monitor for recurrence. Monitor carefully for osteomyelitis with residual hardware in osseous tunnels as shown by increasing edema signal intensity on repeat MRI.
    j. Length of time of intravenous antibiotics is usually 4 to 6 weeks based on organism and cultures, with a subsequent 6 weeks of oral antibiotics. These programs are often empiric and based on surgeon and infectious disease team assessments.

Graft Contamination

In 2014, Khan and associates[29] conducted a systematic review of the management of contaminated ACL grafts. The authors' search found six laboratory studies that contained a total of 495 graft samples. The most successful sterilization protocols used chlorhexidine or mechanical agitation with a polymyxin B-bacitracin solution, which achieved sterility in 100% of tissues. Also effective was a chlorhexidine soak and plain bacitracin soak, which achieved sterility in 97.5% and 97% of samples, respectively. Povidone-iodine and an antibiotic soak of polymyxin-bacitracin were the least effective protocols.

Plante and associates[233] recently investigated bacterial contamination of STG grafts dropped onto the operating room floor and methods of graft decontamination. There was no significant difference in positive culture rates between grafts retrieved in less than 5 seconds (33%) and those retrieved 15 seconds after being dropped (23%). Control grafts (not dropped) tested positive in 23%, although none of the patients developed clinical infections postoperatively. Sixteen unique organisms were identified, with *Staphylococcus aureus* being the most common. Grafts rinsed in either bacitracin solution or 4% chlorhexidine solutions had only one of 30 cultures that were positive.

In 2005, Izquierdo and coworkers[118] reported the results of a survey of 196 orthopedic surgeons on the management of contaminated ACL grafts. Fifty-seven surgeons had managed at least one contaminated graft in their career. The majority (75%) cleaned the graft and proceeded with the reconstruction. Others (18%) harvested a different graft or used an allograft. No infections were reported. The grafts that underwent cleansing were cleaned with either Hibiclens (Regent Medical) or chlorhexidine gluconate, using different protocols. The authors cautioned that potential side effects of graft cleansing should be considered, including increased polymorphonuclear granulocyte toxicity and impaired phagocytic efficiency, intraarticular reactive synovitis and chondrolysis, and increased postoperative morbidity.

Molina and associates[178] measured the incidence of positive cultures resulting from ACL specimens that were dropped on the operating room floor and then treated by soaking in one of three antimicrobial solutions: an antibiotic solution of neomycin and polymyxin B, a 10% povidone-iodine solution, or a chlorhexidine gluconate solution. Sixty percent of the dropped specimens cultured positive, although the majority grew nonvirulent species. The incidence of specimens that tested positive following the treatment protocols was 24% for povidone-iodine solution; 6% for antibiotic solution; and 2% for chlorhexidine gluconate solution. The authors recommended sterilization with chlorhexidine gluconate, although there was no significant difference in the incidence of positive cultures with this method compared with the antibiotic solution.

In our experience, harvest of a second autograft may be preferred to graft cleansing. With an allograft procedure, the contaminated allograft is always discarded and substituted with another allograft.

Fluid Extravasation

The senior author and Spievack[215] conducted a cadaver study many years ago that determined a subtle mechanism for extraarticular fluid extravasation during arthroscopy. Weak tissues in the suprapatellar pouch or semimembranosus bursa ruptured at only moderate intraarticular pressures, with flexion of the knee markedly increasing these pressures. The recommendation was made that the surgeon be constantly aware of the joint pressure, fluid inflow and outflow, increased thigh tension, and any lack of joint distention during arthroscopic procedures. Intermittent palpation of the popliteal and calf region is performed during the operative procedure to detect fluid extravasation caused by an inadvertent rupture of a Baker's cyst.[215]

ILLUSTRATIVE CASES

Case 1. A 47-year-old man presented 6 weeks after a left knee injury sustained during skiing. Physical examination revealed a moderate effusion, a severe restriction in knee motion of 0 to 30 degrees, and moderate quadriceps atrophy. Radiographs demonstrated normal tibiofemoral joint space (Fig. 7-60, *A*). The patient underwent 2 months of physical therapy to improve his knee motion and muscle strength. The patient desired to return to his active lifestyle and was treated with an ACL B-PT-B autograft reconstruction. Under anesthesia, he had 5 mm of increased medial joint opening at 25 degrees of flexion, no increase of medial joint opening at 0 degrees, and a grade III pivot shift. A repair of a complex double longitudinal lateral meniscus tear was also performed. The patient had an extensive area of grade 2B articular cartilage damage on the undersurface of the patella.

The patient recovered with no problems and resumed tennis, squash, and skiing. At 11 years postoperatively, physical examination revealed a normal range of motion, no lateral compartment pain, a negative pivot shift, 2-mm increase in medial joint opening at 25 degrees of flexion, and no increase in AP displacement on KT-2000 testing. However, radiographs demonstrated severe loss of lateral tibiofemoral joint space (see Fig. 7-60, *B*).

He did well until 14 years postoperative, when he slipped and fell onto his left knee. MRI revealed bilateral meniscus tears and the patient underwent a partial medial and lateral meniscectomy. At that time, extensive grade 3A damage (exposed bone) was noted on the lateral femoral condyle.

Comment: This patient required 2 months of rehabilitation owing to muscle atrophy and limitation of motion before the initial ACL surgery. Because he had a grade III pivot shift, a B-PT-B autograft was selected instead of an STG autograft or allograft. Unfortunately, the lateral meniscus repair did not provide a long-term chondroprotective effect.

Case 2. A 44-year-old woman presented 5 weeks after a twisting injury sustained to her right knee while playing badminton. She had a mild effusion, 0 to 120 degrees of knee motion, severe medial joint line pain, a grade II pivot shift, and 8 mm of increase in AP displacement on KT-2000 testing. The patient was treated conservatively for 1 month and wished to remain active in recreational softball and volleyball. She underwent an endoscopic ACL B-PT-B autograft reconstruction. There were no meniscal tears; however, fissuring and fragmentation were noted on the undersurface of the patella.

One year postoperatively, the patient complained of pain over the tibial hardware and saphenous nerve. She underwent removal of the tibial interference screw and scar tissue resection. No neuroma was identified. This procedure successfully resolved her pain and she returned to softball without problems.

At the most recent follow-up evaluation, 11 years postoperatively, the patient had a normal range of knee motion, no effusion, no joint line pain, a negative pivot shift, and 3 mm of increase in AP displacement on KT-2000 testing. Radiographs demonstrated preservation of the medial and lateral tibiofemoral joint spaces (Fig. 7-61). She had no

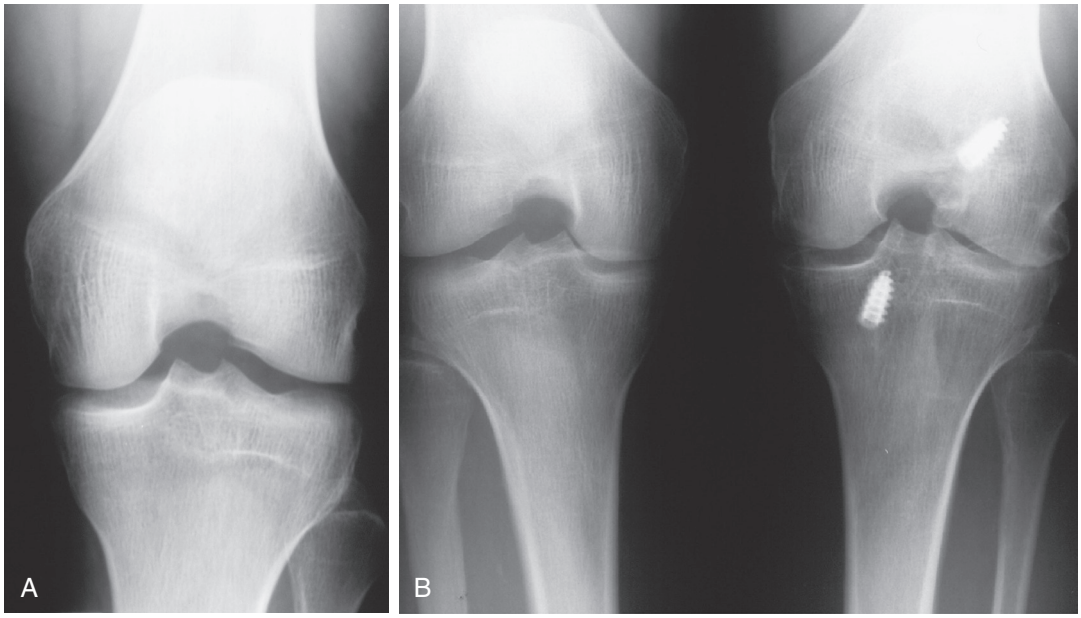


FIG 7-60 Case 1.

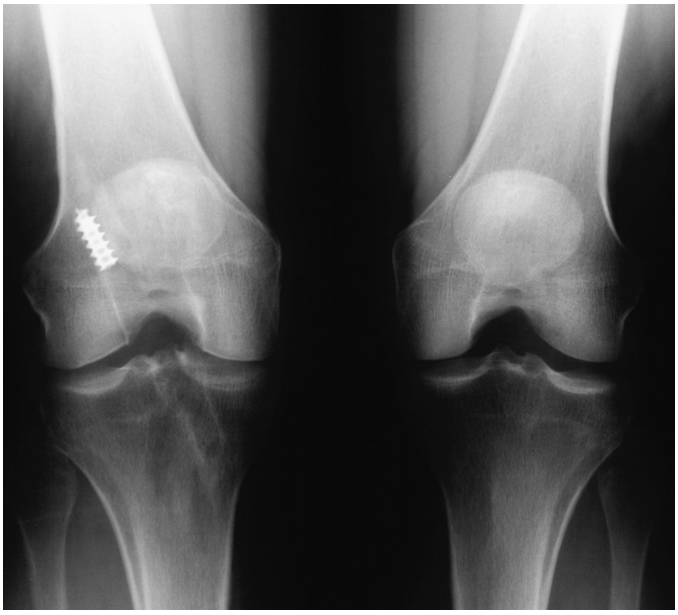


FIG 7-61 Case 2.

symptoms with low-impact activities and rated the overall condition of her knee as good.

Comment: This case, 11 years post ACL reconstruction with intact menisci and no evidence of arthritis, is in marked contrast to the frequent occurrence of arthritis that develops over the long term in patients who undergo meniscectomy.

Case 3. An 18-year-old male collegiate athlete presented 2 weeks after an acute twisting injury sustained to his right knee while playing basketball. He had a mild effusion, medial and lateral joint line pain, a grade II pivot shift, and 13.5 mm of increased AP displacement on KT-2000 testing. He was treated 4 months later with an ACL B-PT-B autograft, and bilateral meniscus repairs for double longitudinal tears. Extensive fissuring and fragmentation on the medial femoral condyle was noted at surgery. The patient had a normal postoperative course and returned to recreational basketball without problems.

Five years later, he injured the left ACL and medial meniscus and underwent an ACL B-PT-B autograft reconstruction and medial meniscectomy elsewhere. The patient then returned to our center 10 years later with complaints of left medial tibiofemoral compartment pain with daily activities. Standing PA radiographs at 45 degrees of flexion demonstrated a weight-bearing line of 28%. AP radiographs showed moderate loss of medial tibiofemoral compartment joint space in both the right (Fig. 7-62, *A*) and left (Fig. 7-62, *B*) knees. The right knee was entirely asymptomatic. The patient underwent a left opening wedge osteotomy with an iliac crest autograft and a locking plate (see Fig. 7-62, *C*). During the procedure, the ACL graft was noted as absent (see Fig. 7-62, *D*). The varus malalignment was corrected to a 60% weight-bearing line (see Fig. 7-62, *E*).

At the most recent follow-up evaluation, 14 years after the right ACL reconstruction and 7 months after the left HTO, the patient had a normal range of knee motion bilaterally. The right knee had a negative Lachman and pivot shift examination. The left knee had a grade II pivot shift and 5 mm of increased anterior drawer. There was no medial or lateral compartment pain in either knee. The patient was asymptomatic with daily activities and had elected not to return to strenuous athletics; therefore, a left ACL revision reconstruction was not performed.

Case 4. A 43-year-old man presented 4 months after a noncontact injury sustained to his left knee while playing basketball. The patient had experienced three additional giving-way episodes during daily activities. Physical examination demonstrated a mild joint effusion, 0 to 120 degrees of knee motion, moderate medial joint line pain, a grade II pivot shift, no increase in lateral or medial joint opening, and 7 mm of increased anterior tibial translation on Lachman testing. Radiographs revealed a weight-bearing line of 32% and moderate narrowing of the medial tibiofemoral compartment (Fig. 7-63, *A*). The patient had pain with daily activities and a walking tolerance of only 20 minutes.

The patient was treated with an opening wedge osteotomy, an ACL STG reconstruction, and a repair of a horizontal medial meniscus tear.

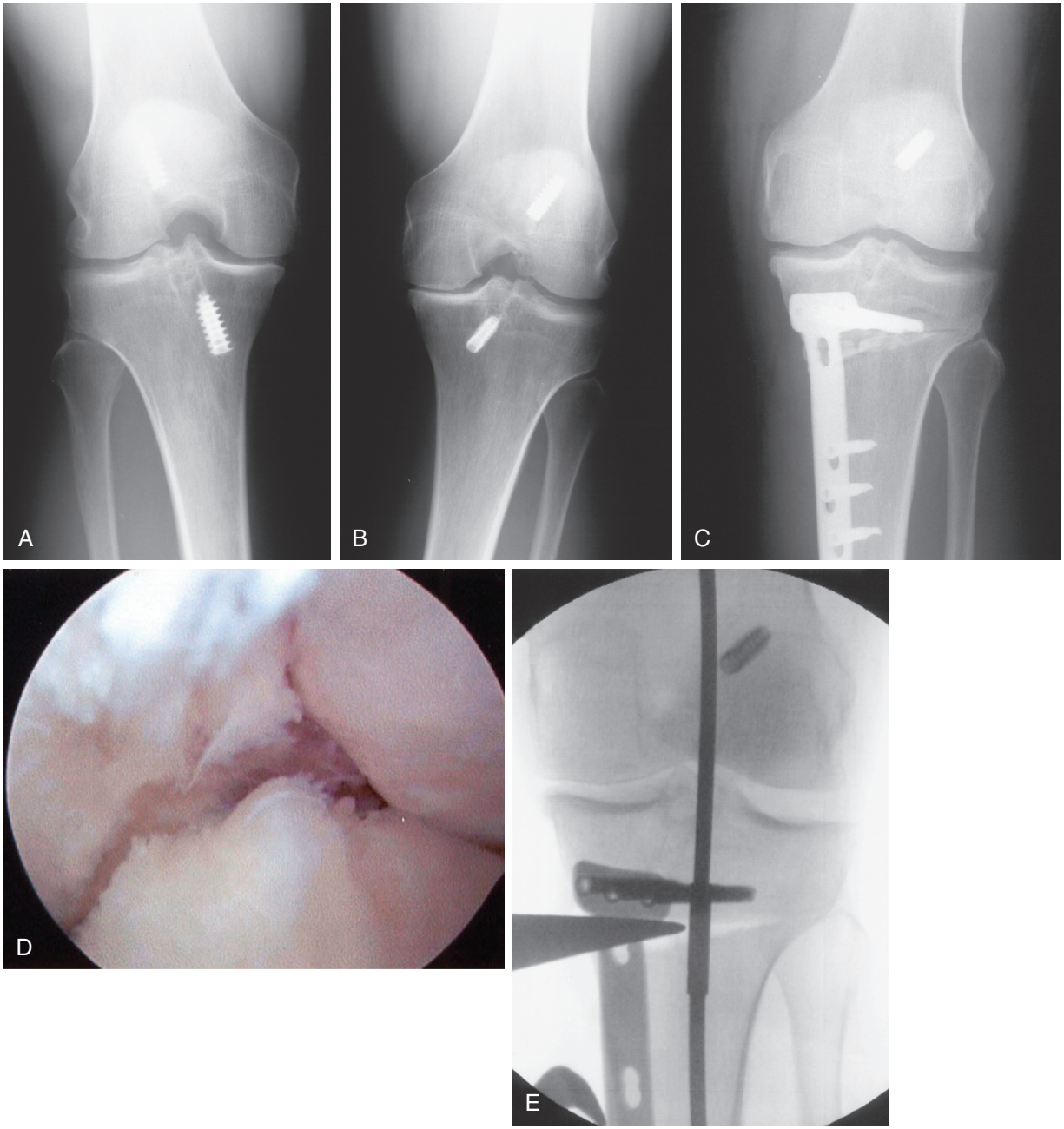


FIG 7-62 Case 3.

Grade 3A damage was noted on the medial femoral condyle and 2B damage was found on the undersurface of the patella during the procedure. No PL procedure was required owing to a normal lateral tibiofemoral opening gap test.

At follow-up 2 years postoperatively, the patient had a normal range of motion, no effusion, a grade I pivot shift, and 4.5 mm of increased displacement on KT-2000 testing. His weight-bearing line was 52% (Fig. 7-63, *B*). He had no problems with daily activities and rated the overall condition of his knee as very good.

Comment: There was no abnormal lateral joint opening in this varus-angulated knee (representing primary varus). Therefore, concurrent ACL reconstruction at the time of osteotomy was performed. The medial meniscus horizontal tear, commonly not amenable to suture repair, was in this case repaired in an attempt to save some meniscus function. The senior author prefers to use a locking plate and screws for fixation of opening wedge osteotomy (see Chapter 26). A two-incision ACL STG procedure was performed to achieve an ideal central tibial and femoral graft location.

Case 5. A 54-year-old woman presented 1 week following a hyperextension injury sustained to her left knee during snow skiing. She had a moderate effusion, mild medial tibiofemoral compartment pain, and a normal range of knee motion. The patient demonstrated 13.5 mm of increased AP displacement on KT-2000 testing, a grade III pivot shift, 12 mm of increase in lateral joint opening at 25 degrees of flexion, no increase in lateral joint opening at 0 degrees of flexion, and 15 degrees of increase in external tibial rotation. The patient attempted conservative treatment for 5 months, but was not satisfied with the

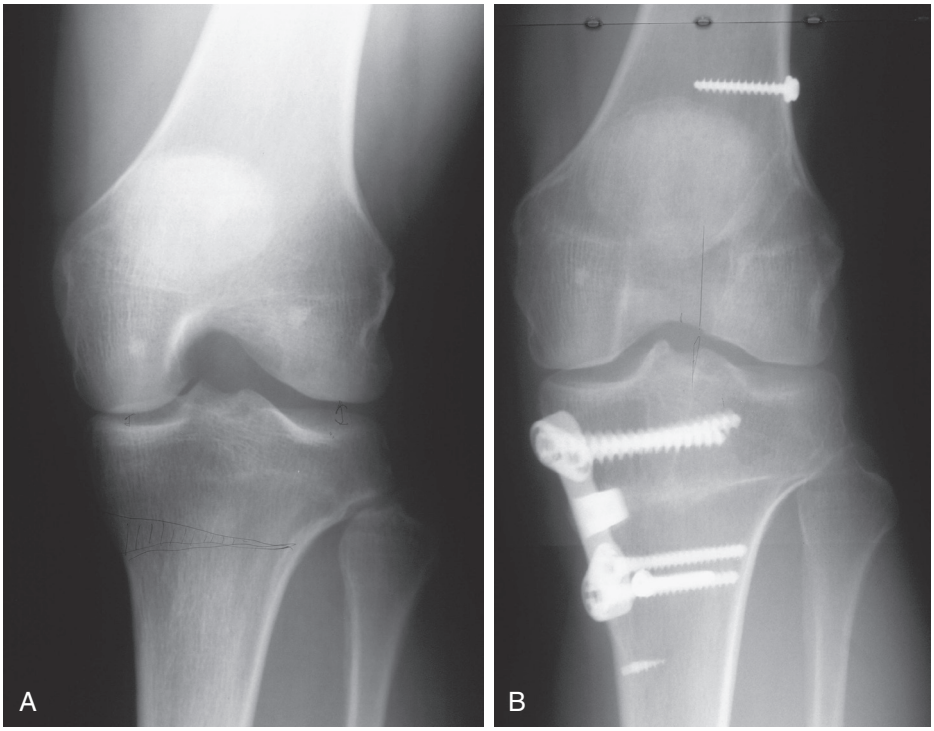


FIG 7-63 Case 4.

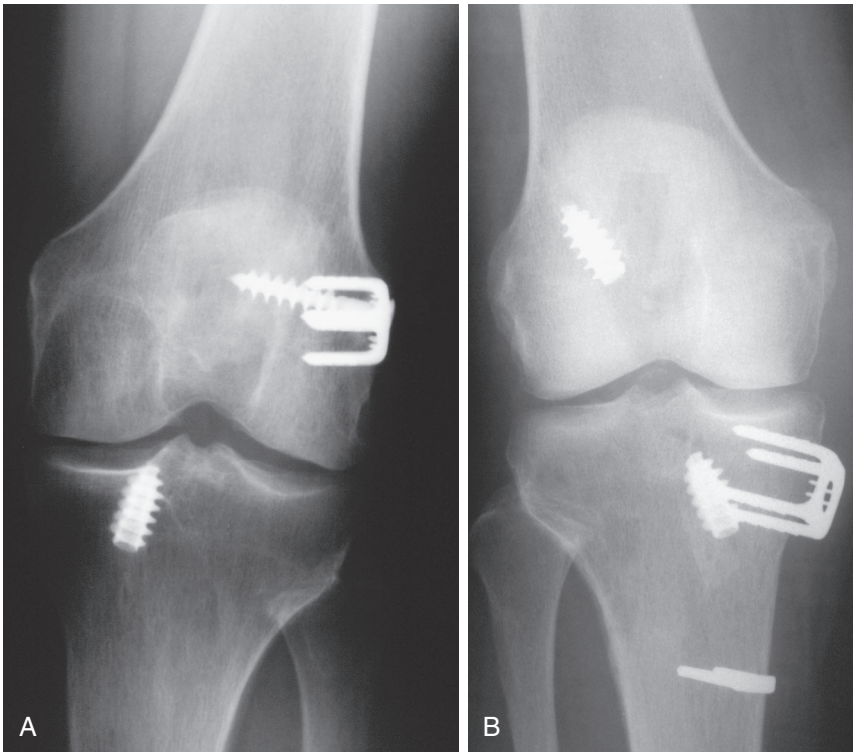


FIG 7-64 Case 5.

function of her knee because she experienced giving-way with daily activities and wished to return to skiing.

The patient was treated with an ACL B-PT-B autograft and a proximal advancement of the PL complex to her left knee (Fig. 7-64, *A*). The lateral exploration showed intact but elongated PL structures and, therefore, a lateral graft reconstruction was not required (see Chapter 17). There were no meniscus tears or noteworthy articular cartilage damage noted. The patient recovered and did well for 9 years, returning to snow skiing without problems.

The patient, now 63 years of age, returned after an injury sustained to her right knee during skiing. Physical examination revealed no effusion, moderate lateral and medial joint line pain, 5 mm of increased

medial joint opening at 25 degrees of flexion, a positive pivot shift test, and 7 mm of increased AP translation. The patient was treated conservatively for 3 months, but continued to experience pain and giving-way symptoms. Owing to her active lifestyle and continued giving-way problems, she was treated with an ACL B-PT-B autograft (see Fig. 7-64, *B*). At surgery, the medial gap test showed 12 mm of tibiofemoral opening; therefore a concurrent MCL STG reconstruction was performed. The articular surfaces and menisci were intact.

At follow-up, 10 years after the left ACL reconstruction and 1 year after the right ACL reconstruction, the patient had a normal range of motion bilaterally, no joint line pain or crepitus, no effusion, and a grade I pivot shift in both knees. She had no symptoms with daily activities.

Comment: This patient shows the successful treatment of ACL rupture combined with PL and medial ligament injuries. Immediate range of motion and closely supervised rehabilitation is the key to avoiding complications after multiple-ligament surgery. A B-PT-B autograft is preferred in grossly unstable knees, particularly with concurrent ligament reconstruction as occurred in this patient. An STG autograft would be a second choice and preferred over an allograft in a grossly unstable knee.

Case 6. A 19-year-old male presented 5 years after a right knee injury sustained during high school football. He had undergone arthroscopy and partial lateral meniscectomy elsewhere. He did well initially but suffered two episodes of giving-way and a recent hyperextension injury. Physical examination revealed no effusion, a mild loss of extension, a grade II pivot shift, and 7 mm of increase in lateral joint opening at 25 degrees of flexion.

The patient was treated with an ACL B-PT-B reconstruction, a proximal advancement of the PL complex (Fig. 7-65), a repair of a complex medial meniscus tear, and a repair of a peripheral lateral meniscus tear. There was grade 2B articular cartilage damage noted on the medial femoral condyle and medial tibial plateau.

At follow-up 3 years postoperatively, the patient had no effusion, a normal range of motion, no tibiofemoral compartment pain, no crepitus, a negative pivot shift, 2 mm of increase in lateral joint opening at 25 degrees of flexion, and no increase in AP displacement on KT-2000 testing. He had no problems with basketball and rated the overall condition of his knee as normal.

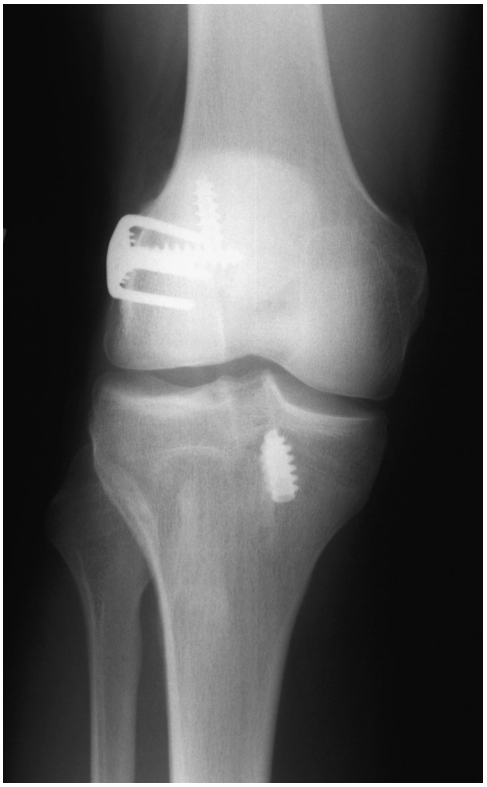


FIG 7-65 Case 6.

Comment: The treatment of a concurrent PL ligament injury with an ACL rupture requires different procedures, described in Chapter 17. In this case, the FCL and PL structures appeared normal, representing a prior interstitial tear with subsequent healing. Therefore, a more simplified proximal advancement procedure restored PL stability.

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Video Content

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8

Anterior Cruciate Ligament Revision Reconstruction: Graft Options and Clinical Outcomes

Frank R. Noyes, Sue D. Barber-Westin

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INDICATIONS

Many factors influence failure of anterior cruciate ligament (ACL) surgery.[3,26,47,60,66,73-75,77,78,84,86,100,101,103] A failed ACL reconstruction is noted by a return of knee instability and increased lateral and medial tibiofemoral compartment anterior translation and subluxation as demonstrated by positive Lachman and pivot shift tests. The surgeon must determine the factors that caused the prior reconstruction to fail, which may include a misplaced vertical ACL graft, inadequate healing and maturation of the graft, associated lateral or medial ligament insufficiency, varus or valgus malalignment, or inadequate postoperative rehabilitation with residual weakness and neuromuscular control (Table 8-1). In many cases, other associated major knee problems are present. These include limitation of knee motion with pain and stiffness, muscle atrophy from inadequate rehabilitation, articular cartilage damage, meniscectomy and its effects on joint symptoms and function, undiagnosed lower limb malalignment, and posterolateral (PL) or medial ligament deficiency. When present, each of these pathologies

TABLE 8-1 Possible Causes of Failure of ACL Reconstructions

- Misplaced femoral and/or tibial tunnel.
- Uncorrected medial, lateral, and/or posterior cruciate ligament insufficiency.
- Uncorrected varus or valgus osseous malalignment.
- Traumatic contact reinjury.
- Inadequate rehabilitation, poor muscle strength and neuromuscular control leading to noncontact reinjury upon return to athletics.
- Inadequate healing, maturation of allograft tissues.
- Family history of anterior cruciate ligament injuries.
- Prior anterior cruciate ligament injury on contralateral leg.
- Small-sized semitendinosus autograft.
- Obesity.
- Inadequate healing, maturation of autograft tissues, uncorrected hyperextension gait abnormality.

ACL, Anterior cruciate ligament.

CRITICAL POINTS Indications

- Determine factors that caused the prior ACL reconstruction to fail
- Address all pathologies before surgery: lower limb malalignment, muscle atrophy, limitation knee motion, gait abnormalities, misplaced tunnels.
- Goals, outcome of surgery depend on preexisting joint damage, associated procedures required.
  - Knees with misplaced tunnels with intact menisci and articular cartilage: most ideal outcome expected.
  - Knees with prior meniscectomy, articular cartilage damage, other ligament insufficiency, or varus malalignment: salvage procedure.
  - Select cases with concomitant articular cartilage restoration procedure, meniscus transplantation

must be addressed and resolved before or during ACL revision. The goal of rehabilitation is to restore the best possible function to the lower extremity before ACL revision to minimize the possibility of failure of the revision procedure.

Importantly, the patient and surgeon must address the expectations and goals of the revision because often associated cartilage damage or meniscectomy requires modification or elimination of strenuous, high-impact activities. In many cases, patients have undergone multiple prior surgical procedures that did not achieve the desired outcome.[74,75,77] The expectation of the revision operation to accomplish the patient's goals must be realistically discussed.[29]

A number of preoperative and operative issues must be addressed in a methodical manner to salvage knee function and obtain a reasonable result after prior ACL procedures have failed. These may include the necessity to perform staged procedures to correct lower limb malalignment with an osteotomy or fill enlarged or misplaced tibial and femoral tunnels with a bone graft. Patients may require extensive rehabilitation before surgery to restore normal joint motion and neuromuscular control. The approach taken is to maximize every aspect of the patient's knee condition and not accept any abnormality, such as a slightly misplaced tunnel or concurrent knee instability, in planning the revision procedure.

Other chapters in this book address issues related to correction of lower limb malalignment, arthrofibrosis, and muscle atrophy; procedures for articular cartilage defects; meniscus transplantation; and PL and medial ligament reconstructions. Although the timing of these procedures will be addressed in this chapter, the principal focus relates to surgical planning and technique decisions that, in our experience, will improve the success of the ACL revision.

Patients presenting for ACL revision fall into one of three categories, each of which has a different prognosis. In the most ideal category are knees with a misplaced tibial or femoral tunnel that have intact menisci and articular cartilage and no associated ligament instability. In these cases, the revision procedure is similar to a primary ACL reconstruction in terms of an expected good functional outcome. In the most severe category are knees that had a previous meniscectomy, articular cartilage damage, associated ligament instabilities, or lower limb malalignment. These patients will have a less than ideal outcome and the revision represents a salvage situation. In the middle of these two categories are patients who have partial or complete loss of meniscus function, associated cartilage damage, and a residual pivot shift from a failed ACL procedure, but no associated lower limb malalignment or other ligament instability. The outcome for providing stability in these cases is good; however, further joint deterioration will occur over time and counseling must be undertaken for activity modification. In select cases, indications exist for an articular cartilage restoration procedure and meniscus transplantation. Clinical studies on ACL revision usually contain a selection bias regarding the inclusion of patients from these three categories, which accounts for the differences in reported outcomes among investigations. The majority of studies report that the outcome of ACL revision is inferior to that of primary reconstruction. Usually, the revision procedures are performed many months or years after the failure of the primary reconstruction, during which time further giving-way episodes and joint deterioration have occurred that compromise the final outcome.

A frequent clinical presentation after an ACL reconstruction with a vertical ACL graft is a negative or mildly positive Lachman test with a positive pivot shift test that reproduces the patient's complaints of residual giving-way with activities. These patients are candidates for an ACL revision in which the entire ACL graft is removed and an anatomic ACL graft replacement is performed. In rare instances, the primary ACL graft may be retained and a second graft is placed in a more suitable anatomic location to provide rotational stability, as is discussed later.

CONTRAINDICATIONS

Patients who are sedentary and do not experience giving-way or swelling episodes with daily activities and have little exposure to strenuous or high-risk activities are treated conservatively. These patients are advised to maintain an ideal body weight and have periodic knee examinations. In addition, patients who are willing to modify their activity level to avoid high-risk knee motions such as pivoting and cutting are placed into a conservative treatment program. Patients who are unable to participate or be compliant with postoperative rehabilitation are not surgical candidates.

The presence of symptomatic patellofemoral or tibiofemoral arthritis is a general contraindication to ACL surgery, because pain symptoms remain postoperatively. Although pain symptoms may be lessened by restoring knee stability, significant joint damage may still limit daily activities. Weight-bearing 45-degree posteroanterior (PA) views are important to determine the millimeters of remaining medial or lateral tibiofemoral joint space. Patients are frequently surprised to learn that the joint space is absent or nearly absent because their symptoms have not yet limited daily activities. In these knees, conservative measures are instituted until such time that unicompartmental or total joint replacement is warranted.

CRITICAL POINTS Contraindications

- Sedentary patient with no symptoms with daily activities.
- Patient willing to modify activity level, avoid high-risk knee motions.
- Patient not able to participate or comply with rehabilitation program.
- Presence of symptomatic arthritis in knees with major loss of joint space.
- Varus-malaligned knees undergo high tibial osteotomy first, may not require subsequent ACL revision.
- Patients with marked muscle atrophy undergo extensive rehabilitation first, restoration of muscle function may avoid ACL revision.
- Complex regional pain syndrome.
- Unrealistic expectations for future athletic activities.
- Obesity, prior joint infection.

CRITICAL POINTS Clinical Evaluation

- Perform thorough history, review prior medical and operative records.
- Comprehensive physical examination assesses knee flexion and extension, patellofemoral indices, tibiofemoral crepitus, tibiofemoral joint line pain, muscle strength, gait abnormalities.
- Perform all stability tests to document abnormal tibial translation, rotations, and tibiofemoral compartment translation.
- Knee arthrometer test: 134 N.
- Radiographs: standing anteroposterior at 0 degree, lateral at 30 degrees; weight-bearing PA at 45 degrees; patellofemoral axial views; double-stance hip-knee-ankle alignment; lateral and posterior stress views as indicated.
- MRI, including articular cartilage image techniques.
- Cincinnati Knee Rating System for subjective, objective, functional scoring.

Patients with ACL deficiency, symptomatic medial tibiofemoral arthritis, and varus malalignment require corrective valgus-producing high tibial osteotomy (HTO). These patients often do not require subsequent ACL surgery, because there are limitations in activities owing to the joint damage.[71] These patients often report improved joint instability because the varus thrust gait pattern is eliminated with osteotomy.

Patients with marked lower extremity muscle atrophy often require a delay in surgery for many months until adequate muscle function has been restored. These patients have an increased risk for postoperative complications, including quadriceps muscle shutdown, patella infera, and arthrofibrosis. In some cases, the restoration of muscle function may lead to increased knee stability, avoiding ACL revision.

The presence of residual signs and symptoms of a complex regional pain syndrome (CRPS) requires careful examination and questioning regarding the presence of burning pain, abnormal skin hypersensitivity, extremity discoloration, and intolerance to cold and ice. Even after resolution of a prior CRPS, there is an increased frequency for return of the syndrome in these knees that must be promptly recognized in the postoperative period (see Chapter 40).

It is not unusual for patients who require ACL revision to have unrealistic expectations of future athletic activities. The goals of the revision procedure are reviewed in detail, and the patient educational process involves recommendation of recreational and low-impact activities only, avoiding strenuous activities in knees with associated joint cartilage damage.

Patients with a body mass index of 30 or greater are usually not surgical candidates. A history of prior infection with subsequent joint arthritis often contraindicates ACL revision. There may be associated medical conditions contraindicating surgery. The use of nicotine products is strongly discouraged and absolutely contraindicated if osteotomy alignment procedures are required.

CLINICAL EVALUATION

A thorough history is performed, including a detailed account of all knee injuries and the operative procedures that have been performed. In revision knees, prior operative records are obtained to verify the surgical findings, condition of the articular cartilage and menisci, and graft placement. A comprehensive physical examination is performed, including assessment of knee flexion and extension, patellofemoral indices, tibiofemoral crepitus, tibiofemoral joint line pain, muscle strength, and gait abnormalities. The surgeon must determine all of the abnormal translations and rotations in the knee joint. The medial posterior tibiofemoral step-off on the posterior drawer test is done at 90 degrees of flexion. Quantification of posterior tibial translation may be performed using stress radiography in knees with posterior cruciate ligament (PCL) ruptures to determine if the rupture is partial or complete (see Chapter 16).[41] The appropriate tests to determine the integrity of the ACL are performed, including KT-2000 (MEDmetric) arthrometer testing at 20 degrees of flexion (134-N force) to quantify total anteroposterior (AP) displacement. The pivot shift test is recorded on a scale of 0 to III, with a grade of 0 indicating no pivot shift; grade I, a slip or glide; grade II, a jerk with gross subluxation or clunk; and grade III, gross subluxation with impingement of the posterior aspect of the lateral side of the tibial plateau against the femoral condyle.

Insufficiency of the PL and medial ligament structures are determined by varus and valgus stress testing at 0 and 30 degrees of knee flexion. The surgeon estimates the amount of joint opening (in millimeters) between the initial closed contact position of each tibiofemoral compartment, performed in a constrained manner avoiding internal or external tibial rotation, to the maximal opened position. The result is recorded according to the approximate millimeters of increase in the tibiofemoral compartment opening of the affected knee compared with that of the opposite normal knee. Abnormal medial or lateral joint opening may be measured with stress radiographs. The results are always confirmed at arthroscopy by the gap test. The tibiofemoral rotation dial test at 30 and 90 degrees detects increases in external tibial rotation with posterior subluxation of the lateral tibial plateau or anterior subluxation of the medial tibial plateau caused by medial ligament injury. A word of caution is necessary, because it is possible to confuse increased external tibial rotation for a PL injury and miss the medial side ligament injury that requires correction.[79] The presence of a varus recurvatum in both the supine and standing positions is carefully assessed. Gait analysis is performed to detect a varus or valgus thrust or hyperextension thrust. Patients can often demonstrate their knee instability on standing, with a few degrees of knee flexion, by producing an external femoral rotation that reproduces the pivot shift phenomena. Abnormal varus or valgus tibiofemoral joint opening may also be demonstrated by the patient.

Radiographs taken during the initial examination include standing AP at 0 degree, lateral at 30 degrees of knee flexion, weight-bearing PA at 45 degrees of knee flexion, and patellofemoral axial views. Double-stance full-standing radiographs of both lower extremities, from the femoral heads to the ankle joints, are obtained in knees in which varus or valgus lower extremity alignment is detected on clinical examination. The mechanical axis and weight-bearing line are measured as discussed in Chapter 26. Magnetic resonance imaging (MRI) is

performed to provide further details of tunnel placement and the condition of the articular cartilage and menisci. Fast-spin-echo and other MRI protocols (T2 mapping) are available to obtain superior quality articular cartilage images.[85] The tibial tunnel placement is visualized on sagittal views and measurements made to determine if the tunnel is too posterior, which often requires a staged bone graft procedure.

At our center, patients complete questionnaires and are interviewed for the assessment of symptoms, functional limitations, sports and occupational activity levels, and patient perception of the overall knee condition according to the Cincinnati Knee Rating System (CKRS; see Chapter 41).[6] The forms are available online for the patient to obtain before their consultation.

PREOPERATIVE PLANNING

The factors that may have been related to or directly caused the failure of the prior ACL reconstruction must be identified and addressed either before or during the revision procedure. A meticulous physical examination, previously discussed, is performed to detect associated ligament deficiencies, valgus or varus lower limb malalignment, or gait abnormalities. The type of hardware used previously is identified to ensure that the proper equipment is available for removal during the revision procedure, if required. If existing hardware does not interfere with new tunnel placement and is in a difficult location to reach, it may be left alone.

All abnormalities or potential problems are addressed preoperatively, including patient expectation issues, muscular weakness, painful neuromas, residual CRPS, and anterior knee pain caused by patellofemoral cartilage damage. A loss of full knee extension creates problems. It is important to obtain full knee motion before revision surgery. The exceptions are grafts placed too far anteriorly or cyclops lesions that produce a mechanical block to full extension or flexion. During the revision procedure, anterior intercondylar blockage is eliminated by adequate notchplasty and correct graft placement. In these knees, there may also be associated tightness to the posterior capsular structures, which have shortened, requiring a vigorous postoperative program. If the lack of extension is greater than 5 degrees, the procedures are staged by first performing an arthroscopic debridement and cyclops lesion excision, followed by rigorous rehabilitation to regain full motion, and then ACL revision reconstruction.

Knees with grossly positive clinical laxity tests have involvement of the secondary ligament restraints, primarily the PL structures. Associated medial or lateral ligament laxity is an indication for medial or lateral ligament reconstruction.

Considerable counseling and patient education are required on the expected results and outcomes from the revision procedure. This is especially important in knees with preexisting arthritis or loss of meniscal function or those that require additional major operative procedures. In nearly one half of revision knees, a major concomitant procedure will be required.[74] Patients need to understand the technical difficulties inherent in the operative procedures and that the results are typically not as favorable as primary ACL reconstruction. A surgeon-rehabilitation team is required to provide instruction on rehabilitation to ensure that the postoperative exercise program will be successfully followed by the patient.

GRAFT SELECTION

Currently, there is no standard graft choice for ACL revision reconstruction.[46,107] Autograft tissue sources include bone-patellar tendon-bone (B-PT-B), quadriceps tendon-patellar bone (QT-PB), and semitendinosus-gracilis (STG) tendons. We prefer B-PT-B autogenous grafts. If the ipsilateral patellar tendon was previously harvested, the contralateral patellar tendon is a potential graft source. Ipsilateral patellar tendon graft reharvest is not recommended because of persistent changes on MRI and graft morphology reported in these knees 7 to 10 years postoperatively.[9,49,53-55,58] A B-PT-B autograft is not recommended if there is associated patellofemoral arthritis (Grade 2B or 3A classification; see Chapter 44), anterior knee pain, or history of patellar subluxation or dislocation. A B-PT-B autograft is not performed when patient issues suggest a decreased ability to follow the more involved rehabilitation program and initial pain related to this graft.

A second option is a QT-PB graft taken from the same or opposite knee, with grafting of any residual patellar bone defect. The quadriceps tendon has the greatest cross-sectional area (100 mm^2) and is ideal in revision knees if the prior tunnels are in the desired anatomic ACL site, but are slightly expanded.

A third option in knees with good bone quality and normal-sized tunnels is an STG autograft, which may be either a four-strand or six-strand graft (see Chapter 7). In recreational athletes and more sedentary patients, a four- or six-strand STG autograft is recommended. Newer fixation methods have increased the success rate and the rehabilitation postoperatively is easier on the patient.

If autograft tissues are not available or the patient refuses a contralateral autograft harvest, then a B-PT-B or Achilles tendon-bone allograft is recommended. A lateral extraarticular iliotibial band (ITB) procedure[18] is recommended with ACL allografts in knees that demonstrate a grade III pivot shift test or greater than 10 mm of increased AP translation on KT-2000 testing to reduce the high failure rate noted after revision ACL allograft reconstruction[45,77,94] and the delay in allograft healing and maturation.[4,43,44,110] A posterior or anterior tibialis allograft is not recommended.[91] It is desirable to have one portion of

CRITICAL POINTS Preoperative Planning

- Determine all factors related to failure index ACL procedure for treatment plan.
- Identify tibial and femoral tunnel location and necessity for bone graft.
- Identify hardware previously used.
- Obtain full knee motion, muscle strength, return of adequate neuromuscular function.
- Determine need for concomitant cartilage/meniscus procedures, extraarticular procedures, and other ligament reconstructions to correct all instabilities.
- Address patient expectation and goals of surgery.

CRITICAL POINTS Graft Selection

- We prefer B-PT-B autograft; use contralateral knee if previously harvested.
- QT-PB autograft second option.
- STG autograft (four- or six-strand) option for recreational athletes, more sedentary patients.
- B-PT-B or Achilles tendon-bone allograft reserved for multiligament procedures, special cases where graft harvest to be avoided, or patient refuses contralateral autograft harvest.
- Graft harvest: See Chapter 7.

the graft with a bone plug for increased rate of graft healing in one of the tunnels.

OPERATIVE TECHNIQUES

Patient Setup

The patient is instructed to use a chlorhexidine wash of the operative limb ("toes to groin") three days before surgery, including the evening before and morning of surgery. Lower extremity hair is removed by clippers, not a shaver. Antibiotic infusion is begun 1 hour before surgery. The use of a nonsteroidal antiinflammatory drug (NSAID) and a postoperative firm double-cotton, double-Ace compression dressing for 72 hours (cotton, Ace, cotton, Ace layered dressing) has proven effective in diminishing soft tissue swelling in knee surgery cases. In complex multiligament surgery, the antibiotic is repeated at 4 hours and continued for 24 hours. A urinary indwelling catheter is not used unless there are specific indications. The patient's urinary output and total fluids are carefully monitored during the procedure and in the recovery room. The knee skin area is initialized by the surgeon before entering the operating room, with a nurse observing the procedure. The identification process is repeated with all operative personnel with a "time out" before surgery to verify the knee undergoing surgery, procedure, allergies, antibiotic infusion, and special precautions that apply. All personnel provide verbal agreement.

The patient setup and positioning and graft harvest techniques for B-PT-B, STG, and QT-PB autografts are done as described in detail in Chapter 7.

All knee ligament subluxation tests are performed after the induction of anesthesia in both the injured and contralateral limbs. The amount of increased anterior tibial translation, posterior tibial translation, lateral and medial joint opening, and external tibial rotation are documented. A thorough arthroscopic examination is conducted, noting articular cartilage surface abnormalities and the condition of the menisci. Appropriate debridement and meniscus repair or partial excision are performed as necessary.

The lateral and medial gap tests are done during the arthroscopic examination (see Chapter 17).[76] The knee is flexed from 25 to 30 degrees and a varus load of approximately 89 N applied. A calibrated nerve hook is used to measure the amount of tibiofemoral compartment opening (Fig. 8-1). Knees that have 12 mm or more of joint opening at the periphery or 10 mm at the midpoint of the tibiofemoral compartment require a PL or medial ligament reconstructive procedure.

The general principles the senior author (F.R.N.) applies to ACL reconstruction are discussed in Chapter 7 (see Table 7-8).

CRITICAL POINTS Operative Techniques: Patient Setup

- Patient uses chlorhexidine wash operative limb three days before surgery.
- Antibiotic infusion 1 hour before surgery.
- Nonsteroidal antiinflammatory medication morning of surgery, continued 5 days postoperative.
- Knee to be reconstructed initialed by surgeon, time-out in operating room.
- Lateral and medial gap test done during arthroscopic examination to determine need for concurrent ligament reconstructive procedures.

Identification of Tibial Tunnel Problems in Revision Knees and Need for Staged Bone Grafting

It is next important to determine that the tibial and femoral tunnels can be placed into the ideal position before the selected graft is harvested and prepared. The selection and preparation of autografts is performed only after the tibial and femoral tunnels have been determined to be adequate or have been bone grafted previously.

It is usually not difficult to identify the prior tibial tunnel entrance into the joint after removal of the soft tissues and graft material at the ACL attachment location. The adjacent lateral meniscus attachment

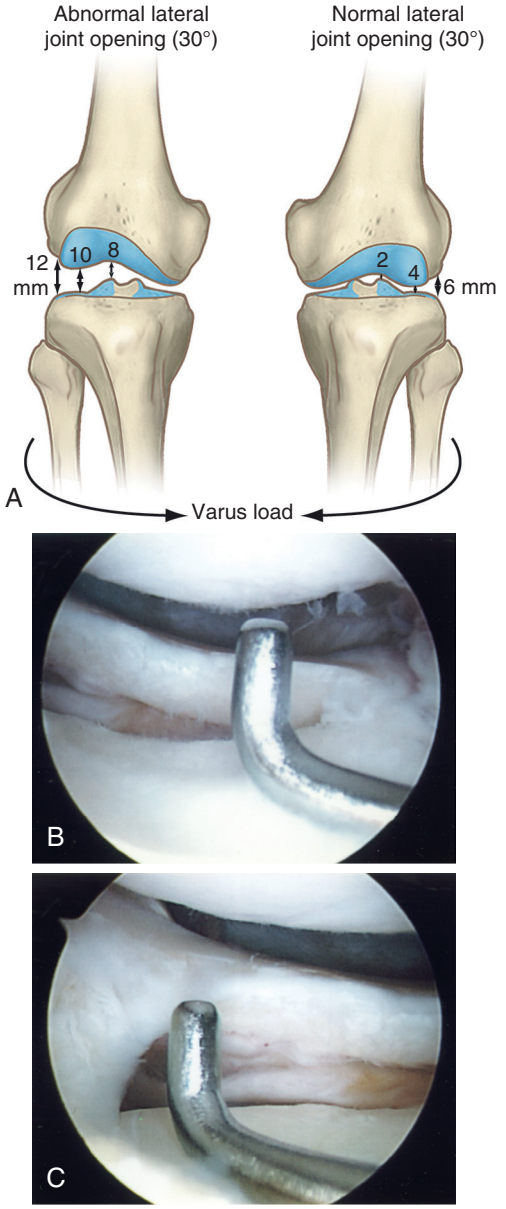


FIG 8-1 The gap test. **A,** The amount of lateral tibiofemoral joint opening is measured with the knee at 25 degrees of flexion. Knees with insufficiency of the posterolateral structures will demonstrate 12 mm of joint opening at the periphery of the lateral tibiofemoral compartment, 10 mm at the midportion of the compartment, and 8 mm at the innermost medial edge. **B,** Normal gap test. **C,** Abnormal gap test.

CRITICAL POINTS Operative Techniques: Identification of Tibial Tunnel Problems in Revision Knees and Need for Staged Bone Grafting

Tibial Tunnel

- Identify prior tibial tunnel entrance after removal of soft tissues and graft material at the ACL attachment location.
- Identify lateral meniscus attachment, PCL, posterior ridge, medial tibial spine, medial articular cartilage.
- Posterior expanded tibial tunnel extending all the way to the RER is not acceptable for revision graft, requires staged bone grafting with autogenous bone.
- Posterior tibial tunnel located in posterior one third of the native ACL attachment, with 5-mm bridge between the tunnel and RER, if not dilated, may be relocated anteriorly.
- Use cortical allograft dowel to fill posterior one third of tunnel.
- Or perform double-bundle reconstruction. Posterior tibial tunnel used for PM bundle, second anterior tibial tunnel used for AM bundle when two femoral tunnels possible.

Femoral Tunnel

- Place arthroscope in AM portal, view entire lateral notch and notch roof.
- Remove all soft tissues and graft material.
- Perform limited notchplasty to view furthest posterior aspect of lateral notch.
- Map out central anatomic ACL; position knee 20 to 30 degrees of flexion.
- Majority knees will have vertical grafts on roof of notch, allowing new lateral wall tunnel to be placed.
- For dilated and slightly misplaced femoral tunnel, use two stacked interference screws to provide a buttress against one side of the tunnel. Only possible if tunnel is close to ideal anatomic position. Otherwise, staged bone graft required.

may be encased in scar tissue and is preserved. The PCL, posterior ridge, medial tibial spine, and medial articular cartilage are all identified. The furthest extent of the posterior ACL tibial attachment is approximately 8 mm anterior to the posterior ridge (RER). This is a critical measurement because many primary ACL operative procedures place the ACL graft into the posterior one third of the ACL attachment. It is often the case that during the drilling procedure for the posterior tibial tunnel, or in using this tunnel for the femoral tunnel placement that the tunnel is enlarged posteriorly out of the native ACL footprint and extends to the RER. This situation results in a vertical ACL graft. Often, the preoperative MRI will allow measurements of the tunnel location relative to the AP width and the surgeon is already aware of this problem (Fig. 8-2).

It may initially appear that the tibial tunnel is acceptable; however, after removing all of the soft tissues or when the tibial tunnel drilling is performed, the surgeon may discover that a posterior tibial tunnel exists that extends all the way to or through the RER, which is not acceptable for the revision graft. These cases require staged bone grafting (Fig. 8-3). On occasion, the posterior tibial tunnel is located in the posterior one third of the native ACL attachment, with only a 5-mm bridge between the tunnel and RER. If the tibial tunnel is not dilated requiring grafting, it is possible to drill and relocate the tibial tunnel approximately 8 mm anteriorly into a more advantageous central ACL attachment position. A cortical allograft dowel is positioned to occupy and fill the posterior one third of the tunnel, maintaining the graft in the ideal central position. Another technique is to fashion the bone plug of a revision allograft, maintaining an enlarged bone block to fill the posterior portion of the tibial tunnel and prevent the collagen portion of the graft displacing posteriorly. A third technique is to perform a double-bundle reconstruction with the posterior tibial tunnel used for the PL bundle (assuming the graft is placed into the native ACL tibial footprint and not located in an abnormal posterior position). A second anterior tibial tunnel is used for the anteromedial (AM) bundle. Use of double-bundle grafts in a revision procedure requires that the femoral tunnel location also be ideal, which is often a problem. A misplaced femoral tunnel may prevent two additional tunnels to be adequately placed because these tunnels could possibly weaken the femoral condyle.

In our opinion, the mistake that is possible at ACL revision is to accept a posterior tibial tunnel position for a single-graft procedure. It is preferable to proceed with the staged bone grafting if there is any question that the bone quality is not ideal and that the revision graft would be placed into the posterior one third of the native tibial attachment and result in a windshield effect on weakened bone posteriorly eroding through to the RER. The alternatives listed previously to relocate the graft tunnel are indicated only when good bone quality exists and the prior tibial tunnel does not extend beyond the native ACL attachment. In our experience, in the majority of revision cases involving a posteriorly placed tibial tunnel, the tunnel is frequently dilated and expanded. This is not suitable for bone incorporation into the revision graft, and there is little question that staged bone grafting is necessary.

Identification of Prior Femoral Tunnel in Revision Knees and Need for Staged Bone Grafting

The arthroscope is placed in the AM portal to view the entire lateral notch and notch roof, and all soft tissues and graft material are removed. An angled curette, suction cutting device, and occasionally a radiofrequency probe are used. Any spurs or overgrowth of the notch are removed and a limited notchplasty performed to view the furthest posterior aspect of the lateral notch. A mistake is to not remove all of the lateral soft tissues adjacent to the lateral femoral condyle articular cartilage edge because this is the landmark for identification of the correct location of the revision graft. With a prior vertical tunnel or anterior tunnel, it is often possible to outline the native ACL attachment, which provides important identification landmarks for graft location. The ACL footprint is mapped out and the determination is made whether an ideal anatomic central tunnel is possible, as described.

In a majority of revision cases, the index graft is placed in a vertical, nonanatomic position on the roof of the intercondylar notch (Fig. 8-4) and it is possible to place the revision tunnel in the ideal central ACL anatomic attachment. We use the two-incision approach to reorient the femoral tunnel entirely away from the index tunnel. It is sometimes possible to perform an endoscopic approach using an AM portal to drill the femoral tunnel with a hyperflexed knee; however, the two-incision technique is preferable in most revision procedures. In posterior wall femoral blowout situations, a reoriented tunnel wall can often be used and the bone portion of the graft fashioned so that the bone is placed in the posterior portion of the tunnel to maintain the collagen portion of the graft within the native ACL femoral footprint.

The more difficult problem is the management of a dilated and slightly misplaced femoral tunnel that is at the native ACL attachment or perhaps extends a few millimeters beyond the native ACL attachment onto the intercondylar roof. The new tunnel will overlap and produce an enlarged dilated tunnel with portions extending proximal and beyond the native ACL footprint. There is a technique in which two stacked interference screws (absorbable or metallic) are used to

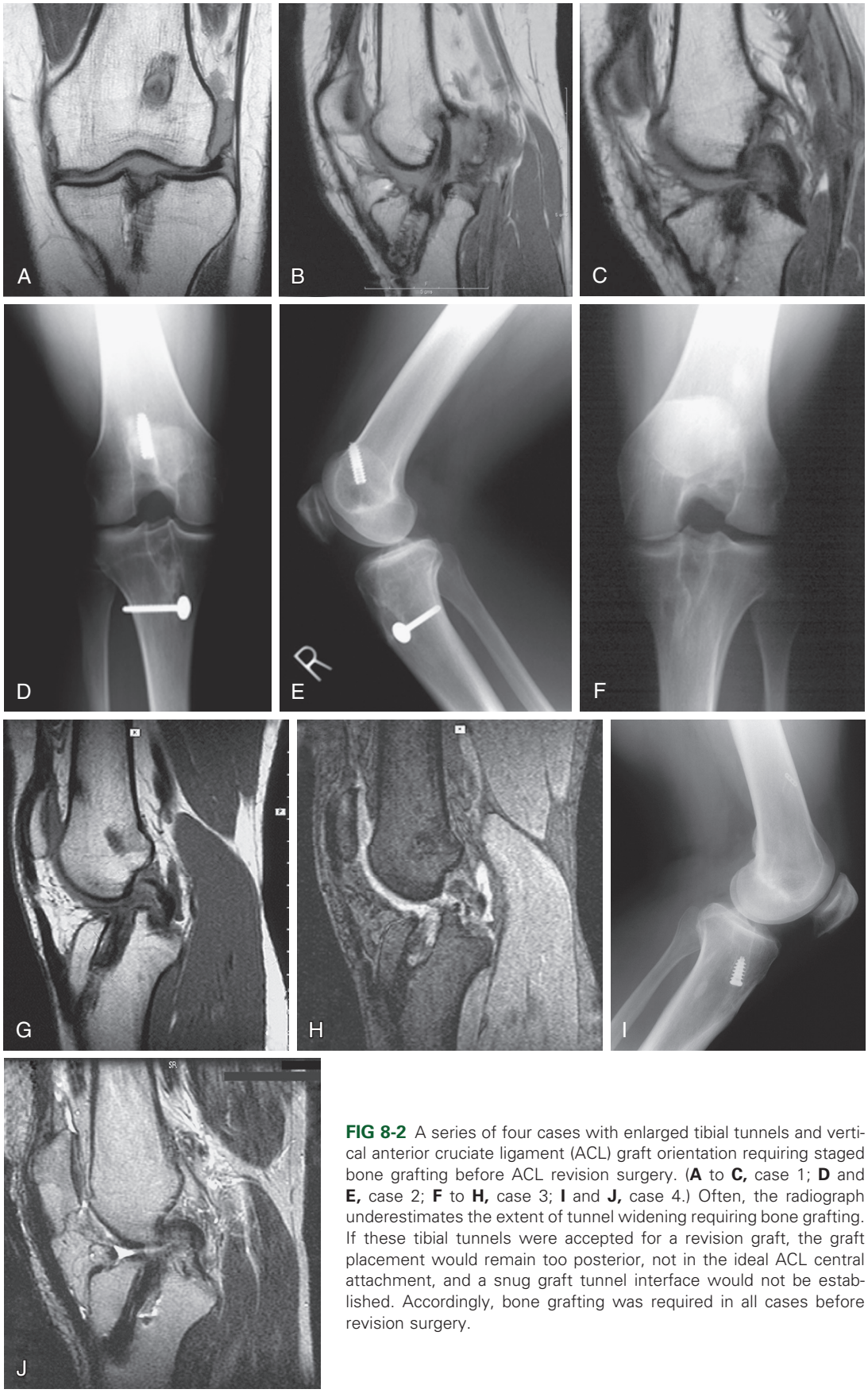


FIG 8-2 A series of four cases with enlarged tibial tunnels and vertical anterior cruciate ligament (ACL) graft orientation requiring staged bone grafting before ACL revision surgery. (**A** to **C,** case 1; **D** and **E,** case 2; **F** to **H,** case 3; **I** and **J,** case 4.) Often, the radiograph underestimates the extent of tunnel widening requiring bone grafting. If these tibial tunnels were accepted for a revision graft, the graft placement would remain too posterior, not in the ideal ACL central attachment, and a snug graft tunnel interface would not be established. Accordingly, bone grafting was required in all cases before revision surgery.

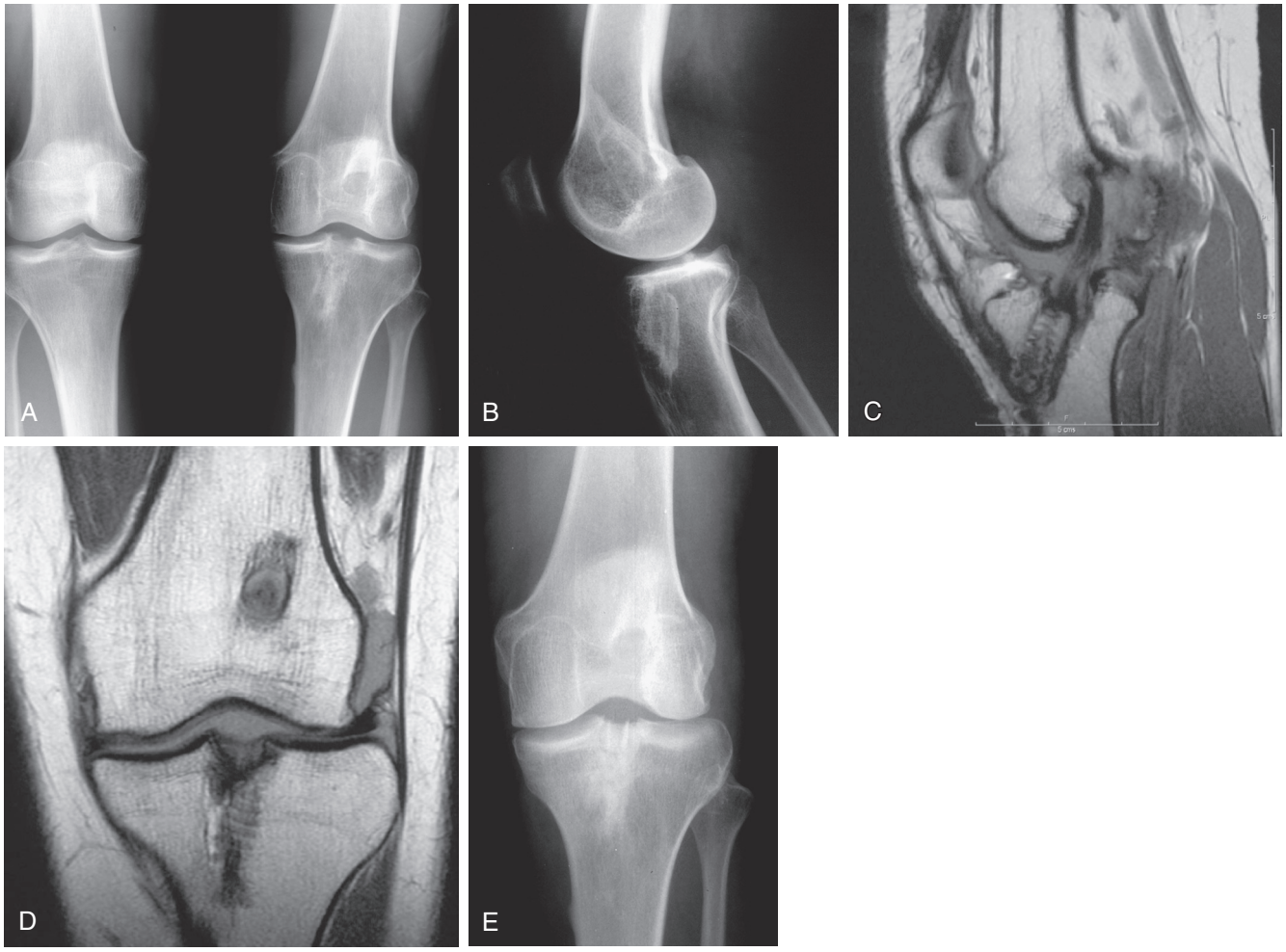


FIG 8-3 **A,** A 31-year-old woman with failure of a primary anterior cruciate ligament (ACL) semitendinosus-gracilis autograft and revision anterior tibial allograft of the left knee. **B,** A bone graft of a large tibial tunnel was performed with allograft. **C** and **D,** The allograft procedure did not provide a restitution of the tibial tunnel and a residual widening was present. **E,** A repeat bone graft using autogenous iliac crest was required to obtain bone of sufficient quality for an ACL revision.

provide a buttress against one side of a dilated tunnel to locate the graft within the ideal femoral attachment. However, this technique is possible only when the femoral tunnel is close to ideal and the stacked interference screw is truly used as a buttress screw against one side of the tunnel wall. The remainder of the femoral tunnel cannot be dilated or enlarged, and the bone quality about the femoral tunnel is not osteopenic and allows for graft fixation. The femoral tunnel for the graft does not extend to the roof of the notch or to the edge of the femoral articular cartilage.

The mistake that may be made is to accept a "slightly enlarged" femoral tunnel in which the graft placement is not ideal, such as too proximal or anterior on the lateral femoral wall. If there is any question, a bone grafting procedure is performed and the revision reconstruction done 5 to 6 months later. Meniscus repairs may be done with the bone grafting procedure to protect the meniscus, and a functional brace used until the revision procedure is performed.

Bone Grafting Procedure for Tibial and Femoral Enlarged Tunnels

There are available principles to follow when performing bone grafting of enlarged tunnels (Table 8-2). The first is to adequately prepare the graft site by removing all soft tissues, curette, and place small drill holes into the cortical tunnel walls to provide the most ideal surface for bone graft healing. Cultures of the removed soft tissues are obtained. Rarely, a Gram stain and frozen section are necessary to exclude an occult infectious process within a tibial or femoral tunnel, particularly when an allograft was used.

CRITICAL POINTS Operative Techniques: Bone Grafting Procedure for Tibial and Femoral Enlarged Tunnel

- Prepare graft site by removing all soft tissues, curette, and place small drill holes into the cortical tunnel walls.
- Culture removed soft tissues, possible Gram stain, cell count.
- Freeze-dried dense cancellous allograft core used in tunnel or to replace posterior tibial RER when deficient.
- Rare cases, minimally invasive iliac crest autograft procedure, remove only the superior and outer portions, do not disturb the inner table and muscle attachments.
- Major defects: cancellous allograft bone in 5- to 8-mm fragments packed between cortical-cancellous strips.

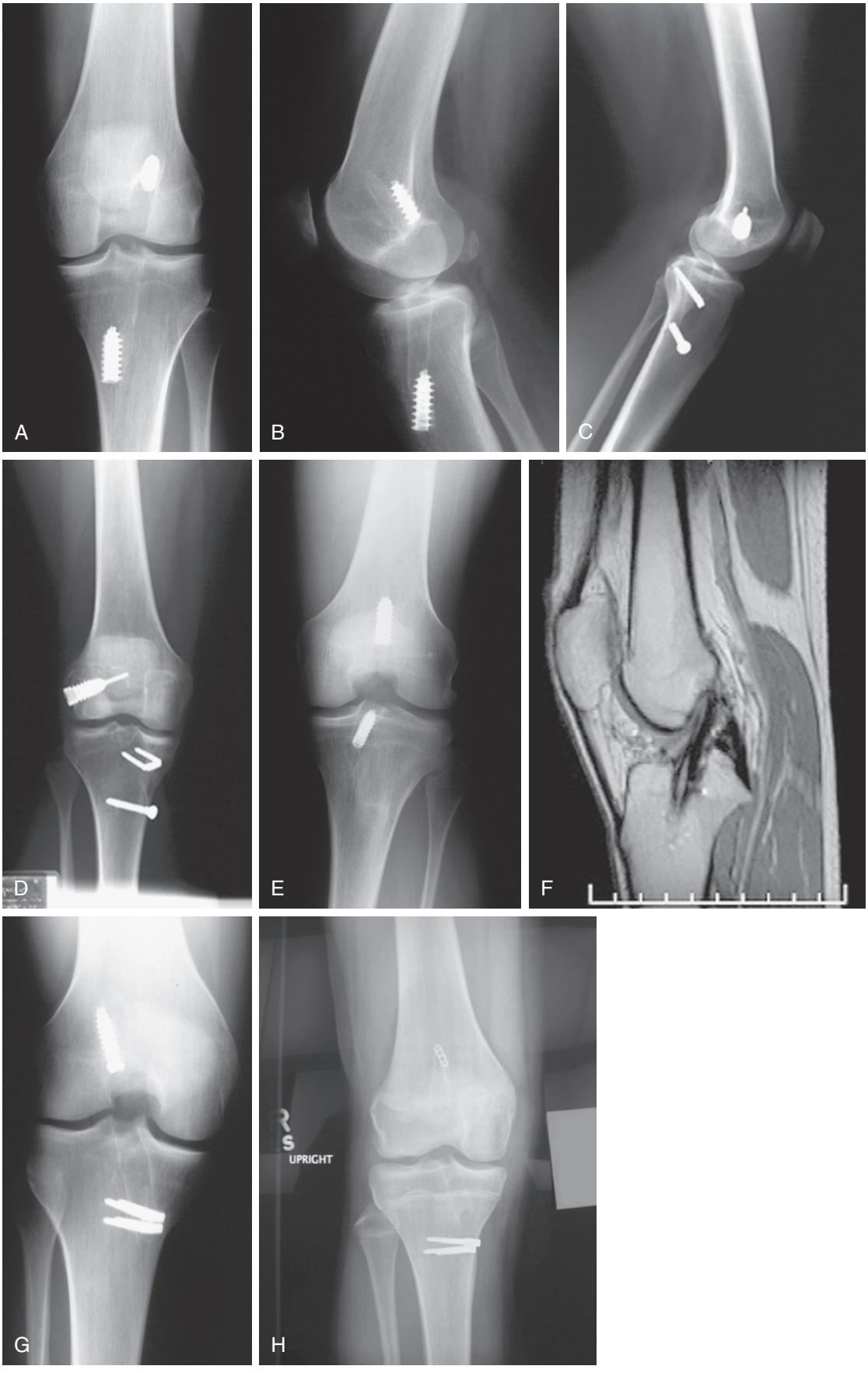


FIG 8-4 Patients who presented to our center for anterior cruciate ligament (ACL) revision with a vertical ACL graft, easily detected on anteroposterior and lateral radiographs and magnetic resonance imaging. The femoral graft location is primarily on the notch roof. In our experience, this vertical graft orientation is the primary cause for ACL failure.

TABLE 8-2 Rules to Follow for Bone Grafting Tibial and Femoral Tunnels in ACL Revision Surgery

1. The goal of bone grafting is to restore good-quality bone for a subsequent staged ACL revision reconstruction. The rule is to never accept a compromised tunnel caused by either malposition or enlargement.
2. In rare instances, a bone graft or interference screw may be used at the time of ACL revision to slightly adjust a graft tunnel; however, the surgeon must ensure that the remaining tunnel is in the correct position and not dilated because this would interfere with good bone healing and graft incorporation. In most ACL revision knees, and in particular, those in which an allograft was previously used, the tunnels are dilated throughout their length and bone grafting of the entire tunnel is required to restore adequate bone quality for the staged ACL revision (see Fig. 8-2). In short, it is not worth taking the chance that the ACL revision procedure will fail (thus requiring another ACL revision operation) because of marginal bone quality.
3. In terms of bone graft selection criteria, a dowel bone allograft that entirely fills the tunnel has the advantage of providing a complete substrate for creeping substitution and tunnel healing (see Fig. 8-5). Packing of cortical-cancellous allograft into a dilated tibial or femoral tunnel is a second option, although the senior author uses this technique only for pockets of bone loss adjacent to the dowel allograft. The freeze-dried dowel is among the safest preparation of all bone allografts owing to its processing and is advantageous because it avoids (in almost all cases) the necessity of harvesting an iliac crest autograft.
4. Approach the tibial tunnel first, remove all graft material, observe for any signs of infection, and send specimens for pathology. Enlarge the tunnel as required so that the diameter is fairly uniform throughout. Use a fully threaded drill and not an acorn drill, which will wander in the tunnel and not provide a symmetric diameter.
5. Follow the same steps described above for the femoral tunnel, which can be reamed in the same orientation as the primary ACL surgery (transtibial, anteromedial portal, or two-incision).
6. Use the arthroscope to examine the interior of the tunnels to be sure all material is removed. For sclerotic tunnel walls, the straight drill provides an abrasion effect to facilitate healing of allografts.
7. Select a dowel bone graft that is 1 mm smaller in diameter than the drill diameter (see Fig. 8-6, *A*). If there is any question that a snug fit will not be obtained, use a drill that is ½ mm larger than the dowel to prevent migration of the dowel out of the tunnel into the joint. Fill the femoral hole first.
8. A core reamer provides an ideal instrument for the bone dowel center hole to secure it for passage in the tunnel (see Fig. 8-6, *B*). Use only gentle pressure to impact the dowel into the tunnels because the freeze-dried allograft is brittle. Determine by arthroscopy that the bone dowel is flush with the tibial and femoral intraarticular tunnels.
9. Preserve tissue over the tibial tunnel on the initial exploration by subperiosteal exposure, which can be sutured to close the tibial tunnel external entrance and prevent graft extrusion.
10. Postoperative rehabilitation involves 50% weight bearing for 3 weeks to prevent undue activity that may cause migration of the bone graft. Then, full weight bearing is resumed, but no strenuous activities are allowed. Radiographs are taken postoperatively and then 6 weeks later to confirm that the allograft dowel is in the correct location. In our experience, at 20 weeks postoperatively, there is very good incorporation of the bone graft that will allow drilling of anatomically correct tunnels in the staged ACL revision procedure.

ACL, Anterior cruciate ligament.

Second, a freeze-dried dense cancellous allograft core that may be fashioned to fit snuggly into the remaining tunnel provides an ideal graft for bony incorporation (Figs. 8-5 and 8-6). Third, the posterior tibial RER, when deficient, may also be replaced with a core allograft. The goal is to prevent the revision graft in the newly placed tunnel from enlarging the tunnel posteriorly by a windshield-wiper effect against poor-quality bone. The same situation applies to an enlarged dilated femoral tunnel where the anterior shallow portion of the tunnel is grafted with a core allograft to obtain a good-quality bone construct. It is rare that an autogenous iliac crest autograft is required. However, in such instances, the outer iliac crest can be fashioned into a rectangular or circular dowel that is wedged into the enlarged tibial or femoral tunnel, providing a near-complete filling of the expanded tunnel and likelihood of the revision procedure being performed in 3 to 6 months. Strips of cortical cancellous bone are packed into any remaining defects. In major defects, cancellous allograft bone in the range of 5- to 8-mm fragments are packed between the cortical-cancellous strips. The bone grafting procedure is easily performed in an arthroscopically assisted manner, enlarging the portals as necessary to deliver the bone graft into the femoral tunnel. The tibial tunnel is packed in a retrograde manner, observing the final position of the graft from an appropriate arthroscopic portal. Bone graft substitutes are commercially available; however, their role instead of autogenous or allograft bone has not been established in clinical studies.

Anterior Cruciate Ligament Bone-Patellar Tendon-Bone Graft Anatomic Tibial and Femoral Technique

A single graft procedure is described in which the graft is located into the central anatomic tibial and femoral attachment locations; the reader is referred to Chapter 7. The graft placement for revision knees specifically avoids the proximal ACL femoral attachment site and the posterior ACL tibial attachment site to circumvent a vertical graft and allow the graft to resist rotational coupled motions in addition to anterior tibial translation (Fig. 8-7). This section describes using a single B-PT-B autograft or allograft procedure; other techniques are described in Chapter 7. Our clinical studies support the concept of a single graft technique for revision procedures. One exception is where a double-bundle procedure may be used in a knee in which a prior vertical ACL graft placement was performed, which limits anterior tibial translation, and a second coronal graft is added to provide added control.

Placement of Tibial Tunnel

The ideal central ACL tibial attachment location is directly adjacent and anterior to the posterior edge of the lateral meniscus anterior horn attachment. The ACL attachment can be easily mapped at surgery based on the anatomic reference maps provided, with the ACL center location based on the anterior-to-posterior and medial-to-lateral attachments. The anterior extent of the ACL attachment may be

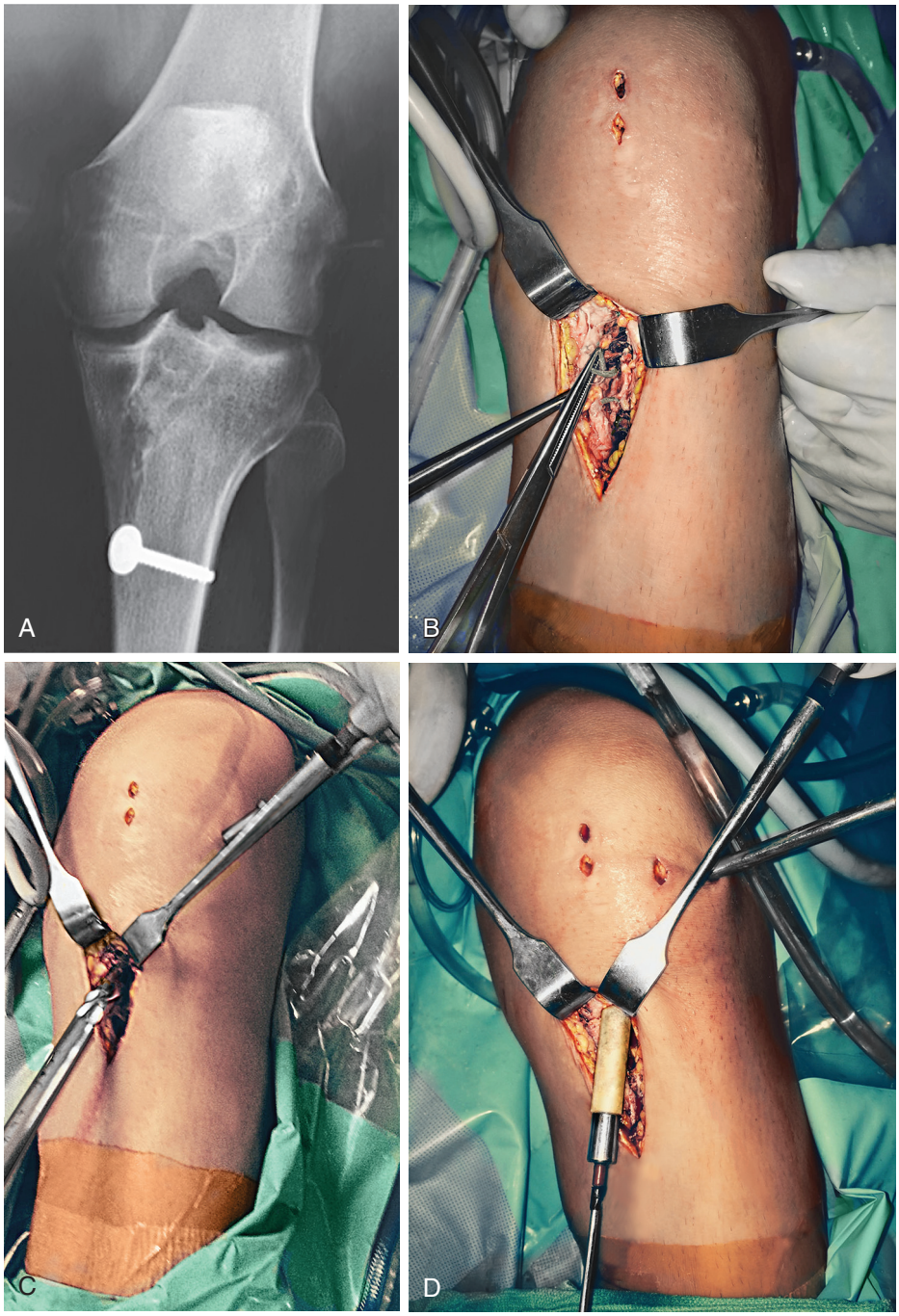


FIG 8-5 A 21-year-old soccer player with a failed anterior cruciate ligament (ACL) semitendinosus-gracilis allograft reconstruction and marked dilation and widening of the tibial and femoral tunnels **(A)** required a staged bone graft. **B,** Debridement of the tibial tunnel. **C,** Drilling of the tibial tunnel over a guide pin placed in the prior tunnel. Instead of an acorn drill, a regular drill was used with complete cutting threads throughout the shaft to provide a constant-diameter tunnel for the core bone graft to be inserted and fit snugly into the tunnel. The femoral tunnel was also debrided and a guide pin placed through the tibial tunnel for a similar drilling procedure. The majority of these cases involve transtibial drilling techniques. If an accessory anteromedial portal is used for the femoral tunnel, then a similar technique is used to bone graft the femoral tunnel. **D,** Insertion of a 12-mm freeze-dried core allograft under arthroscopic control, performed after the femoral tunnel has been grafted.

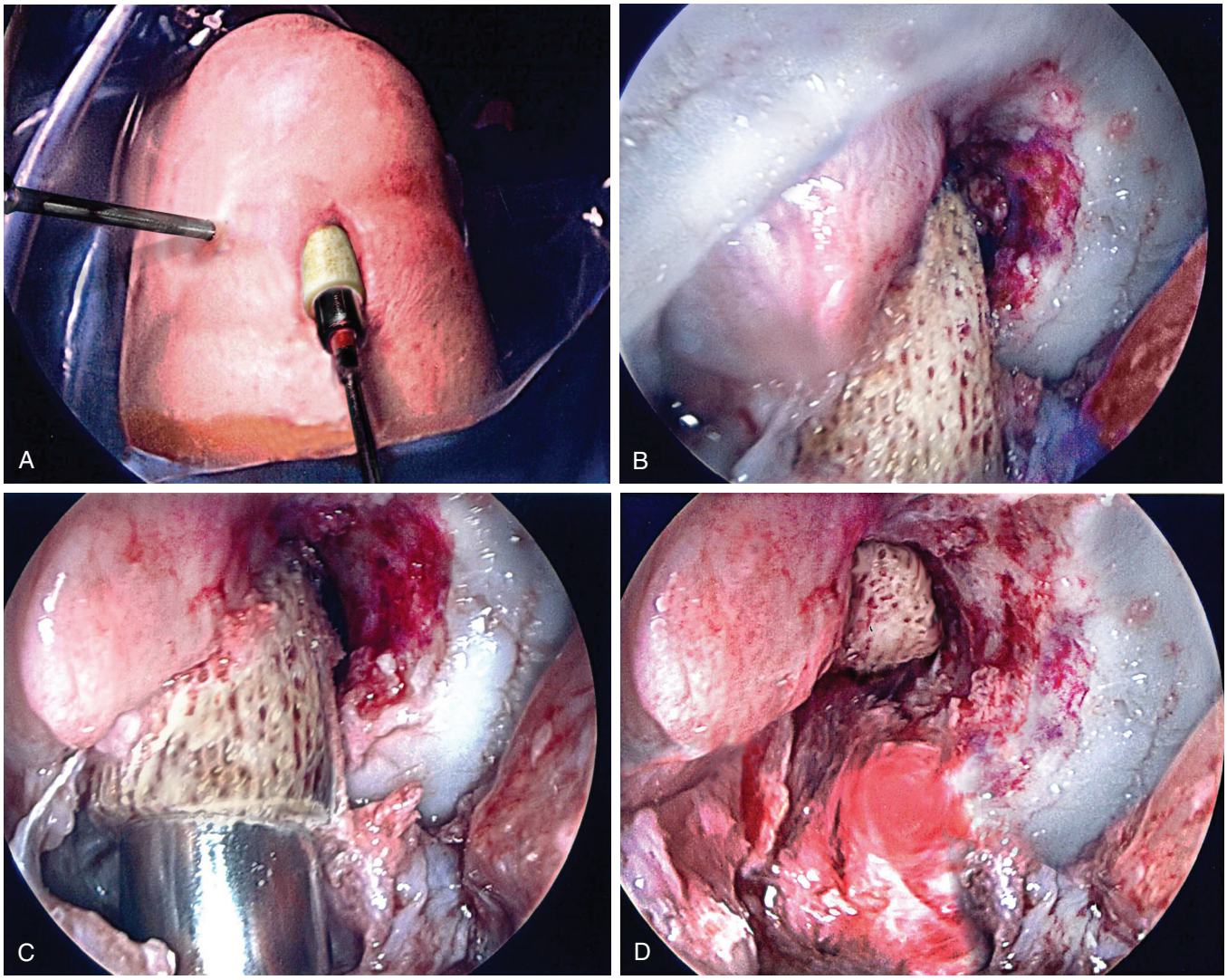


FIG 8-6 Demonstration of bone grafting with core (freeze-dried) allograft of a large vertical femoral tunnel for staged anterior cruciate ligament (ACL) revision reconstruction. First, the tibial and femoral tunnels are debrided and drilled to a constant diameter. **A,** Insertion of core bone graft through existing tibial tunnel. **B,** Careful technique is used as the bone graft enters the femoral tunnel under arthroscopic control. **C,** Impaction of the femoral bone graft into the tunnel. **D,** Final appearance of bone grafted femoral tunnel.

obscured by soft tissues, and the RER or posterior interspinous ridge of the PCL fossa is an important landmark. The center of the ACL will be 16 to 20 mm anterior to the RER or interspinous ridge. The guide pin is placed eccentric and 2 to 3 mm anterior and medial to the true ACL center as the ACL graft displaces to the posterior and medial aspects of the tibial tunnel.[13] This eccentric tunnel places the majority of the graft within the ideal central tibial attachment.

It is important to determine the graft length of the autograft or allograft to ensure a mismatch does not occur between intraarticular length of the tunnel and the length of the graft. The most common problem is with a patella alta and a B-PT-B length greater than 100 mm. The length of the patellar tendon is determined on preoperative lateral radiographs. The normal patellar length based on the Linclau technique[56] (patellar cartilage length to anterior vertical tibial prominence; see Chapter 38) is a 1:1 ratio with the patellar tendon in the 35- to 45-mm range. The intraarticular ACL length is measured on the lateral MRI, and this length is matched with an autograft or allograft. It is possible to accommodate a shorter length patellar tendon by adjusting the proximity of the tibial tunnel. A patella alta with a tendon length greater than 50 mm is usable with the bone portion of the graft adjusted in the tibia and femoral tunnels. A two-incision technique allows adjustment of graft length by proximal advancement in the femoral tunnel and is ideal when there is graft mismatch caused by an excessively long patellar tendon. In rare instances, with a long B-PT-B graft, the tibial bone plug is rotated 180 degrees onto the tendon, sutured to the bone plug, and the tibial tunnel resized. The bone plug sutures are tied to a tibial post. With a graft length mismatch, we do not recommend removal of the bone plug to shorten overall graft length or multiple twisting of the graft.

The ideal tibial tunnel is placed in a coronal manner, at a 55- to 60-degree angle, allowing a tunnel length of 35 to 40 mm. The tunnel is usually 15 mm medial to the tibial tubercle and 10 mm distal to the most proximal point of the patellar tendon tibial tubercle insertion.

A core reamer is used to remove a tibial bone plug when a B-PT-B or QT-PB autograft is used to obtain a core of bone to fill the graft bone defects. As already described, the core reamer provides a more

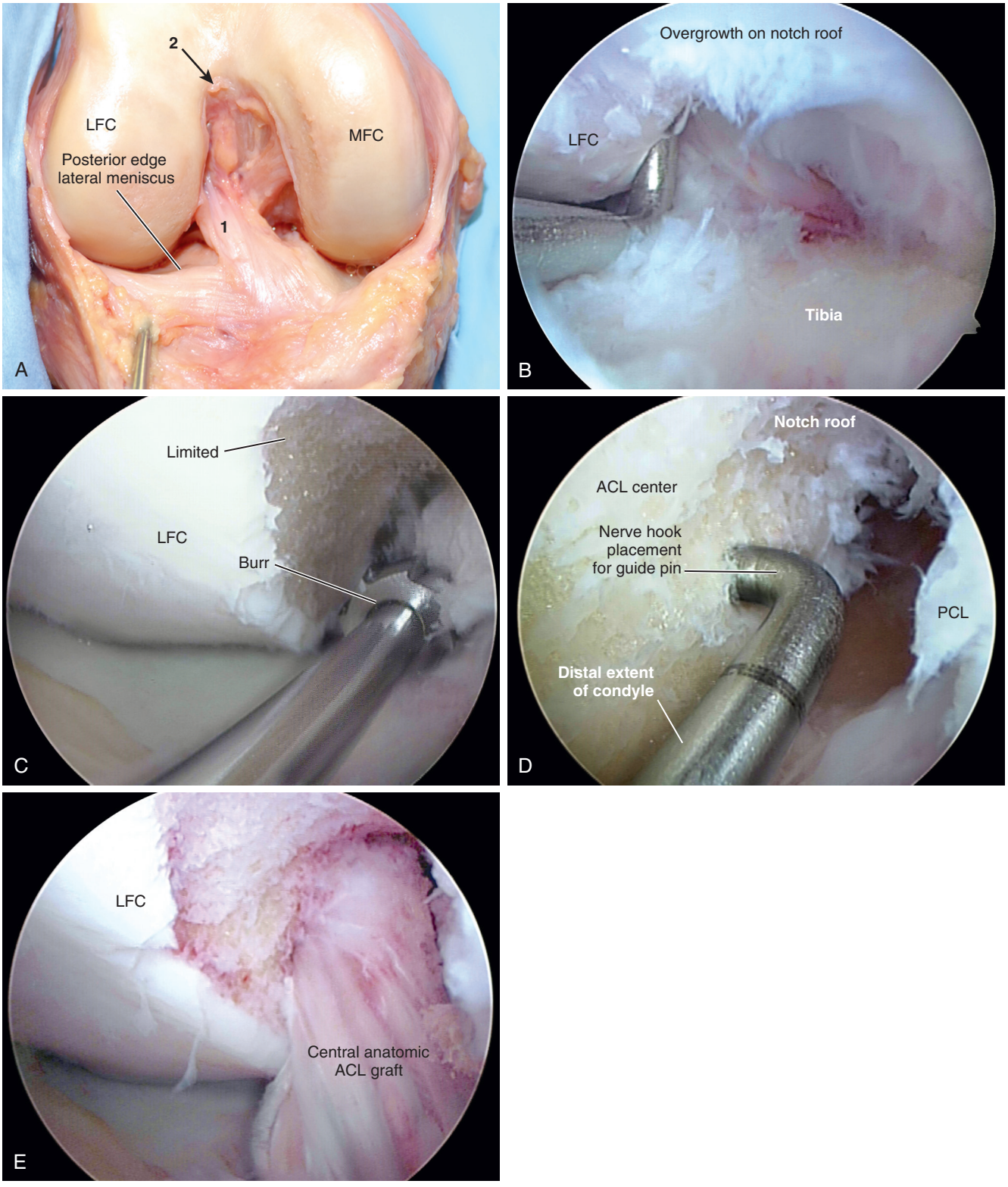


FIG 8-7 **A,** A normal femoral notch is shown, which is viewed at arthroscopy by using the anteromedial portal. *1* shows the normal space between the medial femoral condyle and the posterior cruciate ligament (PCL) which is occupied by the anterior cruciate ligament (ACL). *2* shows the normal anterior notch that should not impinge on the graft. **B,** Revision ACL with failed ACL graft shows overgrowth of the lateral notch and notch roof, requiring a limited notchplasty. **C,** The lateral notch wall is visualized entirely posteriorly to the articular cartilage of the femoral condyle. **D,** The ACL femoral attachment is mapped out and a central small hole is made for placement of the guide pin. The resident's ridge has been removed. The anterior notch region has not been disturbed. **E,** Final placement of a single-bundle graft within a central anatomic tibial and femoral placement that occupies over 75% of the attachment site. *LFC*, Lateral femoral condyle; *MFC*, medial femoral condyle.

CRITICAL POINTS Operative Techniques: ACL Bone-Patellar Tendon-Bone Graft Anatomic Tibial and Femoral Technique

Placement of Tibial Tunnel

- Define center ACL, usually 16 to 20 mm anterior to tibial RER or interspinous ridge.
- Mark ACL center, usually adjacent and always anterior to posterior edge of lateral meniscus anterior horn attachment.
- Place guide pin eccentric and 2 to 3 mm anterior and medial to true ACL center.
- Determine graft length of patellar tendon on MRI.
- Two-incision technique allows graft length to be adjusted by proximal advancement of femoral tunnel.
- Place tibial tunnel in coronal manner, 55- to 60-degree angle, tunnel length 35 to 40 mm.
- Begin tunnel adjacent to superficial MCL, 15 mm medial to tibial tubercle medial border, 10-mm distal proximal patellar tendon insertion.
- Use core reamer to obtain good-quality bone to fill bone defects.
- Drill tunnel, chamfer edges.

Placement of Femoral Tunnel

- Use either two-incision technique (open or flip drill) or anteromedial portal with knee hyperflexed 120 degrees.
- Two-incision technique: Drill tunnel retrograde or antegrade procedure.
- Perform femoral notchplasty to avoid graft impingement.
- Identify ACL attachment with knee in 20 to 30 degrees of flexion, scope in anteromedial portal.
- Place guide pin within central ACL attachment. Always preserve 3 to 4 mm of posterior back wall of the tunnel so that the graft is not placed too far posteriorly. A guide pin placed 8 mm from the posterior articular cartilage at the central ACL attachment will have a 4-mm posterior back wall for an 8-mm graft.
- Drill tunnel, chamfer edges.

Graft Tunnel Passage, Conditioning, and Fixation

- Pass graft gently in retrograde arthroscopically assisted.
- Bring graft proximally until bone is flush with tibia.
- Femoral position of graft at or just proximal to inside femoral tunnel.
- Fix femoral bone graft plug with interference screw.
- Condition graft, 44-N tension, flex knee 0 to 135 degrees, 40 cycles.
- Verify position arthroscopically, no impingement.
- Place knee in 20 degrees of flexion, reduce tension to 10 to 15 N.
- Place interference screw tibia. Use additional sutures tied over suture post if required.
- Perform Lachman test, ensure no overconstraint.
- For STG graft, femoral fixation: Post with sutures and absorbable interference screw if necessary. Tibial fixation: Interference screw plus suture post.

suitable graft material than drill reamings, and the bone defects are filled in an anatomic manner that results in the patient able to kneel on the tibial bone harvest site.

The tunnel is drilled to the desired graft diameter and the joint tunnel edges chamfered to prevent graft abrasion.

Placement of Femoral Tunnel

As previously described, either a two-incision technique, FlipCutter (Arthrex), or AM portal femoral tunnel placement (or flexible drill system) with knee hyperflexion technique is used. These techniques are illustrated in Chapter 7. Baer and associates[5] reported in a cadaver study that at least 110 degrees of knee flexion is required for femoral tunnel drilling through the AM portal (with nonflexible drills) to avoid potential injury to the peroneal nerve, the lateral condylar articular surface, the fibular collateral ligament (FCL), and the popliteus tendon. The use of the AM portal to place the femoral tunnel has the problem in some knees of difficulty with visualization at 100 to 120 degrees of flexion, the potential for the drill to damage the medial femoral condyle, and a shorter femoral socket, which may be a problem with a B-PT-B autograft. The flexible guide system is the senior author's preferred technique. As with any of the ACL techniques, surgeon experience is necessary to achieve a successful result.

In revision knees when the femoral tunnel is close to a prior tunnel, the two-incision procedure allows the guide pin to be more accurately placed and the tunnel divergence angle to be controlled more accurately than the endoscopic procedure. Importantly, the two-incision procedure carries a smaller risk of placing a less than ideal femoral tunnel, as there have been cases where endoscopic revision is performed and the tunnel breaks into the old tunnel, producing a more complex problem.

In the two-incision technique, a lateral incision 2 to 3 cm in length is made at the distal femoral metaphysis and posterior third of the ITB. The posterior third of the ITB is incised for 4 to 6 cm to allow exposure. The interval posterior to the vastus lateralis is entered and the muscle protected. An S retractor is placed beneath the vastus lateralis obliquus (VLO) to gently lift the muscle anteriorly, avoiding entering the proximal joint capsule. The proximal edge of the lateral femoral condyle is bluntly palpated with an instrument (over-the-top location), with the goal of locating the tunnel entrance just anterior and not distal to this point. A 15-mm periosteal incision is made and an elevator used to remove soft tissues from the site for the tunnel proximal entrance. An alternative procedure is to use a FlipDrill to create a femoral socket, as when the TightRope (Arthrex) technique is used (see Chapter 7).

In most revision knees, there is an overgrowth of cartilage and spur formation in the femoral notch, requiring a notchplasty to prevent ACL graft impingement. The notchplasty rules taught by the senior author since the mid-1980s are described in detail in Chapter 7. The ACL femoral attachment is mapped based on the bony landmarks already described. The location of the guide pin for an ACL central femoral tunnel is shown in Chapter 7. The guidewire is placed within the central ACL attachment, which is midway between the lateral notch roof and the distal articular cartilage edge (2:00 to 2:30 o'clock position), 8 mm from the posterior articular cartilage edge. Clock locations are actually an inaccurate description of the tunnel location.[22,23] With the central femoral tunnel, the posterior back wall is 3 to 4 mm thick and the graft occupies approximately two thirds to three fourths of the ACL footprint. Always preserve 3 to 4 mm of the posterior back wall of the tunnel so that the graft is not placed too far posteriorly. Grafts placed too far posteriorly will have increased tension with knee extension of the graft into the tibial tunnel and may potentially block full extension. A guide pin placed 8 mm from the posterior articular cartilage at the central ACL attachment will have a 4-mm posterior back wall for an 8-mm graft. A guide pin placed 10 mm from the posterior articular cartilage at the central ACL attachment would have a 5-mm posterior back wall for a 10-mm graft. One key to define the ACL attachment is to place the knee in 20 to 30 degrees of flexion viewed through the AM portal and map out the oval attachment and center point, measuring the distance to the posterior articular cartilage. The senior author prefers this mapping technique with partial knee flexion rather than at 90 degrees of flexion. Once the ideal center point is selected, the knee is flexed to the position desired. It is easier to mark out the ACL femoral attachment when it is viewed in a vertical plane

rather than the horizontal attachment plane with knee flexion. The tunnel is drilled to the appropriate diameter for a snug graft fit in the tunnel. The edges of the tunnel are chamfered to prevent graft abrasion.

Graft Tunnel Passage, Conditioning, and Fixation

The graft is passed in a retrograde manner either with a Beath pin in the endoscopic technique (placed through the AM portal) or in the two-incision technique with a 20-gauge looped wire passed from the femur to the tibial tunnel. The graft is gently lifted up through the tibia and guided into the femoral tunnels with a nerve hook. It is marked at the bone-tendon junction to adjust its length in each tunnel, and is brought proximally until the bone is flush with the tibia. In most knees, the femoral portion of the graft is at or just proximal to the inside femoral tunnel. The femoral bone graft plug is fixed with an interference screw of a metallic or absorbable type. Graft conditioning is performed by placing approximately 44 N tension on the distal graft sutures and flexing the knee from 0 to 135 degrees for 30 to 40 flexion-extension cycles. The arthroscope is placed to verify that the graft position is ideal and there is no impingement against the lateral femoral condyle or notch with full hyperextension. Appropriate notchplasty is performed when necessary. The knee is placed at 20 degrees of flexion, and the tension on the graft is reduced to approximately 10 to 15 N to avoid overconstraining AP tibial translation. A finger is placed on the anterior tibia to maintain the posterior gravity position of the tibia. An alternative procedure is to fixate the graft with a larger graft tension at 0 degree; however, the senior author believes there is more control of graft tension at the partially flexed position. An interference screw is placed. In cases where the interference screw fixation is not ideal or the screw resistance on placement is not acceptable, the sutures are tied over a suture post. The arthroscope is placed into the joint and final graft inspection performed. A Lachman test is performed and there should be total AP translation motion of 3 mm, indicating that the graft has not been over tightened. If the graft has a "bowstring," tight appearance with little to no anterior tibial translation on testing, the distal tensioning and fixation procedure is repeated with less tension placed on the graft.

Techniques Using Other Grafts

With all other grafts, the same procedure is used with the following exception. In the two-incision technique with a STG graft, a femoral post is always used with the sutures tied first at the femoral site about the post (35 mm, 4.0 mm cancellous self-cutting screw with washer). An absorbable interference screw is added if the graft tunnel interface is not tight. At the tibia, the interference screw is first placed, followed by the suture post fixation. Using the combined interference screw and suture post provides sufficient graft strength fixation for rehabilitation to proceed equal to the B-PT-B graft. The bone portion of the QT-PB is usually placed into the femoral tunnel; however, the graft can be reversed with the bone plug placed into the tibial tunnel and located appropriately to make up for an enlarged tibial tunnel that requires the bone portion of the graft.

A variety of techniques for femoral and tibial fixation are available, based on the preference of the surgeon and have been described in detail (see Chapter 7). The tibial fixation is usually the weakest and a suture post may be required. Interference screw fixation alone of an STG or soft tissue allograft is not recommended.

The postoperative rehabilitation program is described in Chapter 11. We do not administer preoperative or intraoperative intraarticular anesthetic injections because of the known adverse effects on articular cartilage.[39,48,87]

Alternative Procedures

Alternative approaches to ACL reconstruction, including use of the FlipCutter or flexible reamers and guide pins to drill the femoral tunnel, and the all-inside ACL Graft-Link technique that uses the FlipCutter and TightRope devices are described in detail in Chapter 7.

Iliotibial Band Extraarticular Reconstruction

Clinical studies (Noyes and Barber[70] and Ferretti and coworkers[27]) have shown significant improvements in the pivot shift test in chronic and revision knees with gross instability and loss of secondary lateral restraints that had a concomitant extraarticular reconstructive procedure for additional restraint of abnormal tibial internal rotation.[18] The goal is to reconstruct the posterior femorotibial ITB attachment that is an important restraint to abnormal internal tibial rotation. The lateral capsular fibers (referred to as the anterolateral ligament [ALL][12]) may be plicated at surgery. The ALL graft reconstructive procedure is discussed (see Anterolateral Ligament Reconstruction).

The primary indication for a lateral extraarticular reconstruction is a grade III pivot shift on knee examination, indicating loss of the ALL and ITB tibiofemoral osseous fibers (described in Chapter 3). The senior author has successfully used this procedure in grossly unstable revision knees in which an added lateral restraint resists abnormal lateral compartment anterior translation and reduces forces on the ACL graft reconstruction. The extraarticular reconstruction is also of benefit in certain situations where an allograft or STG autograft is used and viewed as a weaker ACL construct, whereby the extraarticular reconstruction provides an added measure of graft protection. In our study,[70] an ITB extraarticular reconstruction significantly reduced the rate of failure of ACL allograft reconstructions compared with a group of knees that did not have this concomitant procedure (3% and 16%, respectively; $P < .05$). It is important to note that involvement of the FCL along with the other lateral extraarticular structures indicates an insufficiency of the posterolateral complex and the operative procedure would involve a posterolateral reconstruction (see Chapter 17). Although extraarticular reconstructions may be indicated more frequently in chronic, grossly unstable revision knees, the roles of an ITB tendosis and ALL graft reconstruction have not

CRITICAL POINTS Operative Techniques: ITB Extraarticular Tenodesis

- Lateral incision 8 to 10 cm in length at the mid-lateral aspect of the knee extending from Gerdy's tubercle proximally.
- Strip of ITB incised, 12 mm wide, 18 to 20 cm long, tibial attachment kept intact.
- Identify femoral attachment ITB: deep fiber insertion to femur, confirm isometric femoral point for screw placement.
- Knee 30 degrees of flexion, neutral tibial rotation.
- Loop ITB strip around soft tissue washer and screw and back to Gerdy's tubercle. Fixate graft at femoral site.
- Suture ITB strip to itself under only mild tension, including posterior ITB fibers.
- Take knee through internal-external tibial rotation to ensure no constraint to normal rotation.
- Close ITB absorbable sutures.
- Examine medial patellar medial glide for normal mobility, do not close or overtension lateral iliopatellar tissues.

been clinically determined and are not yet recommended in acute, first-time ACL reconstructions.

A lateral incision 8 to 10 cm in length is made at the mid lateral aspect of the knee extending from Gerdy's tubercle to the lateral femoral condyle proximally. The skin incision is undermined by subcutaneous dissection to increase the skin mobility and shorten the incision for cosmetic purposes. A strip of ITB is incised proximal to distal from the posterior one third of the band, which is 12 mm wide and 18 to 20 cm long with the tibial attachment intact (Fig. 8-8).

The most isometric point for the femoral attachment of the graft, proximal and posterior to the lateral femoral condyle, is located (see Fig. 8-8, *D*) and tested by using a guide pin placed at this site. This location is usually just distal to the lateral intramuscular septum, posterior and proximal to the lateral epicondyle, and anterior to the gastrocnemius tubercle lateral attachment. The error is to place the ITB graft too anterior, which blocks knee flexion and constrains internal tibial rotation. The posterior placement allows the ITB graft to undergo increasing tension with knee extension. This area is curetted to remove soft tissues to allow for the ITB strip to be in contact with the overlying bone.

The extraarticular graft attachment points have also been reported by Kittl and associates.[52] These authors found that a graft that was attached proximal to the lateral femoral epicondyle and passed deep to the FCL also provided desirable graft behavior. In addition, a graft placed anterior to the lateral femoral epicondyle showed undesirable tension and lengthening with knee flexion. Unfortunately, this study reported graft length changes only with knee flexion and extension and the effect of internal-external tibial rotation was not assessed.

When tensioning the ITB graft, do not overconstrain the joint and block normal internal tibial rotation. After the ACL procedure is completed, the extraarticular tensioning and fixation are performed. The knee is placed at 30 degrees of flexion and neutral rotation. The ITB strip is fixated around a soft tissue washer (Fig. 8-9) and cancellous screw and brought back upon itself to Gerdy's tubercle. The screw is angulated anteriorly away from the ACL tunnel. The ITB graft is then sutured to itself with only slight tension. Sutures are also placed through the graft and posterior third of the remaining intact ITB. This produces a strong restraint to abnormal internal tibial translation and anterior tibial translation. The knee is taken through normal internal-external tibial rotation to ensure that there is no abnormal constraint to internal tibial rotation. The knee is flexed to 135 degrees; usually, increasing knee flexion will provide for increased tension in the graft. There is no true isometric point for the femoral attachment of the graft for flexion-extension and tibial rotation motions. It is probable that even with precautions taken to not overconstrain knee motion, regaining full knee flexion may be more difficult when the extraarticular procedure is performed.

The ITB is closed with absorbable sutures throughout the site where the graft was harvested. The patellar medial glide is examined at 30 degrees of knee flexion to ensure that closing the ITB does not limit the normal patellar mobility. The patella should have at least 10 mm of medial glide with a medially directed manual translation. If there is an abnormal restraint to medial patella mobility, a small lateral release is performed. The anterior fibers of the ITB, which comprise the lateral retinaculum adjacent to the patella, are incised the required length to relieve the undue tension on these soft tissues from closing the ITB defect, thereby avoiding a release of the vastus lateralis tendon.

In the 1980s when extraarticular procedures were used, it was common for the ITB graft to be routed underneath the FCL and then sutured to itself at Gerdy's tubercle (Cooker-Arnold procedure). However, this represents a nonanatomic placement of the ITB graft. In addition, there is concern that a soft tissue structure wrapped around the FCL could induce stretching of the FCL and allow for an increase in lateral joint opening. It is recommended to secure the ITB graft to the femoral attachment as discussed and to avoid looping the graft around the FCL.

Recent robotic studies have been conducted at our laboratory on the effect of the extraarticular reconstruction in limiting anterior tibial translation of the lateral tibiofemoral compartment (Fig. 8-10). The reconstruction had a statistically significant effect in reducing the magnitude of lateral compartment translation in the simulated pivot shift test (loading conditions, anterior translation 100 N, internal rotation 1 N-m, valgus 5 N-m).

In summary, our clinical studies have shown that the surgical technique of the ITB tenodesis has proven successful, particularly in grossly unstable chronic and revision knees with a grade III pivot shift.

Anterolateral Ligament Reconstruction

Sonnery-Cottet and associates[93] described a reconstructive procedure for a deficient ALL. The procedure uses two small incisions and is less invasive compared with the open ITB tenodesis procedure previously described. There are insufficient clinical data on the indications and outcomes of this technique; however, it would appear to fulfill similar conditions and indications that we have used for the open ITB tenodesis procedure. Sonnery-Cottet and associates[93] described further indications of a high level of sporting activity, participation in pivoting sports, chronic ACL rupture, an associated Segond fracture, and a lateral femoral notch sign on radiographs in patients with a grade I or II pivot shift. These authors reported short-term outcomes of a combined ALL and a single-bundle ACL reconstruction in 92 patients. The procedure failed in one knee and seven others sustained a contralateral ACL rupture. In 83 patients followed a mean of 32 ± 4 months postoperatively, 76 had a grade 0 and 7 had a grade I pivot shift. All returned to sports, although 24 did so at a lower level. The authors acknowledged that longer term and comparative clinical studies are required to determine if this combined reconstruction is warranted to improve the results of ACL reconstruction.

Dodds and associates[19] and Kennedy and coworkers[50] reported in anatomic studies that the ALL inserts just proximal and posterior to the lateral femoral epicondyle. The ALL has an oblique course to the anterolateral aspect of the proximal tibia, with attachments to the lateral meniscus, enveloping the inferior lateral geniculate artery and vein. It inserts onto the anterolateral tibia midway between Gerdy's tubercle and the tip of the fibular head, separate from the ITB.

A semitendinosus autograft is used for ALL reconstruction because the cross-sectional area, length, and ultimate loads provide sufficient anatomic and mechanical properties. The minimum graft length is 8 to 9 cm, and the graft is whipstitched 15 mm at one end with a zero or 2-0 FiberWire loop suture. The graft should be tapered at the whipstiched end to facilitate insertion of the graft into the femur. The description of the procedure is shown in Figure 8-11.

The senior author's suggestions and modifications of this technique are as follows. It is important that the femoral guide pin (see Fig. 8-11, *C*) is located 6 to 8 mm posterior and 4 mm proximal to the center of the femoral epicondyle to obtain a graft location that does not have abnormal tension with knee flexion. If the pin is anterior to this location, the graft will undergo large tensile loads with flexion that will risk graft pull-out with early knee motion postoperatively. The senior author determines the isometricity of the graft at this point, using a suture passed over the pin and placed at the

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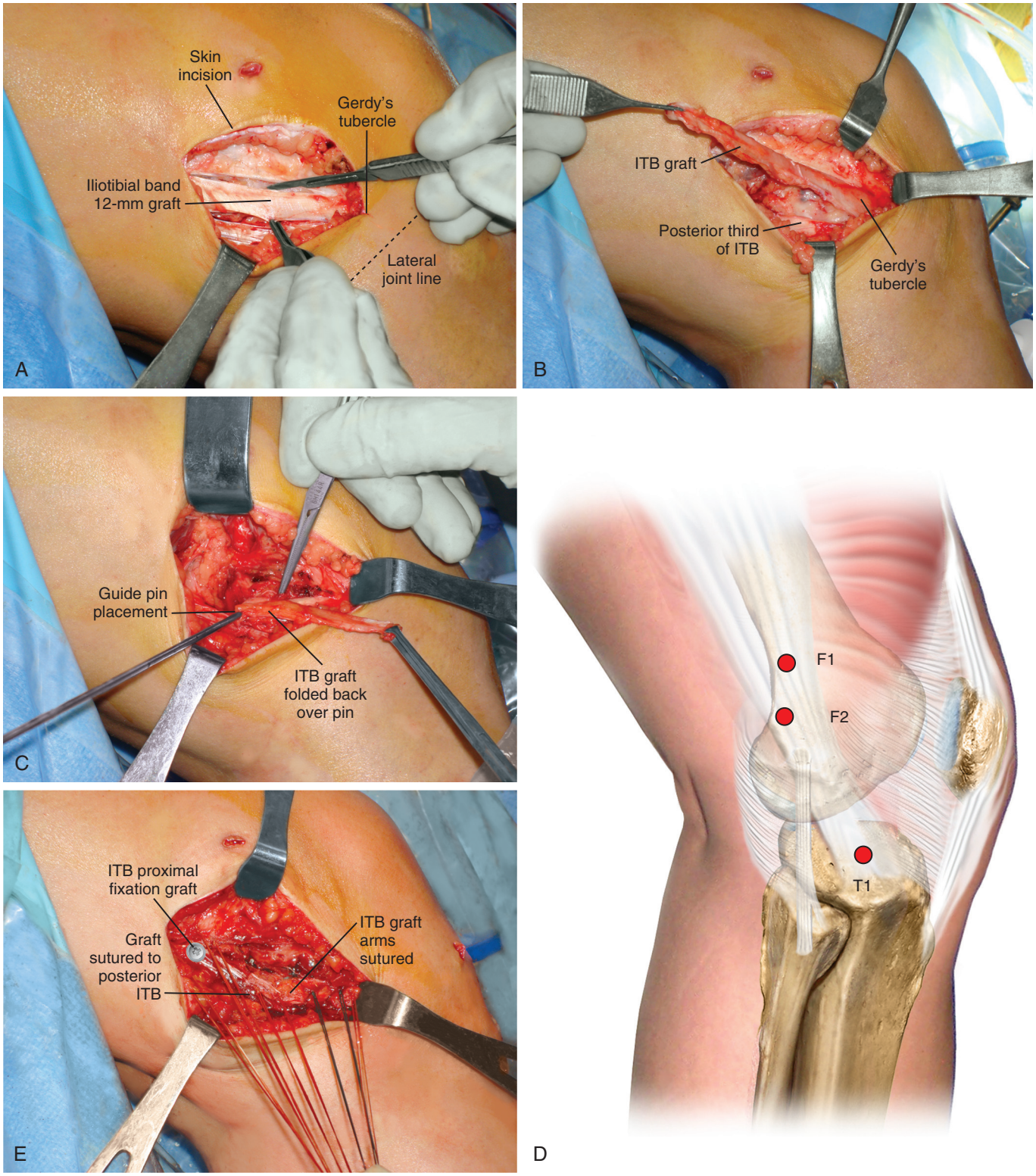


FIG 8-8 **A,** Cosmetic lateral incision is made just proximal to Gerdy's tubercle. A 10-mm strip along the posterior half of the iliotibial band (ITB) is harvested. The proximal skin flap is undermined to obtain a 20-mm long graft. **B,** The ITB graft (10 mm wide) is dissected distally to Gerdy's tubercle where the tibial attachment is left intact. **C,** The ITB graft is looped around a guide pin placed just distal to the lateral intermuscular and proximal to the fibular collateral ligament attachment. The knee is flexed from 0 to 135 degrees, neutral tibial rotation. **D,** The "isometric points" graft attachment sites for an extraarticular reconstruction as measured by Kurosawa et al. The points *T1-F1* provided the least change in length with knee flexion (maximum percentage of strain, 11.6% ± 3.0%). The points *T1-F2* offer a second choice, except that there is an increase in the percentage of strain with knee flexion compared with *T1-F1*. **E,** The graft is looped around a soft tissue screw and washer and both graft ends are sutured to each other and the remaining posterior ITB. This forms a strong femoral-tibial structure that both incorporates the graft and reproduces the normal posterior ITB femoral tibial attachments. The knee is in neutral tibial rotation and graft overtensioning is avoided.

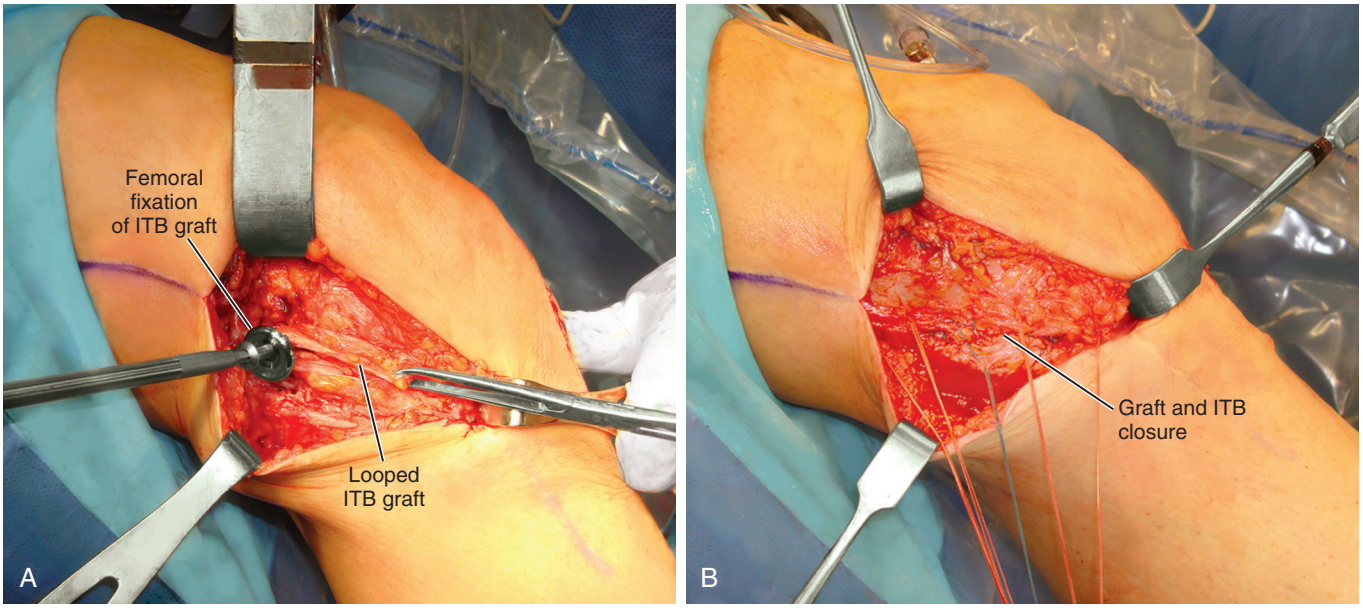


FIG 8-9 **A,** Extraarticular iliotibial band (ITB) graft is shown looped around a soft tissue screw and anchor in a second patient. **B,** Final closure of the overall remaining ITB to the looped ITB graft.

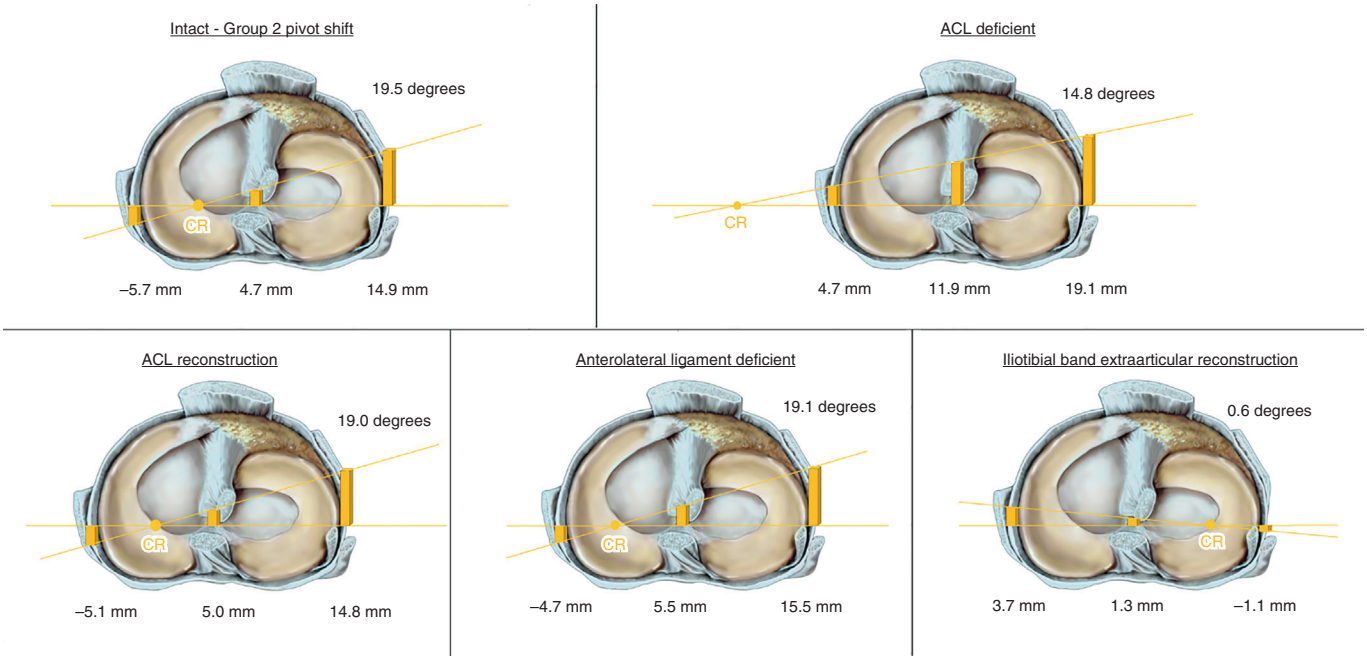


FIG 8-10 A representative right knee specimen in an in vitro robotic study showing compartment translations and tibial rotation under pivot shift loading conditions (100-N anterior, 1 N-m internal rotation, 7 N-m valgus). Note the difference in the intact and anterior cruciate ligament (ACL)-deficient states, which shows major increases in all three compartment translations. The ACL reconstruction with a bone-patellar tendon-bone graft placed in the center anatomic ACL tibial and femoral native sites restored compartment translations to the intact condition. Sectioning the anterolateral ligament produced no differences in compartment translation. The operative procedure of an iliotibial band reconstruction (see Fig. 8-9) does have a marked effect in limiting anterior translation of the lateral compartment. The indications for this procedure are discussed in greater detail in the text. *ALL*, Anterolateral ligament; *CR*, center of tibial rotation.

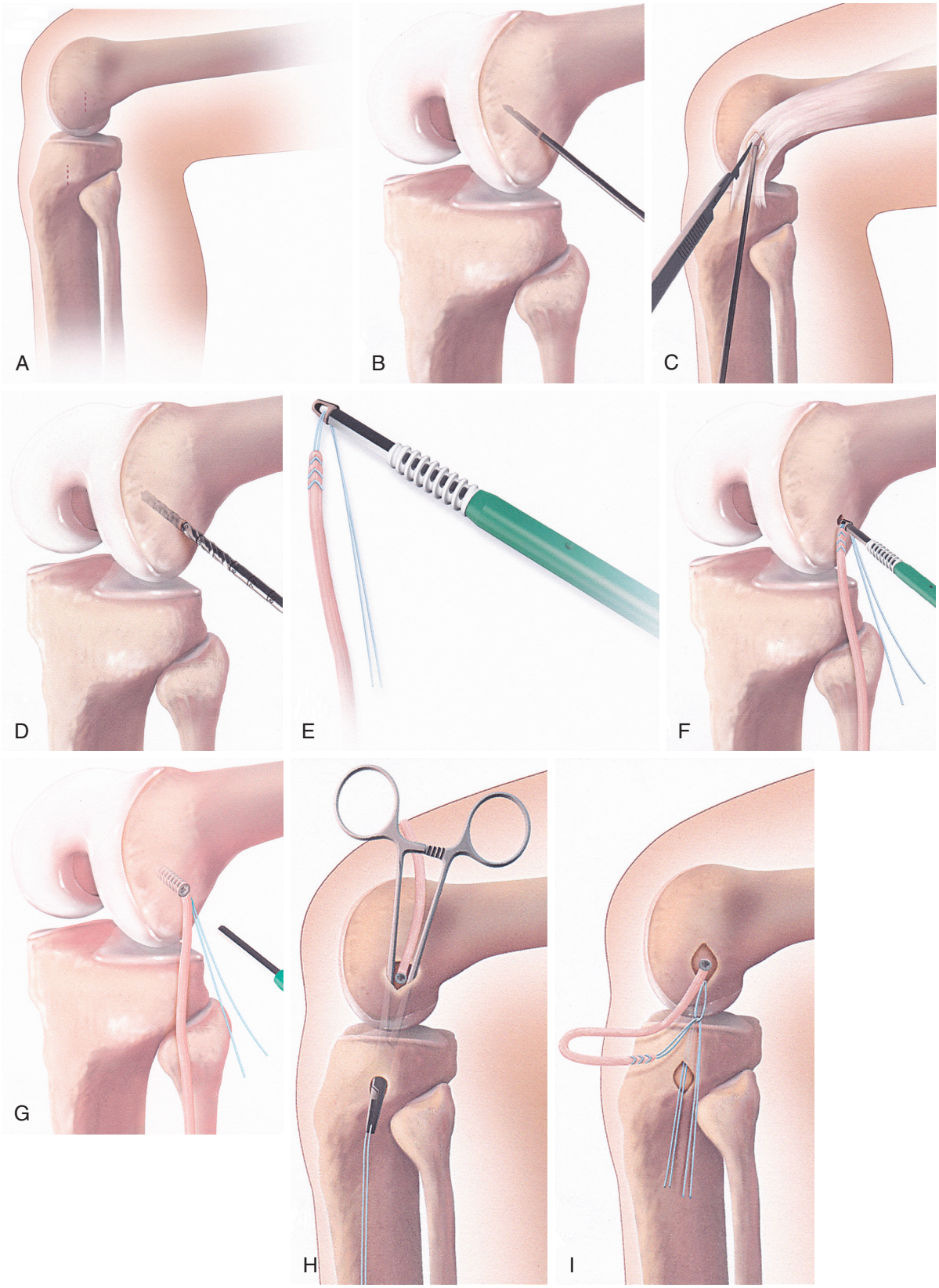


FIG 8-11 The anterolateral ligament (ALL) reconstruction, as described by Steven Claes, MD. **A,** The femoral stab incision is made just posterior to the lateral epicondyle and the tibial stab incision is made midway between Gerdy's tubercle and the center of the fibular head. **B** and **C,** On the femur, drill the 2.4-mm guide pin for the 4.75-mm SwiveLock (Arthrex) slightly proximal and approximately 6 to 8 mm posterior to the lateral epicondyle. Aim slightly anterior and proximal to avoid drilling into the femoral socket of the anterior cruciate ligament reconstruction. After the pin is drilled, split the iliotibial band (ITB) around it with a scalpel to facilitate the insertion of the SwiveLock. **D,** Overdrill the guide pin with a 4.5-mm drill to drill to a depth of 20 mm. **E,** Load the whipstitched sutures of the graft through the PEEK eyelet of the 4.75-mm SwiveLock. **F** and **G,** Insert the SwiveLock into the drilled hole. Ensure the eyelet is fully seated so that the threads of the SwiveLock anchor have started to touch the bone. Hold the paddle of the SwiveLock and turn the knob to insert the anchor. The SwiveLock sutures are removed. **H** to **J,** Use a curved hemostat to dissect underneath the ITB to create a plane from the femoral incision to the tibial incision. Place a passing suture from distal to proximal with the hemostat. Use the passing suture to pass the graft to the tibial side. *Continued*

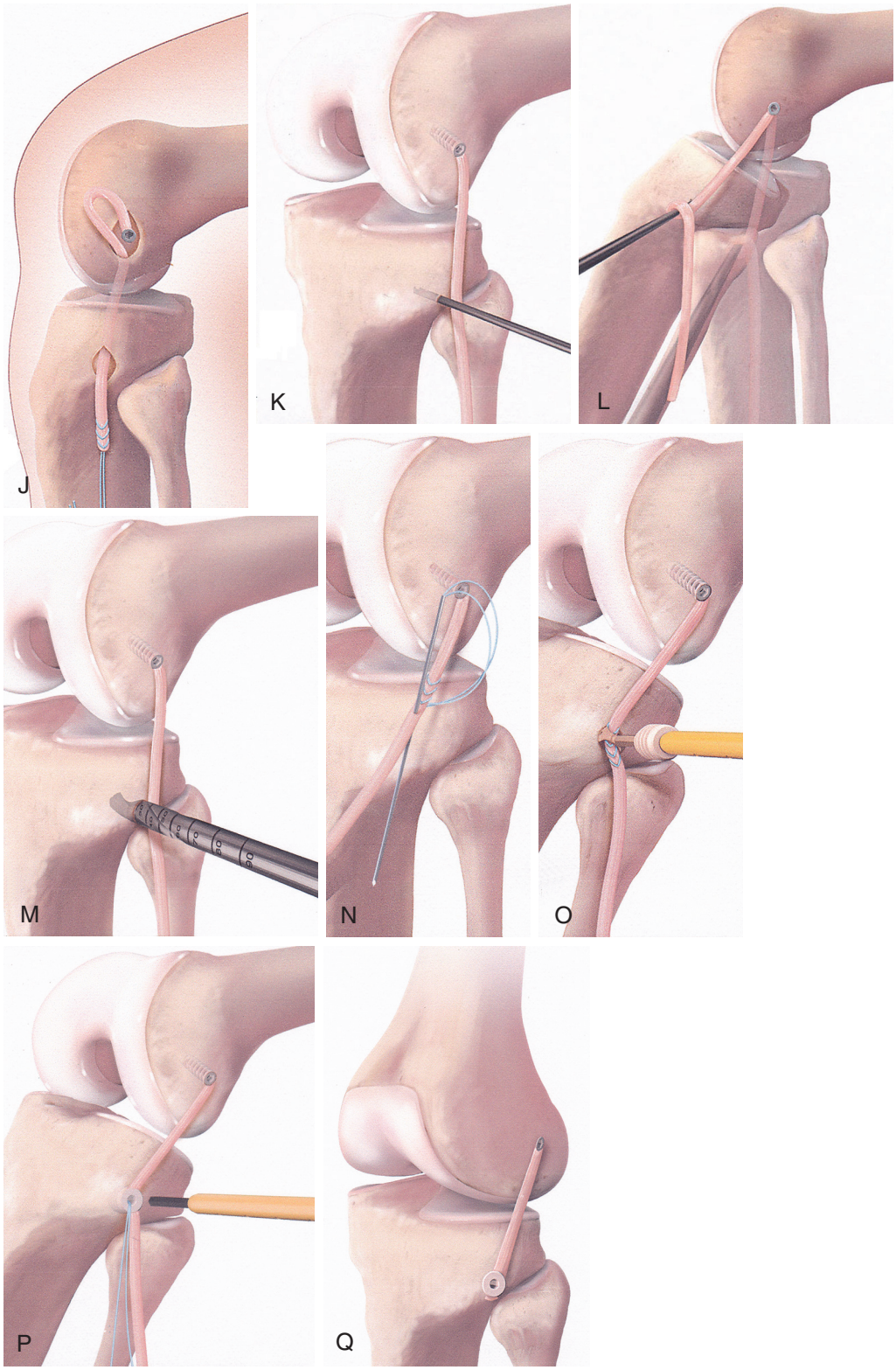


FIG 8-11, cont'd **K,** Drill a 2.4-mm guide pin 22 mm posterior to Gerdy's tubercle and 10 mm distal to the joint line. This should also be the approximate midpoint between Gerdy's tubercle and the center of the fibular head. **L,** Test the isometry of the graft by wrapping it around the pin and moving the leg through the range of motion. The graft should be isometric between 30 and 90 degrees of flexion. The graft should become slightly looser as the knee reaches full extension. **M,** Overdrill the guide pin with a 7-mm cannulated drill to a depth of 20 mm. **N,** Hold the graft to the drilled hole and mark it at that location. Whipstitch the graft distally from the mark, using a No. 2 FiberLoop. This will allow the whipstitches to enter the drilled hole with the SwiveLock and increase the pull-out strength of the graft. **O,** Place the 7-mm forked Tenodesis SwiveLock over the graft. Push the forked end into the tunnel and adjust the tension by pulling on the graft. It is important not to overconstrain the ALL. **P,** Fix the anchor with the knee in 60 degrees of flexion and neutral rotation. Once the anchor is in place, remove the sutures. Cut the end of the graft exiting the tibial socket. **Q,** Final appearance of the ALL reconstruction. (Courtesy Arthrex, Inc., Naples, Florida.)

selected tibial insertion point shown in Figure 8-11, *L*. This allows the femoral graft fixation site to be relocated if necessary. In select knees where there is osteopenia from disuse, or in revision knees, a larger diameter SwiveLock (Arthrex; 8 mm) may be required for adequate fixation. The drill would accordingly be larger in size as required. A modification of the tibial preparation and fixation may be required in osteopenic knees in which the sutures are placed in a transtibial beef pin that allows tensioning of the graft, along using a fully threaded interference screw. The senior author tensions the graft under very low loads (approximately 8-10 N) at 60 degrees of knee flexion and neutral tibial rotation. The knee is taken through a range of motion from 0 to 120 degrees at surgery with neutral rotation under very low tension. Accordingly, the graft will be under increased tension with internal rotation and under no tension with external tibial rotation.

OUR ANTERIOR CRUCIATE LIGAMENT REVISION CLINICAL STUDIES

We conducted three prospective studies on ACL revision reconstruction to determine the causes of failure of the previous operations and effects of revision graft type, concurrent ligament reconstructive procedures, and joint damage on patient outcome.[74,75,77] A total of 145 patients were entered into these investigations, of whom 141 (97%) were followed with formal research visits at our center 2 to 7 years postoperatively. In all patients, the grafts were placed within the ACL anatomic footprint of the femur and the anterior-central portion of the ACL tibial footprint. Patient outcome was assessed using the CKRS and KT-2000 testing. A fourth investigation was conducted to determine the causes of ACL reconstruction failure in a large cohort of patients who presented to our center for consideration of a revision procedure.[61]

Anterior Cruciate Ligament Revision Using Quadriceps Tendon-Patellar Bone Autografts

In 2006, we reported the results of a prospective study of 22 consecutive patients who received a QT-PB autograft ACL revision reconstruction.[75] Twenty-one patients (95% follow-up) were followed for a mean of 4.1 years (range, 2.1 to 6.9 years) postoperatively. Sixty operative procedures had been done before the revision operation, including 32 ACL procedures. Six PL procedures had been done in five knees, of all but one of which had failed. An HTO was done in four knees at our center and in one knee elsewhere a mean of 4.1 years (range, 4 months to 13 years) before the revision. Concomitant operative procedures were done in 15 knees, including a PL reconstructive procedure in five knees and a HTO in two knees. Ten knees had abnormal articular cartilage surfaces.

Multiple factors were involved in the failure of the prior ACL reconstructions, including misplaced femoral or tibial tunnels, vertical ACL graft placement, untreated or failed PL procedures, and untreated varus osseous malalignment. An endoscopic revision procedure was performed in seven knees (Fig. 8-12) and a two-incision in 14 knees (Fig. 8-13).

Statistically significant improvements were found in the mean scores for pain, swelling, and giving-way (Table 8-3; $P < .0001$). Before the revision, 14 knees (67%) had moderate or severe pain with activities of daily living, whereas only 4 knees (19%) had such pain at follow-up. The mean score of the patient rating of the overall knee condition improved from 2.7 ± 1.3 points before the operation to 6.2 ± 2.6 points (scale of 1 to 10 points) at follow-up ($P < .0001$). Eighteen patients (86%) rated the condition of the knee as improved and three rated the condition as the same as before the operation (Fig. 8-14).

CRITICAL POINTS Our Anterior Cruciate Ligament Revision Clinical Studies

Quadriceps Tendon-Patellar Bone Autograft

- 21 patients (95% follow-up) followed mean 4.1 years (range, 2.1-6.9 years) postoperatively.
- 32 prior failed ACL procedures.
- Significant improvements in mean scores for pain, swelling, giving-way.
- 86% rated condition of the knee as improved.
- 81% grafts rated as normal or nearly normal, 19% as failed.
- QT-PB autograft viable for ACL revision

B-PT-B Autograft

- 54 patients (96% follow-up) followed for a mean of 2.8 years (range, 2-6.2 years) postoperatively.
- 60 prior failed ACL procedures
- Significant improvements in mean scores for pain, functions of activities of daily living and sports, patient perception of the overall knee condition, overall rating score.
- 94% patients rated condition of the knee as improved.
- 76% grafts rated normal or nearly normal, 24% failed.
- Graft failure rates: ACL revision reconstruction only: 16%; HTO before revision: 22%; additional ligament procedures: 43%.
- Significant effect of articular cartilage damage on functional scores, symptoms.

B-PT-B Allograft

- 65 patients (98% follow-up) followed up for a mean of 3.5 years (range, 2-6.5 years) postoperatively.
- Significant improvements in mean scores for pain, functions of activities of daily living and sports, overall rating score.
- 64% grafts rated normal or nearly normal, 36% failed.
- Allografts reserved for knees that do not have suitable autogenous tissues or require multiple grafts.
- Consider using ITB extraarticular procedure with allograft to improve success rate.

Prevalence of Nonanatomic Graft Placement in Failed ACL Reconstructions

- 122 consecutive patients referred after failed ACL reconstruction.
- Patients evaluated mean 8.3 years after failed procedure.
- Nonanatomic graft placement in 107 knees (83%).
- Transtibial technique used in 83%.
- 92 underwent revision; 73 required two-incision technique, 18 staged bone grafting.

The mean AP displacement value decreased from 8.4 ± 3.1 mm (range, 4.0-15.0 mm) preoperatively to 2.1 ± 2.2 mm (range, −4.0 to +5.0 mm) at follow-up ($P < .001$). At follow-up, 8 of 21 grafts were rated as normal; 9 as nearly normal; and 4 as failed (Table 8-4).

This study contains too small of a cohort to form definitive conclusions; however, these published data and our subsequent experience in other revision knees demonstrate that the QT-PB graft is an important autograft to consider for this operation. The QT-PB is a large cross-sectional area graft, nearly double that of a B-PT-B, and provides the surgeon with the ability to use the bone portion of the graft at either the femoral or the tibial site, based on any perceived deficiency in bone at one of these sites. However, the overall results of these revision knees were inferior to those previously reported by us for primary ACL reconstructions.[72] Ninety percent of the knees had one or

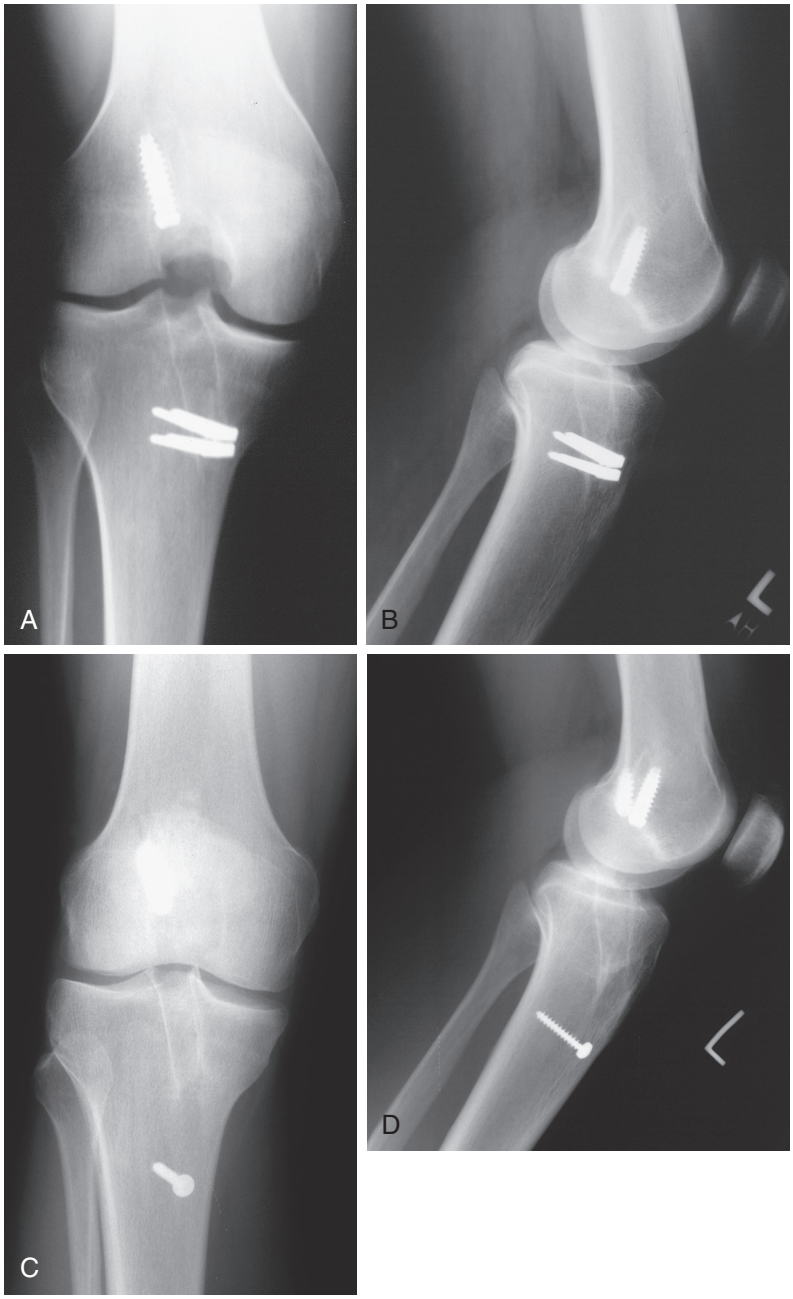


FIG 8-12 Anteroposterior (AP) **(A)** and lateral **(B)** radiographs of the right knee of an 18-year-old woman 26 months after a failed anterior cruciate ligament (ACL) Achilles tendon allograft reconstruction. Note the anterior orientation of the femoral tunnel. AP **(C)** and lateral **(D)** radiographs 50 months postoperatively demonstrate the quadriceps tendon-patellar bone (QT-PB) autograft revision. The femoral cancellous screw was retained from the primary reconstruction to avoid creating an excessively large femoral tunnel. The placement of the new femoral tunnel was accomplished using an endoscopic technique. (From Noyes FR, Barber-Westin S.D. Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. *Am J Sports Med.* 2006;34:553-564.)

more compounding problems, including articular cartilage damage, meniscectomy, varus malalignment, and additional ligamentous injuries, which affected the outcome.

Anterior Cruciate Ligament Revision Using Bone-Patellar Tendon-Bone Autografts

We reported a prospective consecutive study of 57 ACL revision reconstruction using a B-PT-B autograft.[74] Fifty-five knees (96% follow-up) were followed a mean of 2.8 years (range, 2-6.2 years) postoperatively. A total of 218 prior operative procedures had been done in these knees, including 60 ACL procedures. A two-incision technique was used for the revision procedure in 35 knees (64%). Concurrent operative procedures were common and included reconstructive procedures for PL or medial collateral ligament deficiency in 17 knees (31%). During the revision operation, 28 knees (57%) had noteworthy damage of the articular cartilage.

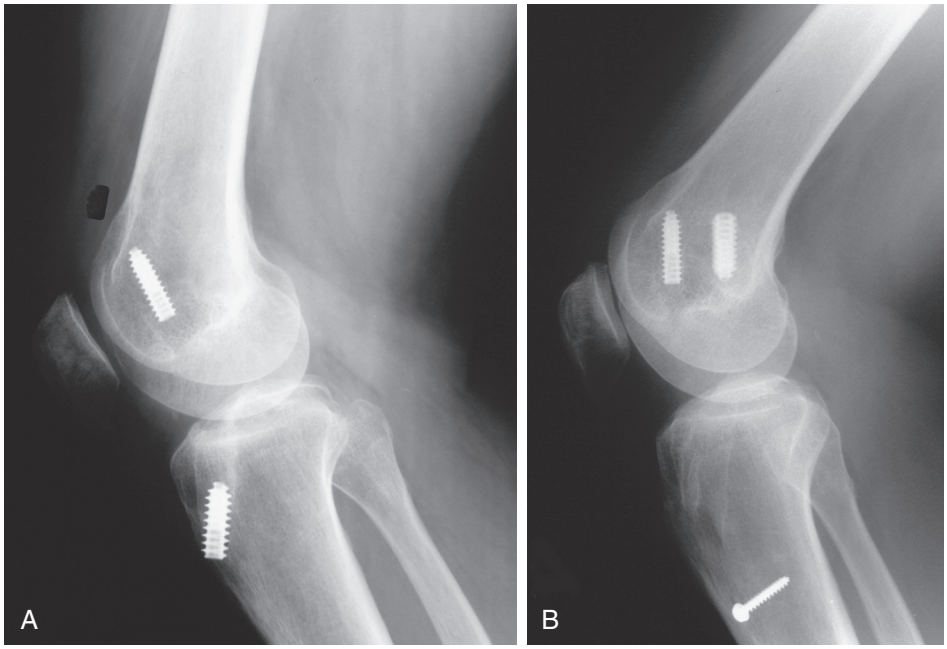


FIG 8-13 A, Lateral radiographs of the right knee of a 46-year-old man 12 months after a failed anterior cruciate ligament (ACL) reconstruction with a patellar tendon autograft demonstrates anterior placement of the femoral and tibial tunnels. **B,** Lateral radiograph 18 months after the quadriceps tendon-patellar bone autograft revision that reestablished the correct anatomic placement of the tibial and femoral attachment sites. The patellar bone was placed in the femoral tunnel, and the quadriceps tendon was placed in a new tibial tunnel located in the central ACL attachment position. The femoral screw from the primary reconstruction was deeply placed and therefore not removed. (From Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. *Am J Sports Med.* 2006;34:553-564.)

TABLE 8-3 Symptoms and Functional Limitations Before and After QT-PB ACL Revision Reconstruction

Factor	Point Scale	Preoperative (Mean ± SD)	Follow-up (Mean ± SD)	*P* Value
Pain	0-10	2.8 ± 1.5	5.6 ± 2.7	<.001
Swelling	0-10	2.9 ± 1.4	6.1 ± 2.7	<.001
Giving-way	0-10	4.3 ± 2.6	7.3 ± 2.9	<.001
Patient perception	1-10	2.7 ± 1.3	6.2 ± 2.6	<.001
Walking	0-40	30 ± 10	34 ± 10	.02
Stair climbing	0-40	24 ± 14	31 ± 12	.002
Squatting	0-40	9 ± 15	19 ± 16	.05
Running	40-100	49 ± 14	70 ± 24	.003
Jumping	40-100	46 ± 11	59 ± 22	.007
Twisting	40-100	48 ± 13	65 ± 24	.003

ACL, Anterior cruciate ligament; *QT-PB,* quadriceps tendon-patellar bone.

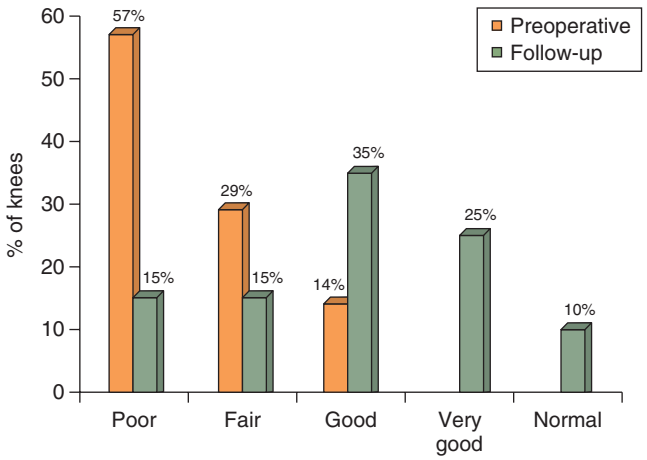


FIG 8-14 The distribution of patient ratings of the knee condition before surgery and at follow-up. The difference among evaluations was significant ($P < .0001$). (From Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. *Am J Sports Med.* 2006;34:553-564.)

There were significant improvements in pain (Fig. 8-15; $P < .0001$), functions of activities of daily living ($P < .05$) and sports ($P < .001$), the patient perception of the overall knee condition ($P = .0001$), and the overall rating score ($P = .0001$). Preoperatively, 19 patients (39%) participated in sports activities, all with symptoms or limitations. At follow-up, 30 patients (61%) had returned to athletics without symptoms. Seven other patients were participating in sporting activities with symptoms against our advice.

The mean preoperative patient perception score of 4.2 ± 2.8 points significantly improved to 6.4 ± 2.0 points at follow-up ($P = .0001$). Forty-six knees (94%) indicated that the overall condition had improved by circling at least one point higher on the scale at follow-up compared with the preoperative questionnaire (Fig. 8-16). Two patients

TABLE 8-4 Summary of Our Revision ACL Reconstruction Clinical Studies: Knee Arthrometer Data and Final Failure Rates

Study	No. Patients, Follow-up	Graft Type, Allograft, Sterilization	Preoperative Total AP Displacement (mm) (Mean, Range)	Follow-up, Total AP Displacement (mm) (Mean, Range)	FOLLOW-UP TOTAL AP DISPLACEMENT CATEGORIES (I-N) (%)			Final Failure Rate* (%)
					<3 mm	3-5 mm	>5 mm	
Noyes & Barber-Westin[75] (2006)	21, 2-7 yr	QT-PB, autograft	8.4 ± 3.1 (4.0-15.0)	2.1 ± 2.2 (–4.0 to 5.0)	42	37	21	19
Noyes & Barber-Westin[74] (2001)	55, 2-6 yr	B-PT-B autograft, all combined	11.2 ± 3.9 (5.0-21.0)	2.2 ± 4.9 (–6.0 to 15.5)	64	15	21	24
		Revision only, no other operative procedures (32)	10.9 ± 4.3 (5.0-21.0)	0.7 ± 3.6 (–3.5 to 10.5)	82	7	11	16
		Revision staged after HTO (9)	10.7 ± 2.1 (8.5-13.0)	4.8 ± 5.9 (–1.0 to 15.0)	33	33	33	22
		Revision and other ligament operative procedures (17)	11.9 ± 4.0 (6.0-18.5)	4.1 ± 5.8 (–6.0 to 15.5)	38	23	38	35
Noyes & Barber-Westin[77] (1994)	66, 2-6.5 yr	B-PT-B allograft, irradiated (40)	9.3 ± 3.1 (5.5-19.0)	4.1 ± 4.7 (–4.0 to 17.5)	44	32	24	26
		Fresh-frozen (26)	9.1 ± 2.8 (5.5-15.0)	1.8 ± 3.2 (–3.0 to 5.0)	52	39	9	8

*Failed: >5-mm increase total AP displacement or grade II or III pivot shift.
ACL, Anterior cruciate ligament; *AP*, anteroposterior; *B-PT-B*, bone-patellar tendon-bone; *HTO*, high tibial osteotomy; *I-N*, involved knee-noninvolved knee; *QT-PB*, quadriceps tendon-patellar bone.

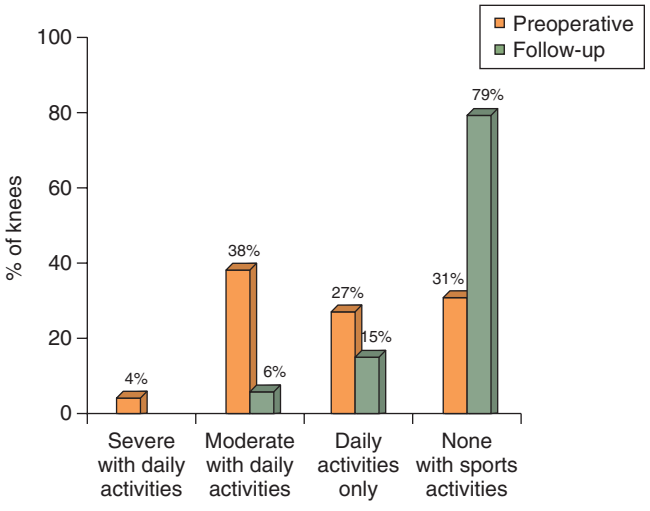


FIG 8-15 The preoperative and follow-up distribution of patient responses on the rating scale for pain. The improvement was significant (P = .0001). The scale shows the highest level of activity possible without the patient experiencing pain. (From Noyes FR, Barber-Westin SD. Revision anterior cruciate ligament surgery with use of bone-patellar tendon-bone autogenous grafts. *J Bone Joint Surg Am.* 2001;83:1131-1143.)

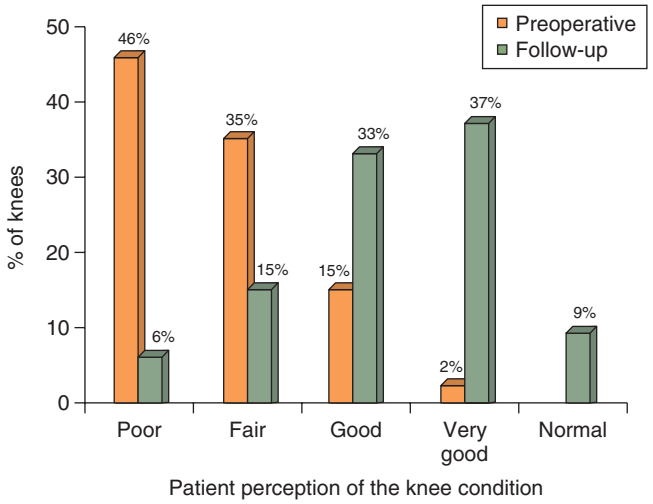


FIG 8-16 The preoperative and follow-up distribution of patient responses on the rating scale for perception of the overall knee condition. The improvement was significant (P = .0001). (From Noyes FR, Barber-Westin SD. Revision anterior cruciate ligament surgery with use of bone-patellar tendon-bone autogenous grafts. *J Bone Joint Surg Am.* 2001;83:1131-1143.)

rated the overall condition as the same, and one rated the knee condition as worse at follow-up.

AP displacements significantly decreased from a mean of 11.6 ± 3.9 mm preoperatively to a mean of 1.2 ± 4.0 mm at follow-up (P = .0001). At follow-up, 60% of the grafts were rated as normal, 16% as nearly normal, and 24% as failed.

The population was sorted according to concurrent operative procedures performed with the ACL revision reconstruction to determine the effect of these procedures on outcome (Table 8-5). In regard to graft failure, 5 of the 32 knees (16%) that had only the ACL revision reconstruction failed, 2 of the 9 knees (22%) that had an HTO before the revision procedure failed, and 6 of the 14 knees (43%) that had additional ligament procedures failed. There were statistically significant differences among the knees that had the revision reconstruction

TABLE 8-5 Effect of Additional Operative Procedures on Outcome of ACL B-PT-B Revision Reconstruction

	PAIN (POINTS)			PATIENT PERCEPTION (POINTS)			Graft Failure	OVERALL RATING SCORE (POINTS)		
Procedure	Preop	Follow-up	*P* Value	Preop	Follow-up	*P* Value	Rate (%)	Preop	Follow-up	*P* Value
Revision with no other major operative procedures ($n = 32$)	4.1 ± 1.7	5.7 ± 0.7	.0001	3.2 ± 1.6	7.1 ± 1.6	.0001	16	64 ± 10	64 ± 10	.0001
Revision staged after HTO ($n = 9$†)	2.9 ± 1.4*	4.9 ± 2.0	.05	2.0 ± 1.4	4.3 ± 1.9*	.03	22	53 ± 9*	81 ± 10*	.0004
Revision and other ligament procedure ($n = 17$†)	3.5 ± 1.7	4.7 ± 2.3	.05	3.2 ± 1.9	4.8 ± 2.2	.02	35*	56 ± 9*	84 ± 12*	.0001

*The value was significantly different from that in the subgroup with revision and no other major procedure ($P < .05$).
†Three knees had both a high tibial osteotomy and another ligament procedure.
ACL, Anterior cruciate ligament; *B-PT-B,* bone-patellar tendon-bone; *preop,* preoperative.

only and those that had HTO before the revision procedure. Patients who underwent HTO (usually indicating more advanced medial arthrosis) had poorer mean patient perception scores and overall rating scores at follow-up ($P < .05$).

There were no complications related to the graft harvest procedure. There was a statistically significant difference between the 31 knees (56%) that had abnormal articular cartilage surfaces and the knees with normal surfaces in the scores for twisting and turning activities and the ability to return to strenuous activities ($P < .05$). The study concluded that B-PT-B autograft knees had improved knee stability and avoided the added risk of infection and expense of the allograft.

Anterior Cruciate Ligament Revision Using Bone-Patellar Tendon-Bone Allografts

We conducted a prospective study on 66 consecutive patients who received a B-PT-B allograft ACL revision reconstruction, of whom 65 (98% follow-up) were followed an average of 3.5 years (range, 2-6.5 years) postoperatively.[77] Concomitant procedures were common and included reconstruction of the FCL (seven knees), advancement of the PL complex (11 knees), reconstruction of the MCL (four knees), and reconstruction of the PCL (two knees). Forty of the allografts had been sterilized with gamma irradiation (25,000 Gy) and 26 were fresh frozen.

At follow-up, significant improvements were found for pain, swelling, giving-way, walking, stair climbing, kneeling, running, jumping, and twisting/turning ($P < .0001$). Forty-two patients (65%) returned to mostly low-impact sports without problems.

Thirty-seven knees (56%) had noteworthy deterioration of the articular cartilage surfaces. At follow-up, significant differences were found between these knees and those with normal cartilage surfaces for the variables of pain (Fig. 8-17), stair climbing, kneeling, running, jumping, twisting/turning, sports activity level, and the overall rating score (Table 8-6).

The preoperative CKRS overall rating score for all 65 knees of 54 ± 10 points significantly improved to 77 ± 13 points at follow-up ($P < .0001$). All patients except one had an improvement in this score; the average increase was 23 ± 11 points.

At follow-up, 43% of the grafts were rated as normal; 21%, as nearly normal; and 36% failed. There appeared to be an effect of irradiation on the failure rate of this study, because 40 of the 66 allografts had undergone irradiation (2.5 mrad). The increased failure rate in allograft studies (excluding irradiation effects), the cost of allograft tissue, and risk of disease transmission (even though rare) led us to recommend in 1997[72] that autografts be used as the primary graft source for ACL revision reconstruction. Allografts are reserved for knees lacking suitable autogenous tissues or that required multiple ligament reconstructive procedures.

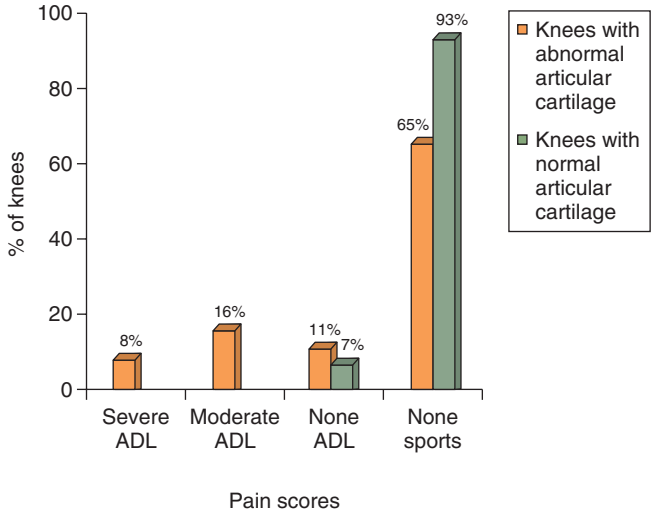


FIG 8-17 Comparison of the pain scores at the most recent follow-up evaluation among 28 knees with normal articular cartilage and 37 knees with abnormal articular cartilage. The difference between groups was significant ($P < .05$). Severe activities of daily living (ADLs), severe pain (constant, not relieved) with ADLs; moderate ADLs, moderate pain (frequent, limiting) with ADLs; no ADLs, no pain with ADLs but pain with any sports activity; and no sports, no pain with sports activity. (From Noyes FR, Barber-Westin SD, Roberts CS. Use of allografts after failed treatment of rupture of the anterior cruciate ligament. *J Bone Joint Surg Am.* 1994;76:1019-1031.)

Prevalence of Nonanatomic Graft Placement in Failed Anterior Cruciate Ligament Reconstructions

A consecutive series of 122 patients who presented to our center for treatment of one or more failed ACL reconstructions was analyzed to

TABLE 8-6 Effect of the Condition of the Articular Cartilage at the ACL Allograft Revision Reconstruction on the Subjective Scores and Overall Rating at the Latest Follow-up Examination

Variable	Point Scale	Patients With Normal Articular Cartilage* (Mean ± SD)	Patients With Abnormal Articular Cartilage (Mean ± SD)	*P* Value
Pain	0-6	5.9 ± 0.5	4.6 ± 2.1	.03
Swelling	0-6	5.8 ± 0.6	5.2 ± 1.4	NS
Partial giving-way	0-6	5.9 ± 0.4	5.2 ± 1.5	NS
Full giving-way	0-6	6.0	5.5 ± 1.4	NS
Walking	0-40	38 ± 4	34 ± 8	NS
Stair climbing	0-40	36 ± 5	29 ± 11	.01
Kneeling	0-40	28 ± 14	21 ± 14	.01
Running	40-100	84 ± 18	61 ± 21	.001
Jumping	40-100	78 ± 21	57 ± 22	.01
Twisting and turning	40-100	73 ± 21	55 ± 20	.01
Overall rating	0-100			
Follow-up		85 ± 9	71 ± 12	.0001
Improvement from preoperative		26 ± 10	21 ± 11	NS

*Abnormal was defined as fissuring and fragmentation of 15 mm or more in diameter that extended into more than one half of the involved surface or any exposed subchondral bone.
ACL, Anterior cruciate ligament; *NS,* not significant; *SD,* standard deviation.

determine the prevalence of a nonanatomic ACL graft placement.[61] The cohort included 63 patients who had undergone both a primary and failed revision procedure elsewhere. Radiographs, MRI, and operative reports were used to determine graft placement, which was considered nonanatomic when 50% or more of the graft was outside of the native femoral and tibial insertions. The patients were evaluated a mean of 8.3 years after the failed ACL reconstruction. All patients had a grade II or III pivot shift and 77% rated their overall knee condition as fair or poor.

A nonanatomic graft placement was found in 107 knees (83%). A transtibial technique had been used in 83% of the failed primary ACL procedures and in 70% of the failed revision ACL procedures. The mean values for the coronal and sagittal graft placement showed a significantly increased vertical orientation when compared with a control group ($P < .01$). Forty-two of these 107 knees had undergone one or more ACL revision without correction of the misplaced graft tunnels, and these procedures also failed.

A total of 92 knees underwent anatomic revision at our center. Of these, 73 were done with a two-incision independent-drilling technique for the femoral and tibial tunnels. Staged bone grafting was required in 18 patients. The conclusion was reached that the transtibial tunnel drilling technique may result in a vertical graft orientation and eventual failure. In revision knees, the new graft tunnels should be placed at the native ACL attachments with independent drilling of each tunnel using either a two-incision or anteromedial portal technique (see Chapter 7).

OTHER AUTHORS' CLINICAL STUDIES

Risk Factors for Failure of Anterior Cruciate Ligament Reconstruction

Many investigations have been conducted to determine factors that are associated with failure of ACL reconstructions (Table 8-7). The majority of studies showed age to be a significant risk factor, especially in patients younger than 20 years old.[47,57,59,60,84,89,91,99-101] When compared with B-PT-B autografts, STG autografts, particularly those less than 8 mm in diameter, were shown to have higher failure rates.[37,60,62,83,84] Allograft tissue was noted to have a higher failure rate than autografts,[10,24,25,40,57,82,100] with irradiation possibly having an additional deleterious effect.[65] (This issue was also discussed in Chapter 7.) Poor graft placement from femoral tunnels placed too far anteriorly and/or tibial tunnels placed posteromedially relative to the native ACL position was noted in several studies to be a major factor for graft failure.[42,67,86,97]

Most studies found that gender was not a significant risk factor for failure of ACL reconstruction.[57,59,60,62,83,84,86,100,101] In addition, most agreed that height, weight, BMI, cartilage damage, and meniscal damage were not risk factors.[3,57,59,60,83,86,100,101] Disagreement existed in regard to the effect of the activity level patients returned to postoperatively and the timing of return to sports.

As studies become more sophisticated, all possible factors from large cohorts (such as the Multicenter Orthopaedic Outcome Network study) may be assessed in multivariate statistical models to determine which factors (alone and in combination) are most likely to cause failure of this operation. We avoid the use of allografts in younger, active patients and do not allow a return to unrestricted athletic activities until the patient demonstrates return of normal neuromuscular indices and other factors that are discussed in detail in Chapter 11.

Bone-Patellar Tendon-Bone Autograft

A common autograft source for ACL revision reconstruction is the B-PT-B (Table 8-8). Failure rates range from 0% to 15% and subjective outcomes tend to be somewhat inferior when compared with primary ACL reconstructions. However, this is frequently because of the preexisting meniscal and chondral damage in revision knees. The contralateral patellar tendon has been used in knees in which the ipsilateral patellar tendon had previously been harvested, although few clinical outcomes have been published after this procedure.[38,49,90]

Reharvested Bone-Patellar Tendon-Bone Autograft

Although authors of early studies[8,14,15,81,105] postulated that reharvest of the ipsilateral patellar tendon was feasible for revision reconstruction, others disagreed.[9,49,53-55,58] Liden and associates[54] followed 11 patients who underwent ACL revision surgery using reharvested ipsilateral patellar tendon grafts. At 10 years postoperatively, MRI demonstrated a significant increase in the thickness of the tendon at the donor site compared with the contralateral side (6.4 ± 1.3 mm and 4.5 ± 1.3 mm, respectively; $P = .02$) and a visible donor site gap. Nine patients were rated as abnormal or severely abnormal on IKDC scores.

Kartus and colleagues[49] compared the results of 12 knees in whom the ipsilateral patellar tendon was reharvested with 12 knees that received contralateral patellar tendon grafts for ACL revision reconstruction. Two years postoperatively, no differences were found among the subgroups on MRI for patellar ligament length, width, thickness, or donor site gap measurements. However, the knees that received the reharvested grafts had lower functional scores and a higher rate of complications, including one patellar fracture and one patellar ligament rupture postoperatively.

TABLE 8-7 Risk Factors for Failure of ACL Reconstruction

Study	Population	Failure Rates	Significant Risk Factors	Nonsignificant Factors
Andernord et al[3] (2014)	1205 B-PT-B autograft; 15,725 STG autograft; F/U, 2 years	1.82%	Age 13-19 yr ($P < .001$); soccer (male, $P = .009$; female, $P = .04$)	Gender, height, weight, BMI, use of tobacco
Persson et al[84] (2014)	3248 B-PT-B autograft; 9215 STG autograft; F/U, 4 years	B-PT-B: 2.1%; STG: 5.1%	Age 15-19 yr and 20-29 yr ($P < .001$); STG graft ($P < .001$); age 15-19 yr and STG graft (P = NP)	Gender
Webster et al[101] (2014)	561 (97% STG autograft); F/U, 4.8 years	ACL graft: 4.5%; contralateral ACL: 7.5%	Age <20 yr ($P < .0001$); contact mechanism original injury ($P = .005$); return to cutting/pivoting sports ($P = .01$), family history of ACL injury ($P < .05$)	Gender, chondral damage, meniscectomy, graft diameter, prior contralateral ACL injury
Kamien et al[47] (2013)	98 STG autograft, >2 yr	15.3%	Age ≤25 yr ($P = .009$)	Graft size, Tegner activity level
Maletis et al[60] (2013)	4014 allograft; 3012 STG autograft; 2791 B-PT-B autograft; F/U, 1.5 yr	Allograft: 1.74%; STG: 1.56%; B-PT-B: 1.18%	Age: 1-yr increments ($P < .001$); when adjusted for age, gender, ethnicity, BMI, allograft 3× higher risk ($P < .001$) and STG 1.8× higher risk ($P = .02$) compared with B-PT-B autografts; Hispanic and "other" vs. white ($P < .05$)	Gender, BMI, ethnicity (Asian, Black, Native American vs. white)
Mariscalco et al[62] (2013)	263 STG autograft; F/U, 2 yr	5%	Graft diameter <8 mm ($P < .05$)	Gender
Park et al[83] (2013)	296 STG autograft; F/U, 4.5 yr	4%	Graft diameter <8 mm ($P < .05$)	Gender, age <30 vs. ≥30 yr, height, weight, BMI, athlete vs. nonathlete, meniscectomy, meniscus repair, chondral defect
Rahr-Wagner et al[86] (2013)	1646 STG autograft; 183 B-PT-B autograft; F/U, 2 yr	8%	Anteromedial femoral drilling technique with STG autograft (P = NP)	Gender, age, cartilage damage, meniscal damage
Wasserstein et al[100] (2013)	11,605 autograft; 676 allograft; F/U, 5 yr	Autograft: 2.6%; Allograft: 3.7%	Age 15-19 yr ($P < .0001$); allograft ($P = .02$); academic hospital ($P < .001$)	Gender, meniscectomy, meniscal repair, procedures for chondral damage
Hosseini et al[42] (2012)	16 revision autograft; 7 revision allograft; F/U, NA	NA	Tibial tunnel placed posteromedially, femoral tunnel placed anterior to native ACL position	NA
Lind et al[57] (2012)	12,193 primary ACL; 1099 revision ACL; F/U, 5 yr	Primary: 4.1%; revision: 5.4%	Age <20 yr for primary; allograft tissue for revision ($P < .01$)	Gender, mechanism injury (sports/nonsports)
Magnussen et al[59] (2012)	256 STG autograft; F/U, 1.2 yr	7%	Age <20 yr ($P < .0001$); graft diameter ≤7 mm ($P < .05$)	Gender, femoral drilling technique, height, weight, BMI
Morgan et al[67] (2012)	276 revisions; 70% autografts; F/U, NP	NA	Femoral tunnel malposition: 47%	NA
Pallis et al[82] (2012)	61 B-PT-B autograft; 45 STG autograft; 16 allograft; F/U, 1.6-1.8 yr	B-PT-B: 11%; STG: 13%; allograft: 44%	Allograft tissue ($P < .001$)	Autograft tissue
Ellis et al[24] (2012)	70 B-PT-B autograft; 2 B-PT-B allograft (BioCleanse or low-dose irradiation); F/U, 4.2 yr	Autograft: 3%; allograft: 35%	Allograft tissue ($P = .001$)	Gender, age, chondral defect treatment, meniscal treatment
van Eck et al[99] (2012)	206 allograft; F/U, 2.5 yr	13%	Age ≤19 years ($P < .05$); early return to sports ($P = .007$); weight ($P < .05$); height ($P < .05$)	Single- or double-bundle reconstruction

Continued

TABLE 8-7 Risk Factors for Failure of ACL Reconstruction—cont'd

Study	Population	Failure Rates	Significant Risk Factors	Nonsignificant Factors
Trojani et al[97] (2011)	200 revision B-PT-B autograft; 87 revision STG autograft; 6 revision QT autograft; F/U, 2.5 yr	NA	Technical problems (anterior position femoral tunnel, malposition tibial tunnel, fixation)	NA
Mehta et al[65] (2010)	173 B-PT-B autograft; 17 B-PT-B allograft, fresh-frozen; 14 B-PT-B allograft, irradiated; F/U, 4.1 yr	Autograft: 0.7%; allograft: 9.7%	Irradiation of allografts ($P = .02$)	NA
Borchers et al[10] (2009)	5 failed autografts; 16 failed allografts; 42 age- and gender-matched controls; F/U, NP	Autografts: 3.70%; allografts: 8.56%	Allograft tissue ($P = .009$); postoperative activity level Marx score ≥13 ($P = .03$).	Activity level at time of initial injury
Shelbourne et al[89] (2009)	1415 B-PT-B autografts; F/U ≥5 yr	Reconstructed knee: 4.3%; contralateral knee: 5.3%	Age <18 yr ($P < .0001$) for all injuries; female ($P = .004$) for contralateral knee	Return to sports <6 mo postoperatively
Singhal et al[91] (2007)	69 anterior tibialis allograft; F/U, 4.6 yr	23%	Age ≤25 years ($P = .004$)	NA

ACL, Anterior cruciate ligament; *BMI*, body mass index; *B-PT-B*, bone-patellar tendon-bone; *F/U*, follow-up; *NA*, not applicable; *NP*, not provided; *STG*, semitendinosus-gracilis.

TABLE 8-8 Clinical Outcomes of Autograft Anterior Cruciate Ligament Revision Reconstruction

Study	No. Patients Seen/Entered in Study	Follow-up	Graft(s) Used	Failure Rate*	Subjective and Functional Results	Authors' Comments
Ferretti et al[28] (2013)	12/12	Mean, 3 yr	STG doubled + EA: contralateral	8%	IKDC objective: NL/nearly NL, 92%; abnormal, 8% IKDC subjective: mean, 95.4 ± 7 points	Procedure effective for patients with prior failed STG reconstructions
Franceschi et al[31] (2013)	30/30	Mean, 6.7 yr (range, 5-9 yr)	STG quadrupled; all two-stage femoral tunnel bone graft	0%	IKDC overall: NL/nearly NL, 90%; abnormal, 10%; Lysholm: mean preoperative, 65 ± 8; F/U 90 ± 8 points	All patients had reinjury; authors attempted to restore integrity of femoral condyle before revision with tibial autograft bone plug
Gifstad et al[36] (2013)	56	Mean, 7.5 yr (range, 2.7-13.2 yr)	B-PT-B	15%	Lysholm: mean, 80 ± 15 points KOOS: mean, 70 ± 21 points	Results significantly inferior to primary ACL reconstruction group
Mayr et al[64] (2012)	14/17	Mean, 5.7 ± 0.5 yr	B-PT-B	0%	IKDC overall: NL/nearly NL, 100% IKDC subjective: 90 ± 8 points	No differences in outcomes between B-PT-B autografts and fresh-frozen allografts
Trojani et al[96] (2012)	163/163	Mean, 3.6 yr (range, 2-10 yr)	B-PT-B: 83 STG: 64 QT: 16	B-PT-B: 10% STG & QT: 12%	IKDC overall: NL/nearly NL, 72%; abnormal/severely abnormal, 28%	EA used in 51%; significantly more knees with negative pivot shift, but no difference in IKDC grades of NL and nearly NL
Muneta et al[68] (2010)	18/21	Mean, 3.3 yr (range, 28.2 yr)	ST double bundle	9%	Lysholm: mean, 88 ± 7 points IKDC ligament: NL/nearly NL, 91%; abnormal, 9%	Results inferior to primary ST double bundle for outcome scores and positive pivot shift results

TABLE 8-8 Clinical Outcomes of Autograft Anterior Cruciate Ligament Revision Reconstruction—cont'd

Study	No. Patients Seen/Entered in Study	Follow-up	Graft(s) Used	Failure Rate*	Subjective and Functional Results	Authors' Comments
Niki et al[69] (2010)	20	Mean, 2.8 ± 0.9 yr	B-PT-B	0%	IKDC overall: NL/nearly NL, 70%; abnormal, 30%	Results similar to primary ACL reconstruction
Diamantopoulos et al[17] (2008)	107/148	Mean, 6.1 yr (range, 3-9.2 yr)	STG: 45 B-PT-B: 41 QT: 21	6.6%	IKDC subjective: NL/nearly NL, 65%; abnormal, 35% IKDC symptoms: NL/nearly NL, 80%; abnormal: 20%	Early revisions had better results; meniscal and chondral lesions correlated with poorer results
Denti et al[16] (2008)	58/58	Mean, 3.5 yr, (range, 2-6 yr)	B-PT-B: 27 STG: 37	B-PT-B: 11% STG: 13%	IKDC overall: NL/nearly NL, 89% B-PT-B, 77% STG; abnormal, 11% B-PT-B, 23% STG	Results similar to primary reconstruction; revision done in motivated patients
Weiler et al[102] (2007)	50/55	Mean, 2.5 ± 1.8 yr	STG quadrupled	6.5%	Lysholm: mean preoperative, 65 ± 17; F/U 90 ± 9 points	Inferior subjective results compared with primary ACL STG; no difference in knee stability
Ferretti et al[27] (2006)	28/30	Mean, 5 yr (range, 2-8 yr)	STG doubled + EA	10%	IKDC subjective: NL/nearly NL, 93%; abnormal, 7%	Fewer patients in IKDC NL category compared with primary STG ACL patients; STG and EA preferred revision technique
Salmon et al[88] (2006)	50/57	Mean, 7.4 yr, (range, 5-9 yr)	STG four strand	10%	IKDC overall: NL/nearly NL, 50%; abnormal/ severely abnormal, 50% IKDC symptoms: NL/nearly NL, 63%; abnormal/ severely abnormal, 37%	11 patients sustained contralateral ACL tear; poor results correlated with articular cartilage damage
Garofalo et al[33] (2006)	28/31	Mean, 4.2 yr, (range, 3.3-5.6 yr)	QT	3%	93% returned to preinjury sports levels; NL/nearly NL, 93%	QT viable graft option for revision
Thomas et al[95] (2005)	49/49	Mean, 6.2 yr (range, 3-11 yr)	STG: 34 B-PT-B: 15 All two-stage tibial tunnel bone graft	4%	IKDC subjective: mean, 61.2 ± 19.6 points	Staged procedure effective in restoration of stability; subjective and functional results inferior to primary reconstruction
O'Neill et al[80] (2004)	48	Mean, 7.5 yr, (range, 2-13 yr)	B-PT-B: 23 STG: 25	6%	IKDC ratings: NL/nearly NL 87%; PT, 88% STG; abnormal, 13%; PT, 12% STG; severely abnormal, 9% PT	PT failures endoscopic technique; high learning curve and also longest F/U
Fules et al[32] (2003)	29	Mean, 4.1 yr (range, 1-8.1 yr)	STG: 26 QT: 2 B-PT-B: 1	4%	IKDC ratings: nearly NL, 76%; abnormal, 17%; severely abnormal, 7%	1 Medial OA, 1 arthrofibrosis, 1 transient RSD; most revisions done for failed prosthetic ligaments
Shelbourne[90] (2002)	31/61 clinical, 51/61 subjective	Mean, 3.5 yr (range, 2-9.1 yr)	B-PT-B: contralateral	3%	Level I sports competitive, 69%; level I sports recreational, 18%	Lower scores correlated with arthrosis
O'Shea et al[81] (2002)	8/11	Mean, 4.1 yr, (range, 2.1-5.6 yr)	B-PT-B: reharvested	0%	Means only given	

*Failures designated if KT-1000 >5 mm involved-noninvolved or Lachman/pivot shift IKDC grade C or D.
B-PT-B, Bone-patellar tendon-bone; *EA*, extraarticular; *F/U*, follow-up; *IKDC*, International Knee Documentations Committee; *KOOS*, Knee injury and Osteoarthritis Outcome Score; *NA*, not available; *NL*, normal; *STG*, semitendinosus gracilis tendons; *ST*, semitendinosus tendon; *QT*, quadriceps tendon.

Semitendinosus-Gracilis Autograft

Multiple investigations have documented acceptable outcomes following STG revision reconstructions.[16,27,28,31,32,63,68,80,88,94,95,102,109] Ferretti and associates[27] followed a group of 30 knees that received an ACL revision STG autograft that was combined with an extraarticular ITB tenodesis. The failure rate was 10%. In another investigation, Ferretti and coworkers[28] harvested the contralateral STG after failure of the primary ACL reconstruction using the ipsilateral STG had occurred in 12 patients. A mean of 3 years postoperative, 1 patient had experienced graft failure. The other patients were rated as A or B on the IKDC objective evaluation.

Salmon and associates[88] followed 50 patients who received this operation and documented a 10% failure rate. However, only 56% of the knees were rated as normal or nearly normal according to the IKDC rating. The poor subjective and functional outcomes were related to the degree of joint (articular cartilage) damage. Weiler and colleagues[102] reported a 6.5% graft failure in 62 patients who underwent four-strand STG ACL revision. However, compared with a group of knees that had primary ACL STG reconstruction, the revision patients had inferior subjective knee function results. A greater percent of the revision knees had undergone prior meniscectomy, which may have led to the poorer outcome.

Muneta and associates[68] studied the outcome of primary and revision ACL reconstruction using a double-bundle technique with a multistrand semitendinosus graft. Twenty-one patients who had a revision procedure were followed a mean of 3.3 years, and 86 patients who had a primary reconstruction were followed a mean of 2.7 years postoperatively. There was a significant difference in pivot shift test because 22% of revision and 10% of primary knees had a positive result ($P < .05$). However, there was no difference in the mean KT-1000 measurements or the Lachman test. The revision knees had a poorer mean Lysholm knee score ($P < .0001$).

Staged Bone Grafting

Thomas and associates[95] reported the outcome of a staged ACL revision procedure in 49 patients who required bone grafting of the tibial tunnel first to achieve an anatomic ACL reconstruction. Thirty-four patients received a STG autograft and 15 had a B-PT-B autograft; all were followed a mean of 6.2 years postoperatively. The results were compared with a group of patients who underwent primary ACL reconstruction matched for age, gender, type of graft used, and follow-up time period. The revision patients demonstrated a greater number of meniscus tears, a significantly greater number of chondral lesions in the patellofemoral ($P = .015$) and lateral tibiofemoral compartments ($P < .001$), and had significantly lower IKDC subjective ($P = .006$) and objective ($P = .035$) scores than the primary ACL reconstruction group. There was no difference in instrumented laxity measurements. The results demonstrated that revision ACL knees without major associated instability, with abnormal bone tunnels grafted and bone quality restored, have a good success rate in terms of achieving postoperative stability. There were two failures in the revision group and one in the primary ACL reconstruction group. The results apply to knees that have intact secondary restraints, as knees requiring an additional medial or lateral ligament reconstruction were excluded and 9 of the 49 knees (18%) had only 3 to 4 mm of increased anterior tibial displacement before the operative procedure.

Franceschi and colleagues[31] performed staged ACL STG revision reconstruction in 30 patients who first underwent a bone graft of the femoral tunnel. All patients had posttraumatic knee instability after a prior B-PT-B autograft reconstruction. Although the femoral and tibial tunnels were deemed to be in the correct location, the authors removed the femoral fixation and filled the large defect (8-11 mm in diameter; 20 to 30 mm in length) with autologous bone grafts harvested from the anterior tibial metaphysis in an attempt to "restore the integrity of the femoral condyle." At a mean of 6.7 years postoperatively, no patient had experienced a graft failure and 27 patients were rated as normal or nearly normal on the overall IKDC score.

Quadriceps Tendon-Patellar Bone Autograft

Fewer investigators[17,33,96,104] have reported outcomes using the QT-PB autograft for ACL revision reconstruction. Garofalo and associates[33] followed 28 patients 3.3 to 5.6 years postoperatively at which time 25% had a grade I+ pivot shift and only one graft failed. Patient satisfaction was high, with 93% grading their knee condition as normal or nearly normal. Trojani and colleagues[96] used the QT-PB autograft in 16 revision knees that were followed a mean of 3.6 years postoperatively. The investigators reported that 73% were rated as normal or nearly normal on IKDC overall grading, and that 12% had failed. This graft is preferred after failure of a STG or B-PT-B autograft by these authors owing to donor-site morbidity incurred after B-PT-B harvest.

Allografts

Although historically allograft tissue was used in several studies for ACL revision reconstruction,[30,35,38,45,92,94,98] fewer reports have been published in more recent years[7,11,51,64] because surgeons appear to now favor autograft tissue for this procedure.[63] The issue of graft irradiation has been addressed by a few studies, with those using fresh-frozen tissue usually showing better stability outcomes compared with those using irradiated tissue. For instance, Mayr and associates[64] retrospectively compared the outcome of 15 patients who received fresh-frozen B-PT-B allografts with 14 patients who received B-PT-B autografts, a mean of 5.7 years postoperatively. There were no significant differences in mean IKDC subjective, Tegner, or Lysholm scores. There was also no difference in mean KT-1000 scores and no patient had more than 5 mm of increased anterior tibial translation. The authors attributed the results to the lack of irradiation or chemical sterilization of the allografts. Fox et al[30] followed 32 patients who received fresh-frozen B-PT-B allografts from 2 to 12 years postoperatively. Preoperatively, only 9% of these patients had more than 5-mm increased anterior tibial translation on knee arthrometer testing. At follow-up, 84% had a functional reconstruction, 9% had partial function, and 6% failed.

In contrast, Kievit and colleagues[51] followed 25 patients who received revision fresh-frozen allografts (13 tibialis tendon, 15 Achilles tendon, 2 B-PT-B) a mean of 5 years postoperatively. Compared with a group of primary STG reconstructions, the revision group had significantly worse pivot shift scores because 16% had 2+ test result compared with 4% of primary knees ($P = .007$). The revision knees also had significantly worse Knee injury and Osteoarthritis Outcome Score (KOOS) for pain, symptoms, and activities of daily living, sports, and quality of life.

Johnson and coworkers[45] reported that 36% of patients had greater than 5 mm of increased anterior tibial translation and 88% were rated as abnormal by IKDC guidelines a mean of 2.5 years after revision ACL reconstruction that was performed with irradiated allografts.

Conclusion

Most authors agree that the outcomes of ACL revision reconstruction are inferior to those of primary ACL procedures, usually because of preexisting articular cartilage damage and loss of meniscal tissue.[7,34,106,107] A recent systematic review by Wright and associates[107] that included 863 patients from 21 studies found that the failure rate of revision ACL reconstructions (13.7%) was nearly three to four times the failure rate of previously published primary ACL procedures (2.9%-5.8%).[106,108]

Problems with published studies include small cohorts, heterogeneous populations with regard to grafts used and/or concomitant procedures required,[1,7,17,95] and lack of concurrent control groups as issues preventing definitive conclusions on the optimal treatment for these knees.

Irradiated allografts and small-sized STG autografts appear to have higher failure rates than B-PT-B autografts. Although the QT-PB autograft seems to be a reasonable graft choice, few data have been published on the outcome after ACL revision reconstruction.

ILLUSTRATIVE CASES

Case 1. A 19-year-old male presented two years following a failed ACL B-PT-B autograft reconstruction. The procedure had been done 16 months following a left knee injury sustained during a hockey game for symptoms of full giving-way and pain. Although the patient completed a rigorous postoperative rehabilitation program, his giving-way symptoms persisted. He had given up all sports activities and noted generalized pain with daily activities. Physical examination demonstrated no effusion, a full range of knee motion, a grade III pivot shift, and 16.5 mm of increased AP displacement on KT-2000 testing. The patient also had 5 mm of increased lateral joint opening at 25 degrees of flexion, but no increase in external tibial rotation. He had a bilateral varus thrust on ambulation and increased recurvatum of the left knee. Full standing radiographs revealed bilateral varus malalignment, with a weight bearing line of 20% on the involved left knee (Fig. 8-18, *A*) and 40% on the contralateral right knee.

The patient underwent an HTO, followed 4 months later with a two-incision ACL B-PT-B autogenous reconstruction. During the procedure, the lateral tibiofemoral gap test was normal, indicating that a posterolateral procedure was not required. The B-PT-B graft was harvested from the contralateral knee. A new femoral tunnel, required to achieve anatomic graft placement on the lateral wall, was positioned adjacent to the previous tunnel. Fixation was achieved with interference screws proximally and distally. The patient had grade 2-A articular cartilage damage on the medial femoral condyle, and a stable lateral meniscus tear that did not require treatment.

At the most recent follow-up evaluation, 10 years postoperatively, the patient had no effusion, a normal range of knee motion, a grade 0 pivot shift, and 1 mm of increase in AP displacement on KT-2000 testing. He had no symptoms with light recreational activities and rated the overall condition of his knee as good. Standing PA radiographs at 45 degrees of flexion showed no difference between the noninvolved (Fig. 8-18, *B*) and involved knees (Fig. 8-18, *C*), with only mild narrowing of the medial tibiofemoral joint space.

Our comment: In revision knees, we prefer autogenous grafts because of the higher success rate compared with allografts. Contralateral graft harvest carries low postoperative morbidity, with careful attention to handling of soft tissue and bone grafting of the patellar and tibial defects. In this case, a closing wedge osteotomy of the tibia and fibular neck was performed, protecting the proximal tibiofibular joint and proximal fibular ligament attachments. We favor opening wedge osteotomy, which does not require fibular osteotomy and is described in Chapter 27.

Case 2. A 40-year-old male presented five years following a failed ACL allograft reconstruction on the right knee. The operative procedure had included a primary repair of the medial collateral ligament, a lateral meniscus repair, a medial meniscus repair, and a proximal patellar realignment. The patient had also undergone an ACL allograft reconstruction on the left knee two years following the right knee procedure. At the initial evaluation, he described a feeling of looseness in the right knee that began gradually but had recently become more symptomatic, although he had not experienced full giving-way episodes. He had given up all sports activities and desired an active lifestyle. Physical examination demonstrated a full range of knee motion, a grade III pivot shift test, and moderate crepitus in the lateral

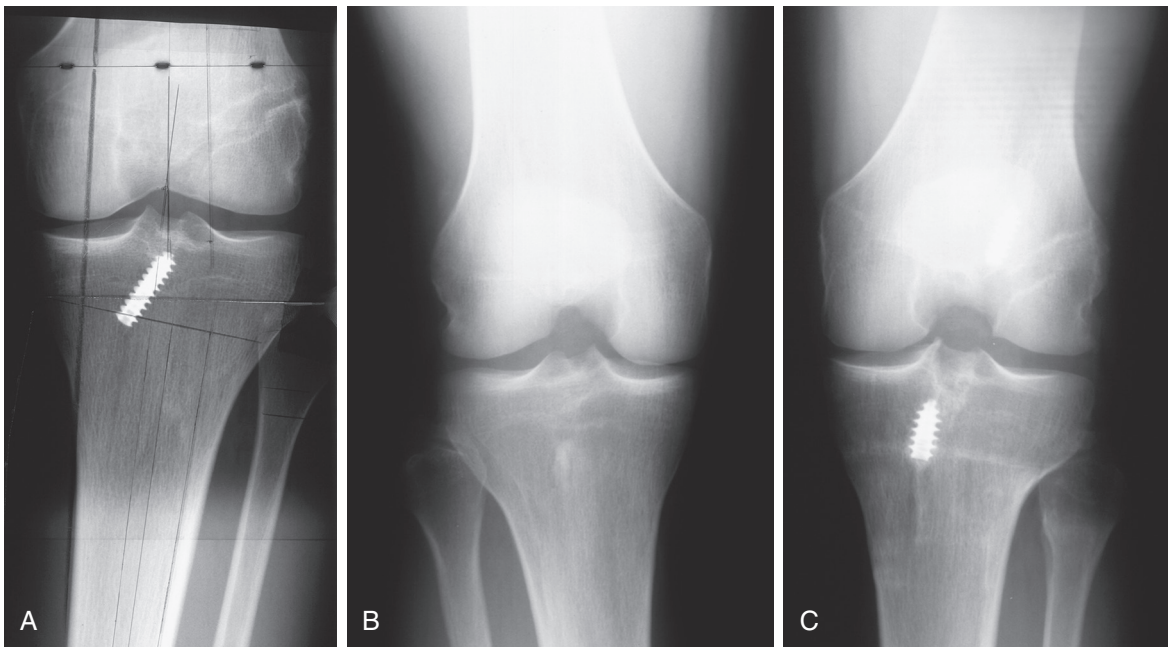


FIG 8-18 Case 1.

Video Content

Video 3-1
Video 7-1
Video 7-5
Video 8-1
Video 8-2

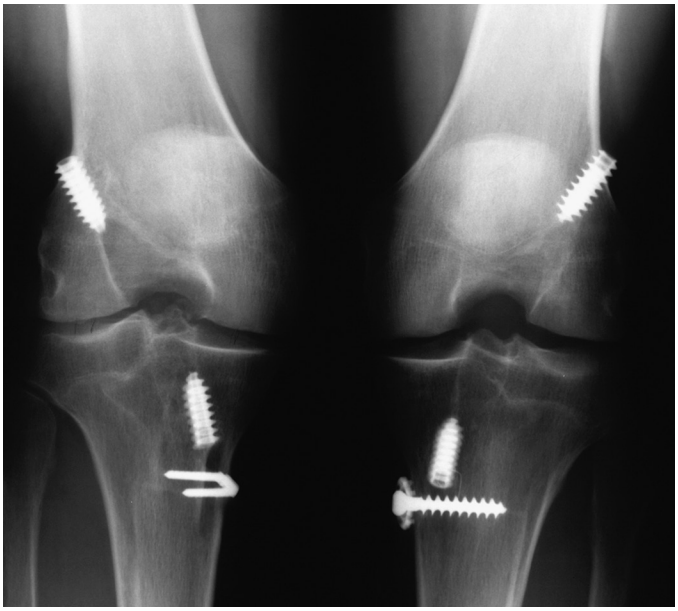


FIG 8-19 Case 2.

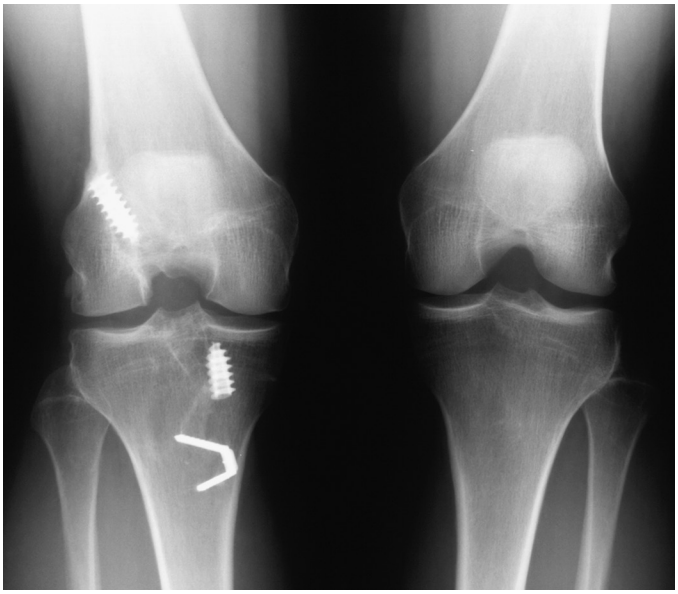


FIG 8-20 Case 3.

tibiofemoral compartment. There was normal axial alignment and no valgus alignment requiring corrective osteotomy.

The patient was treated with a revision ACL B-PT-B autogenous reconstruction of the right knee and a repair of a complex longitudinal medial meniscus tear located at the red-white junction. The allograft and ligament augmentation device were removed and the autogenous graft placed in the previous bone tunnels, as they were in an anatomically correct position. Fixation was achieved with an interference screw proximally (two-incision technique) and distally with an interference screw and a small staple over which the sutures from the bone plug were tied. Noteworthy articular cartilage damage (grade 2-B) was noted on the lateral femoral condyle.

At the most recent follow-up evaluation, 11 years postoperatively, the patient had no knee pain or complaints of giving-way. He participated in low-impact activities and rated the overall condition of his right knee as good. Physical examination demonstrated a grade I pivot shift with a solid endpoint, a normal range of knee motion, mild lateral joint line tenderness, and no effusion. Radiographs revealed 2 mm of lateral joint space narrowing and tunnel enlargement (Fig. 8-19). The patient was advised to continue low-impact activities and return if the lateral tibiofemoral symptoms worsened.

Our comment: This case demonstrates the probable long-term function of the medial meniscus repair, as preservation of the medial joint space is evident on radiographs.

Case 3. A 27-year-old female physician presented after two failed ACL reconstructions, including a primary repair and an allograft with a ligament augmentation device. The allograft failed in a low-energy trauma reinjury. Physical examination demonstrated a grade III pivot shift with no endpoint, 16 mm of increased AP displacement on KT-1000 testing, and a full range of knee motion. She had no symptoms with daily activities but had given up all sports and was having pain and giving-way symptoms at work.

The patient underwent a revision ACL B-PT-B autograft reconstruction using a two-incision outside-in approach. The allograft and ligament augmentation device were removed and the graft placed in the previous bone tunnels, which were in an anatomically correct position. Fixation was achieved with an interference screw proximally and an interference screw and a post (sutures in the bone plug) distally. Mild articular cartilage damage (grade 2-A) was noted on the undersurface of the patella and medial femoral condyle. The menisci were intact.

At the most recent follow-up evaluation, 12 years postoperative, the patient was doing well with low-impact activities and had no symptoms at work. She rated the overall condition of her knee as very good. Physical examination showed no effusion, a normal range of knee motion, no joint line tenderness, a grade I pivot shift, and 4 mm of increase in AP displacement on KT-2000 testing. Radiographs demonstrated no loss of joint space (Fig. 8-20).

Our comment: A two-incision, outside-in femoral approach is favored in most revision knees to place the graft entirely on the sidewall of the lateral femoral condyle at the anatomic footprint. An endoscopic technique drilling of the femoral tunnel through an anteromedial portal in knee hyperflexion is an alternative technique, based on the location of the prior femoral tunnel.

Case 4. A 21-year-old female presented with a history of two failed left ACL procedures, including an ITB extraarticular procedure and a B-PT-B autograft. The patient experienced recurrent giving-way symptoms following both reconstructions. She had also undergone a total medial meniscectomy following the first ACL operation. The patient's chief complaints were pain and giving-way with daily activities. She had given up all sports activities and rated the overall condition of her knee as poor. Physical examination revealed a full range of knee motion, a grade III pivot shift, 9 mm of increased AP displacement on KT-2000 testing, 8 mm of increase in lateral joint opening, and 10 degrees of increase in external tibial rotation.

The patient was treated with an ACL B-PT-B autograft reconstruction and a proximal advancement of the posterolateral complex. A new femoral tunnel was placed on the lateral wall with an outside-in technique to achieve anatomic graft placement. The prior interference screw was removed and a new screw inserted into the prior tunnel to prevent collapse into the new tunnel. Fixation of the ACL graft was

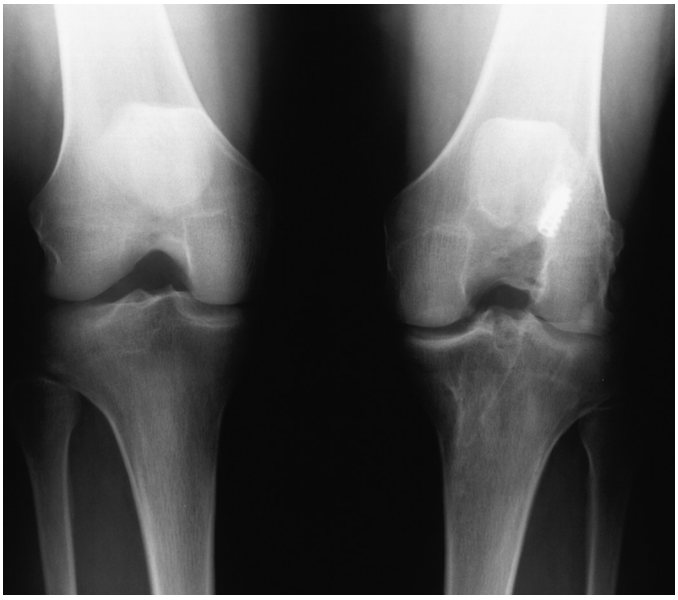


FIG 8-21 Case 4.

achieved with interference screws proximally and distally. The patient had grade 2-A articular cartilage damage on the undersurface of the patella, medial femoral condyle, and medial tibial plateau. The lateral meniscus was intact.

At the most recent follow-up evaluation, 13 years postoperatively, the patient had no symptoms with strenuous activities including motorcycle racing. She rated the overall condition of her knee as good. Physical examination demonstrated a negative pivot shift, no increase in lateral joint opening on stress radiographs, 4 mm of increase in AP displacement on KT-2000 testing, a normal range of knee motion, and moderate patellofemoral and lateral tibiofemoral crepitus. Radiographs demonstrated moderate narrowing of the medial tibiofemoral compartment and severe narrowing of the lateral tibiofemoral compartment (Fig. 8-21). The patient was advised to avoid high-impact activities and to monitor the patellofemoral and tibiofemoral joints for future pain.

Our comment: This case demonstrates the progression of arthritis frequently reported after prior meniscectomy in ACL revision knees. The lateral compartment has progressed past the point of considering a meniscus allograft, but fortunately, the patient is functioning well. She is following a nonoperative arthritis protocol designed to buy time and remain recreationally active.

Case 5. A 32-year-old female physical therapist presented after undergoing a total of 22 operative procedures on her right knee elsewhere. The operative history included four failed ACL procedures (an extraarticular ITB procedure, two B-PT-B autografts, and an STG autograft), seven failed posterolateral procedures (four proximal advancements of the posterolateral complex, an FCL allograft, an FCL B-PT-B autograft, a biceps tendon transposition), two failed HTOs, and a derotational osteotomy performed distal to the prior osteotomy site. The patient had moderate pain, swelling, and giving-way with daily activities. Physical examination demonstrated a grade III pivot shift with no endpoint, 15 mm of increased lateral joint opening at 25 degrees of flexion with no endpoint, 10 degrees of increased external tibial rotation, 15 degrees of hyperextension, a varus thrust on ambulation, varus recurvatum, and 12 mm of increased AP displacement on KT-2000 testing. Full-length radiographs revealed a 75% weight-bearing line on the right limb compared with a 56% weight-bearing line on the left limb.

The patient was treated with an ACL B-PT-B autogenous reconstruction using the contralateral patellar tendon. New femoral and tibial tunnels were required to achieve anatomic graft placement. Fixation was accomplished with interference screws proximally and distally. In addition, an anatomic reconstruction of the posterolateral structures (see Chapter 17) was done using a B-PT-B autograft to replace the FCL, a semitendinosus tendon autograft to replace the popliteus tendon and popliteofibular ligament, and a proximal advancement of the posterolateral capsule (Fig. 8-22, *A* and *B*). Advancement of the ITB and posteromedial capsule were also required. The patient had noteworthy articular cartilage damage (grade 2-B) on the undersurface of the patella, the trochlea, and the medial femoral condyle.

At the most recent follow-up evaluation, 10 years postoperative, the patient reported no problems with low-impact activities. She rated the overall condition of her knee as very good and was able to ski with minimal complaints. Physical examination demonstrated a negative pivot shift, no increase in lateral joint opening on stress radiographs (Fig. 8-22, *C* and *D*), 5 mm of increased AP displacement on KT-2000 testing, no increase in external tibial rotation, and an overall valgus lower limb alignment. Weight-bearing PA radiographs at 45 degrees of flexion demonstrated early narrowing of the lateral compartment (Fig. 8-22, *E*). An unloader brace and continued avoidance of impact activities were advised.

Case 6. A 27-year-old male presented following three failed ACL reconstructions, including an ipsilateral B-PT-B autograft, a contralateral B-PT-B autograft, and an ipsilateral (reharvested) B-PT-B autograft. The patient had also undergone a total medial meniscectomy. The history and medical records revealed that the causes of failure of the reconstructions were anterior graft placement on the femur, uncorrected varus osseous malalignment, and uncorrected deficiency of the posterolateral structures. Physical examination demonstrated a grade III pivot shift, 15 mm of increased AP displacement on KT-2000 testing, 5 mm of increase in lateral joint opening, and a weight-bearing line of 15%. The patient complained of symptoms with all activities and ambulated with a varus thrust.

The patient underwent a closing wedge HTO and proximal advancement of the posterolateral structures, followed later with a QT-PB autogenous ACL reconstruction. A new femoral tunnel to achieve a central ACL graft placement was required and the previously placed vertical femoral tunnel screw was left intact. Fixation was achieved with an interference screw proximally, and an interference screw and graft suture post. Noteworthy articular cartilage damage (grade 2-B) was evident on the undersurface of the patella and on the medial femoral condyle.

At the most recent follow-up evaluation, 6 years later, the patient had a grade I pivot shift bilaterally, 1.0 mm of increased AP displacement on KT-2000 testing, no increase in lateral joint or external tibial rotation, a normal range of knee motion, and correction to a valgus alignment. Radiographs demonstrated medial compartment joint space narrowing (Fig. 8-23). The patient declined further surgery such as a meniscus transplant. He was able to participate in low-impact activities and had only minimal problems in his occupation as a flooring installer. He rated the overall condition of the knee as good. The patient was advised that the long-term prognosis of the knee joint was poor.

Our note: This case demonstrates a protracted course of treatment that included two prior ACL revision procedures that failed, in part, because of vertical graft placement. In addition, the varus

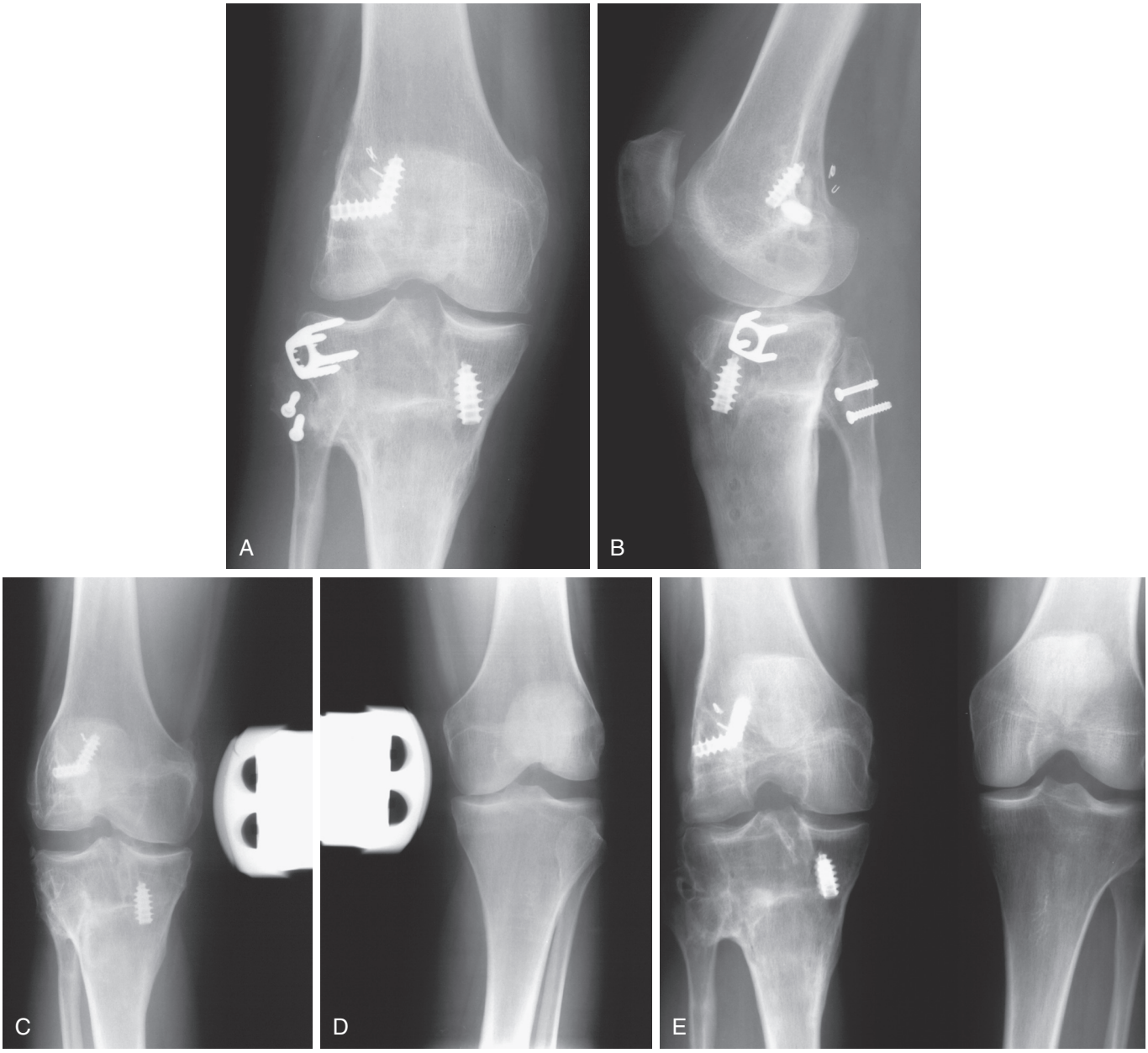


FIG 8-22 Case 5.

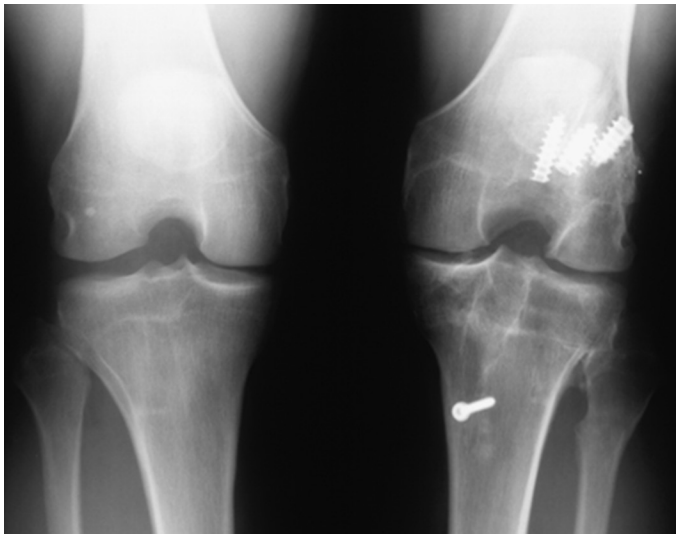


FIG 8-23 Case 6.

malalignment was not corrected, which produced pain and an obvious varus thrust with walking. Following the valgus-producing osteotomy and posterolateral reconstruction, a QT-PT autograft was favored over an allograft to decrease the possibility of failure of the third ACL revision procedure. Tibial tunnel dilation does occur in a small percentage of cases when the QT-PT graft is selected. In this case, the collagenous tendon portion was placed in the tibial tunnel and the patellar bone plug was placed in the femoral tunnel. The QT-PT graft provides the option of placing the bone plug at either the tibial or femoral location, based on the best graft fit at surgery.

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9

Anterior Cruciate Ligament Reconstruction in Skeletally Immature Patients

Edward M. Wojtys, Kelly L. Vander Have

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INTRODUCTION

Mid-substance anterior cruciate ligament (ACL) injuries in the skeletally immature athlete are being recognized with increasing frequency. ACL injury has been reported in 10% to 65% of pediatric knee injuries with acute hemarthroses. This increased incidence is largely attributed to changes in the activity patterns of young athletes. Participation in sports is on the rise, with young athletes training year-round and specializing at earlier ages. Increased demand for peak performance at an age of major physiologic change and neuromuscular deficits may also contribute to an increase in ACL injuries in young athletes.

Ongoing debate regarding the optimal treatment for ACL injuries in children has not resulted in a clear consensus for initial nonoperative treatment or operative reconstruction. The age and relative skeletal maturity of the child influence management. Although nonoperative treatment avoids iatrogenic injury to open physes, the current literature supports the trend toward early operative treatment to restore knee stability and prevent meniscal and chondral damage that is irreversible.

The optimal surgical approach to ACL reconstruction in this age group also continues to be debated. The concern regarding iatrogenic growth disturbance in children prevents the routine use of anatomic ACL reconstruction that has proved successful in adults. The armamentarium of operative techniques for treating ACL injuries in skeletally immature patients has expanded over the past decade. Alternative surgical treatment options include primary repair, extraarticular reconstruction, and all-epiphyseal and transphyseal intraarticular reconstruction. Although these injuries are occurring with increasing frequency, long-term studies to help guide optimal management approach are still lacking.

INDICATIONS

Historical recommendations for nonsurgical management of ACL insufficiency in the skeletally immature patient were based primarily on the concern for complications related to physeal injury. However, the majority of active patients treated nonsurgically were unable to return to sports, developed symptomatic instability, sustained meniscal tears, and experienced long-term sequelae of articular cartilage damage. Unfortunately, the options for the young patient who develops traumatic osteoarthritis are very limited. Therefore, instability (giving-way) must be controlled. If activity modification can successfully eliminate episodes of instability, nonoperative treatment is an option.

CRITICAL POINTS **Indications**

- Historically, recommendations for nonsurgical treatment were based on concerns about physeal injury.
- A majority of active patients who are treated nonsurgically are unable to return to sports, develop symptomatic instability, sustain meniscal tears, and experience long-term sequelae of articular cartilage damage.
- If instability persists, the permanent sequelae of nonoperative treatment can be more difficult to manage than growth plate injury.

If instability persists, the permanent sequelae of nonoperative treatment are seemingly more difficult to deal with than physeal injury.

Graf and associates[9] reported poor results at 15 months after ACL injury, with new meniscal tears and episodes of instability in seven of eight skeletally immature patients who did not undergo reconstruction. Similarly, in a series of 18 skeletally immature patients examined an average of 51 months after complete ACL tear, Mizuta and colleagues[31] found that all patients had symptoms, 6 had meniscal tears, and 11 had developed radiographic changes. McCarroll and associates[26] reported superior results with surgical management of complete ACL tears in prepubescent and junior high school patients compared with patients receiving conservative treatment. Of 16 prepubescent patients treated nonoperatively, 9 stopped all sports participation, 4 sustained at least one reinjury, and only 3 were able to return to sport.[26] In their study of a separate group of 75 junior high school athletes with mid-substance tears, McCarroll and colleagues[27] reported that 37 of 38 patients who were initially treated nonoperatively had instability and 27 (71%) developed meniscal tears. Overall, 92% (55 of 60) of those treated with reconstruction were able to return to play.[27] Prolonged delay between injury and reconstruction has been associated with irreparable meniscal injury. Lawrence and colleagues[21] reported on a cohort of 29 patients who underwent ACL reconstruction more than 12 weeks from the time of injury. There was a significant association between time to reconstruction and severity of both chondral lesions and medial meniscal tears.[21] Henry and colleagues[13] compared two treatment strategies for the management of ACL rupture in skeletally immature patients. Group 1 patients were treated at a children's hospital with physeal-sparing reconstruction. Group 2 participants underwent delayed reconstruction at an adult hospital once skeletally mature. Patients in group 2 had a higher rate of medial meniscal tears (41% vs 16%) and a higher rate of meniscectomy.[13]

In a recent metaanalysis of nonoperative versus operative treatment, Ramski and colleagues revealed multiple trends that favored early surgical stabilization over nonoperative or delayed treatment. Patients treated nonoperatively or with delayed reconstruction experienced more instability and inability to return to previous activity levels.[33]

Similarly, in a systematic review of 48 studies[41] that included both surgical and conservative treatment of complete ACL tears in immature individuals, Vavken and Murray found that conservative treatment resulted in poor clinical outcomes as well as a high incidence of secondary meniscal and chondral injuries. They concluded that surgical stabilization should be considered the preferred treatment.[41]

CONTRAINDICATIONS

Nonoperative treatment is contraindicated in patients with giving-way episodes that produce meniscal tears or articular cartilage damage. If surgical intervention is chosen, the patellar tendon autograft should not be harvested in a skeletally immature individual, because it violates the proximal tibial apophysis and may result in tibial recurvatum. The placement of bone blocks into tunnels drilled across the femoral or tibial physis reliably causes growth arrest and must be avoided. Similarly, disruption of the periosteum surrounding a growth plate (perichondrial ring) can alter growth. In the pubescent patient in whom a final growth spurt is anticipated, a soft tissue graft can be used.

Clinical reports of growth disturbance following ACL reconstruction in the skeletally immature athlete are rare. A survey of the Herodicus Society noted 15 cases of growth disturbance.[17] Associated risk factors included fixation hardware across the physis, large tunnels (≥12 mm), lateral extraarticular tenodesis, dissection in proximity to the perichondrial ring of LaCroix, and suturing near the tibial tubercle.[17] Yoo and associates[42] reported a retrospective review of 43 patients who underwent transphyseal reconstruction of the ACL using a soft tissue graft with postoperative magnetic resonance imaging (MRI) at a mean of 16 months. A focal bone bridge was observed in five patients, four involving the tibial physis and one at the femoral physis. Despite this, physeal angles did not change significantly during follow-up in either the coronal or sagittal plane.[42] The risk of physeal arrest following trauma with fractures involving the distal femoral and proximal tibial growth plates is much higher (30%-50%). If parents are unwilling to accept the risk of growth plate injury to their child, reconstruction should be delayed until the physes are closed.

CLINICAL EVALUATION

History

A tear of the ACL can result from a direct impact to the knee, but more commonly it is the result of a noncontact twisting or landing injury. The timing of injury, either acute or chronic, and any prior knee injury should be noted. Knee effusion, pain, and ability to bear weight are important factors in diagnosing an ACL tear. An audible pop heard at the time of injury may be reported. An acute hemarthrosis, particularly in the first 6 to 12 hours after injury, should raise concern for ACL injury. Stanitski and coworkers[37] found that 47% of preadolescents with a knee effusion had an ACL injury. Acute patellar dislocations may present with a similar mechanism and symptoms. Children with congenital limb deficiencies, such as tibial and fibular hemimelia, congenital short femur, or proximal femoral focal deficiencies, are a subset of patients with ACL insufficiency. These children may develop knee instability at a much younger age and without any history of trauma to the knee. These cases are more complex and must be evaluated on an individual basis.

Risk Factors for Injury

Notch volume. Prior studies have demonstrated a correlation between femoral intercondylar notch stenosis and ACL injuries in collegiate athletes.[20] In a recent study, Swami and associates[38] used MRI to compare notch volumes in skeletally immature patients with or without a torn ACL ligament. Their study results showed that notch volumes were significantly lower in knees with ACL tears than in control knees. Notch volumes were also significantly smaller in girls than in boys.[38] A decrease in notch volume implies a smaller ACL that has decreased strength on a congenital basis.

Landing mechanics. Existing studies have demonstrated that frontal knee motions and torques are strong predictors of noncontact ACL injury risk in female athletes. Video analysis studies also indicate a frontal plane "valgus collapse" mechanism of injury in females. Females have typically been found to land with greater peak knee abduction angles compared with males. Because the load-sharing among the knee ligaments is complex, coronal as well as sagittal plane loading mechanisms likely contribute to noncontact ACL injury. Risk factors are discussed in detail in Chapter 13.

CRITICAL POINTS Clinical Evaluation

- The most important component of diagnosing pediatric knee injuries is the physical examination.
- MRI can assist in detection of anterior cruciate ligament tears, as well as associated meniscal pathology and chondral injury. However, MRI does not quantify abnormal translation or rotation.
- An examination of the contralateral knee and generalized laxity is essential.

Physical Examination

The most important component of diagnosing pediatric knee injuries is the physical examination. The presence of an effusion should be noted. Palpation of the joint line as well as the distal femoral and proximal tibial physes should be performed. Active and passive motion should be documented. Varus and valgus laxity should be checked in full extension and at 30 degrees of flexion. A Lachman test should be performed and graded. Pivot shifting may be unreliable in the acute setting if the child is guarding. If the Lachman test is positive acutely, the pivot shift test can be deferred until the examination while the patient is under anesthesia if surgical intervention is chosen. Findings should always be compared with those in the contralateral uninjured knee. The patient should also be assessed for generalized ligamentous laxity, with the degree of knee hyperextension and tibial translation on the uninjured side noted.

Diagnostic Tests

Routine anteroposterior (AP) and lateral radiographic series should be obtained. The formation of the tibial spine and femoral notch should be assessed. Children with congenital limb deficiencies often have a deficient tibial eminence and hypoplastic lateral femoral condyle. In addition, a decrease in the size of the femoral notch has been implicated in ACL injury.[7] Comparison views and stress views may be selectively needed if physeal injury is suspected. MRI can assist in detection of ACL tears as well as associated meniscal pathology and chondral injury in those individuals who are difficult to examine. However, physical examination is more sensitive and specific than MRI in the evaluation of young patients. MRI may also be helpful in assessing for other intraarticular pathology in the young patient, including tibial eminence fractures, periarticular (physeal) fractures, and congenital absence of the ACL.

PREOPERATIVE PLANNING

Skeletal Maturity

The patient's level of skeletal maturity should be defined preoperatively. It is generally assumed that girls grow until 14 years of age and boys grow until age 16. However, age is not the only indicator of potential growth. Peak growth velocity occurs in girls aged 10 to 11 years and boys aged 13 to 14 years. Closure of the triradiate cartilage, which can be seen on a standard radiograph of the pelvis (Fig. 9-1), typically marks the end of peak growth velocity. The patient can be assessed physiologically for signs of development, as noted by Tanner and Davies.[39] A study by Slough and colleagues[36] suggested that preoperative Tanner staging performed by orthopedic surgeons has large interobserver variability and may not be reliable. The child can be classified as either prepubescent or pubescent. The prepubescent patient has physiologic findings consistent with Tanner stages 1 and 2 and a bone age younger than 12 years in boys and younger than 11 years in girls. The pubescent patient has physiologic findings consistent with Tanner stages 3 and 4 and a bone age of 13 to 16 years in boys and 12 to 14 years in girls. In girls, age at onset of menses can be useful. After menarche, girls enter a deceleration phase of growth and typically reach skeletal maturity 18 months later. Familial height can also be used as an approximate estimate of growth potential.

The patient can be assessed radiographically to determine skeletal maturity using the Risser sign on the pelvis. The Risser sign is a radiographic measurement based on ossification of the iliac apophysis, beginning on the lateral aspect and progressing medially (Fig. 9-2). Divided into four quadrants, the Risser sign proceeds from 0 (no ossification) to Risser 4, in which all four quadrants show ossification

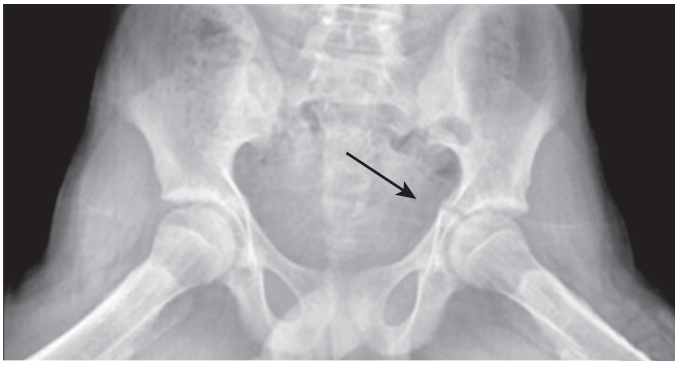


FIG 9-1 Radiograph of pelvis showing closure of the triradiate cartilage (*arrow*).

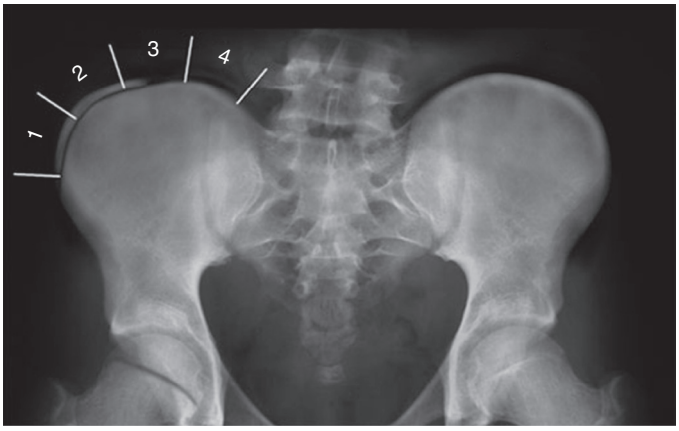


FIG 9-2 Skeletal maturity can be evaluated radiographically using the Risser sign on the pelvis, a measure of ossification of the iliac apophysis along four quadrants as shown. A Risser sign of 0 indicates little or no ossification (skeletal immaturity), whereas Risser 4 shows full ossification of the apophysis (skeletal maturity).

CRITICAL POINTS Preoperative Planning

- The patient's skeletal maturity should be defined preoperatively.
- The patient can be assessed both physiologically (Tanner stage) and radiographically to determine skeletal maturity using the Risser sign or bone age.

of the apophysis. Patients with Risser 0 or 1 have significant growth remaining, and the Risser 4 patient is skeletally mature. Bone age can be determined on the basis of examining a radiograph of the hand and wrist and comparing it with the standards in the Greulich and Pyle atlas.[10] The "rule of thirds" suggests that the distal femur and proximal tibia grow an average of 0.9 cm and 0.6 cm, respectively, per year of growth remaining. Limb lengths and bilateral lower-extremity alignment can be measured objectively using a mechanical axis radiograph. Genu valgum, more common in adolescent females, has been associated with ACL injury.

Associated Intraarticular Pathology

Previous studies have shown that 20% to 100% of pediatric patients who sustain ACL injuries have a concomitant meniscal injury. Although lateral meniscal tears are more common with acute injury, Millett and coworkers[30] found that the incidence of medial meniscal tears increases significantly with chronic ACL insufficiency. Of the 22 patients who

underwent surgery more than 6 weeks after injury, 72% had associated meniscal tears. If unstable meniscal tears exist, more aggressive management to salvage the meniscus in children may be indicated. Meniscectomy in this age group carries an even more ominous prognosis. Manzione and associates[25] evaluated the results of partial and total meniscectomy in 20 patients with a mean age of 15 years (range, 5-15 years). At 6-year follow-up, 16 knees had grade I osteoarthritis and 4 had grade II or III changes. Osteochondral injuries may also require debridement, drilling, and/or stabilization at the time of ACL reconstruction.

INTRAOPERATIVE EVALUATION

A complete physical examination of the affected knee should be repeated with the patient under anesthesia for laxity, including Lachman and pivot shift tests, and again compared with the contralateral side. Before ligament reconstruction, arthroscopic visualization of the knee may be needed to assess for the partial or complete nature of the ACL tear if the examination done while the patient was under anesthesia is inconclusive. Partial tear decisions should be based on the functioning of the remaining intact ligament and the degree of instability. Kocher and associates[16] performed a study on 45 adolescents with partial ACL tears. One third of patients underwent subsequent ACL reconstruction. The risk factors associated with failed nonsurgical management included tears involving more than 50% of the ACL, a positive pivot shift test, and older chronologic and skeletal age.[16]

OPERATIVE TECHNIQUES AND CLINICAL OUTCOMES

Treatment strategies for the ACL-deficient knee have evolved as recent studies have identified unique considerations specific to the skeletally immature patient. The current literature now supports a trend toward operative treatment to restore knee stability and prevent meniscal and/or articular cartilage injury, but the optimal approach to ACL reconstruction in the skeletally immature patient remains controversial. Conventional surgical ACL reconstruction techniques used in adults, when used in children, risk potential iatrogenic growth disturbances caused by physeal injury. The spectrum of surgical techniques used in skeletally immature patients includes primary repair, extraarticular tenodesis, physeal sparing, and partial or complete transphyseal reconstruction. Skeletal age, activity level, associated injuries, reported success, and expected graft longevity are among the factors to consider when selecting a technique.

CRITICAL POINTS Operative Techniques and Clinical Outcomes

- Conventional techniques used in adults risk potential iatrogenic growth disturbances in children, owing to physeal injury.
- Surgical techniques used in children include
  - Primary repair
  - Physeal sparing techniques
  - Transepiphyseal reconstruction
  - Partial transphyseal reconstruction (tibia only)
  - Transphyseal reconstruction
- Graft selection controversial; there are no prospective, randomized studies comparing the clinical success of graft type, graft placement, or graft fixation in skeletally immature patients.

Primary Repair

DeLee and Curtis[6] reported on three patients who underwent primary ACL repair through sutures tied across the physis. At 21 months of follow-up, all had clinical laxity and two of the three had episodes of giving-way. Engebretsen and colleagues[8] reviewed eight patients between 3 and 8 years of age following primary repair; they found that all experienced a decrease in activity level, and five of the eight demonstrated instability on clinical examination. Grontvedt and associates[11] also noted that primary repair of the ACL in the skeletally immature patient had poor results, similar to those in adults.

Although primary repair is not considered a treatment option, basic science studies suggesting that it may be a viable option in the future continue to emerge. A recent study of ACL repair in large animal models has indicated promising results with the use of a bioactive and biocompatible scaffold in the form of a clot to enhance cellular proliferation and biosynthesis at the torn ACL edges. Human clinical studies are necessary before any clinical application of this technique is undertaken.[40]

Physeal-Sparing Techniques

Early reports of physeal-sparing intraarticular reconstruction describe use of a hamstring autograft left attached distally, passed into the knee under the medial meniscus, and fixed to the lateral femoral condyle with staples in the over-the-top position on the femur (Fig. 9-3). This technique is nonanatomic and therefore does not reproduce the normal knee and ligament kinematics. In a report of nine patients at 36.5 months of follow-up, all had a 1+ Lachman test result and 1+ anterior drawer test score.[4] Six of nine patients had returned to sports, but with bracing and precautions. No growth disturbances were reported.[4]

More recently, Chicorell and colleagues[5] described the Micheli technique, which is a combined intraarticular and extraarticular reconstruction using autogenous iliotibial band (ITB) without violation of the physes. An incision is made obliquely from the lateral joint line to the superior border of the ITB. The ITB graft is harvested free proximally and left attached to the Gerdy tubercle distally, and it is tubularized with a whipstitch. Arthroscopy of the knee is then performed

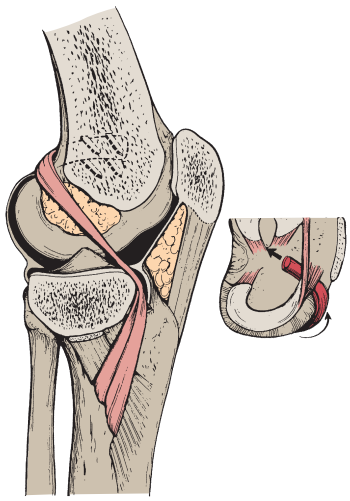


FIG 9-3 Cross section of the left knee shows the trajectory of the graft. The *inset* shows the tibial plateau with the graft coursing under the anterior horn of the medial meniscus. (Modified from Brief LP. Anterior cruciate ligament reconstruction without drill holes. *Arthroscopy*. 1991;7:350-357.)

through standard portals. The free end of the graft is brought into the knee in the over-the-top position of the femur posteriorly. A second incision is made over the proximal medial tibia. Dissection is carried down to the periosteum, and a curved clamp is placed into the joint under the intermeniscal ligament. The graft is then brought through the knee, under the intermeniscal ligament anteriorly, and out through the tibial incision. The graft is secured to the lateral femoral condyle using sutures placed at the insertion of the lateral intermuscular septum with the knee in 90 degrees of flexion and external rotation. On the tibial side, the graft is sutured to the periosteum of the proximal tibia just distal to the physis with the knee flexed 20 degrees while tension is applied to the graft (Fig. 9-4).

Postoperatively, the patient ambulates with crutches and toe-touch weight-bearing for 6 weeks. A hinged knee brace is set to allow 0 to 90 degrees of flexion initially, followed by progression to full motion after 2 weeks.

Micheli and coworkers[29] reported the results of 17 patients with an average chronologic age of 11 years and mean bone age of 10 years (range, 2-13 years) who underwent the physeal-sparing reconstruction described above. The mean follow-up was 66 months. All knees were subjectively stable and objectively stable by KT-1000 (MEDmetric) arthrometer testing. No child developed a growth disturbance. Although this was initially thought to be a temporizing procedure until adult-type reconstruction could be performed after skeletal maturity, a follow-up study of 44 skeletally immature patients (Tanner stage 1 or 2) with a mean chronologic age of 10.3 years (mean skeletal age, 10.1 years) by Kocher and associates[18] showed excellent results. Functional outcome, graft survival, and growth disturbance were evaluated at a mean of 5.3 years (range, 2-15.1 years) after surgery. Lachman test results were normal in 23 patients, nearly normal in 18 patients, and abnormal in 1 patient. Only two patients required revision reconstruction for graft failure, at 4.7 and 8.3 years postoperatively, respectively. No patient had an angular deformity or limb-length discrepancy clinically or radiographically. We strongly recommend this technique for prepubescent (Tanner stages 1 and 2) patients requiring ACL reconstruction.

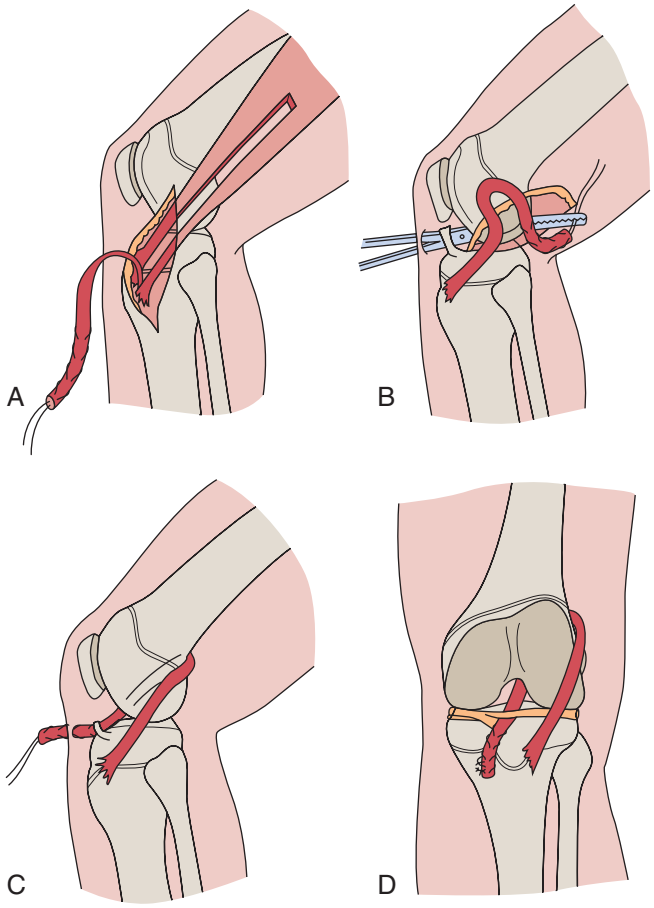


FIG 9-4 Physeal sparing combined with intraarticular and extraarticular reconstruction using an autogenous iliotibial band for prepubescent patients. **A,** The iliotibial band graft is harvested free proximally and left attached to the Gerdy tubercle distally. **B,** The graft is brought through the knee in the over-the-top position posteriorly. **C,** The graft is brought through the knee and under the intermeniscal ligament anteriorly. **D,** The graft is fixed to the intermuscular septum on the femoral side and to the periosteum of the proximal part of the tibia on the tibial side. (Modified from Kocher MS, Garg S, Micheli LJ. Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents. Surgical technique. *J Bone Joint Surg Am.* 2006;88[suppl 1 pt 2]:283-293.)

Transepiphyseal Reconstruction

The nonanatomic, nonisometric positioning of physeal-sparing ACL reconstruction techniques creates concern for the biomechanics of the graft and, consequently, its longevity. Transepiphyseal ACL reconstruction generally follows the principles of ACL reconstruction in adults, but it minimizes the risk of physeal injury by not crossing the tibial or femoral physis.

The affected leg is positioned with the hip flexed approximately 20 degrees. A fluoroscope is positioned on the side of the table opposite the injured knee, and the femoral and tibial growth plates are visualized in both planes before prepping and draping the patient. An oblique incision is made over the hamstring tendons. The semitendinosus and gracilis tendons are harvested and then doubled. Arthroscopy of the knee is accomplished in a standard fashion. With the C-arm in the lateral position, the point of the guidewire is positioned on the skin over the lateral femoral condyle, corresponding to the location of the footprint of the ACL. A small lateral incision is made, and the ITB is split longitudinally. The guidewire is advanced across the femoral epiphysis, and the C-arm is used to confirm that the guidewire is not angulated in the AP or inferosuperior planes. The guidewire is visualized in the intercondylar notch arthroscopically, entering the joint at the proximal femoral footprint. A second guidewire is then inserted into the anteromedial tibia at the level of the epiphysis. The guidewire is advanced, clearing the tubercle anteriorly and entering the joint at the free edge of the lateral meniscus on the tibia (center of the footprint of the ACL). Tendon sizers are used to measure the diameter of the tendon graft and the smallest appropriate reamer and the appropriate EndoButton (Smith & Nephew) fixation device are chosen. The EndoButton and tendons are pulled up through the tibia and out the femoral tunnel with a suture. An EndoButton washer is placed over the EndoButton and the graft is placed under tension, pulling the EndoButton and washer to the surface of the lateral femoral condyle. With the knee in 10 degrees of flexion, the graft is secured distally over a screw and post placed medial to the tubercle and distal to the tibial physis (Fig. 9-5).

Two series in which transepiphyseal ACL reconstruction was performed in skeletally immature patients have been reported. Guzzanti and coworkers[12] reported the results of using this technique in five preadolescent patients (Tanner stage 1) with ACL injuries. The hamstring graft was left attached to the tibia, a transepiphyseal tibial tunnel was used, and the graft was looped over a staple placed at the femoral attachment of the ACL. At a minimum follow-up of 4 years, KT-1000 arthrometer testing revealed an average side-to-side difference of

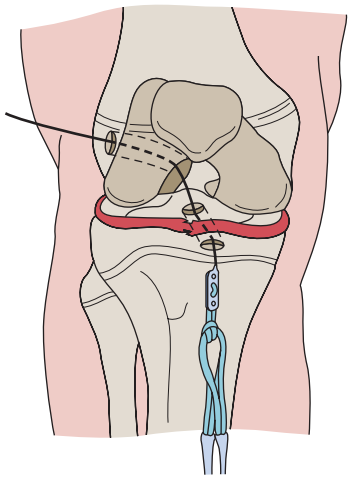


FIG 9-5 The semitendinosus and gracilis tendons are pulled up through the tibia and out the lateral femoral condyle with use of a No. 5 suture in the EndoButton fixation device. (Modified from Anderson AF. Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients. A preliminary report. *J Bone Joint Surg Am.* 2003;85:1255-1263.)

1.8 mm. Anderson[1] reported his results of using the technique described above in a series of 12 patients (Tanner stages 1-3). At a mean follow-up of 4.1 years (range, 2-8.2 years), KT-1000 arthrometer testing revealed a mean side-to-side difference of 1.5 mm. In both series, there were no reported growth abnormalities and no subjective or objective evidence of recurrent instability in a minimum of 4 years of follow-up.

Lawrence and associates[22] reported a modification of this technique using an intraoperative O-arm (Medtronic) for tunnel placement in prepubescent, skeletally immature patients. With their method, intraoperative computed tomographic scanning with 3-dimensional reconstruction is used to confirm the precise localization of the all-epiphyseal femoral and tibial tunnels. The femoral tunnel is drilled entirely in the epiphysis of the lateral femoral condyle. The tibial tunnel is drilled from inside out to the level of the tibial physis using a retrograde drill. Fixation of the soft tissue graft is achieved with a retrograde interference screw in the tibia and an interference screw in the femur. Lawrence and associates[22] reported results for three boys ages 10 to 12 years (Tanner stage 1) with a minimum follow-up of 1 year. All three patients objectively had stable knees based on Lachman and KT-1000 testing. There was no evidence of growth disturbance in any of these patients, and all three returned to sports activity using a custom ACL brace.

Partial Transphyseal Reconstruction

The partial transphyseal technique is a hybrid technique in which the graft is placed through a transphyseal tibial tunnel and fixed to the femur in the over-the-top position. A soft tissue graft is passed through a 6- to 8-mm drill hole that crosses the tibial physis. The tunnel is placed more vertically to decrease the risk of damage to the physis. The graft is secured in the over-the-top position on the femur, with care taken not to damage the distal femoral physis during fixation.

Lipscomb and Anderson[23] reported a series of 24 patients (21 males, 3 females) aged 12 to 15 years who underwent partial transphyseal reconstruction. Eleven patients had a completely open physis, and 13 had a partially open physis. Skeletal age was not recorded. A hamstring autograft was placed across the tibial physis (6.4-mm tunnel) and exited through a femoral epiphysis. In addition, an extraarticular reconstruction of the lateral side was routinely added for rotational stability. At an average follow-up of 35 months, the side-to-side difference found in Lachman tests averaged 1.8 mm, and all patients denied swelling or giving-way. One patient developed a 2-cm limb-length inequality as a result of stapling across the femoral and tibial physes.[23]

Andrews and colleagues[2] performed ACL reconstruction in eight adolescents using either a 7-mm fascia lata or Achilles tendon allograft placed centrally across the tibial physis and secured to the femur in the over-the-top position. At skeletal maturity, there were no detected limb-length discrepancies (Figs. 9-6 and 9-7).

Lo and coworkers[24] reported on five patients with an average age of 12.9 years (range, 8-14 years) who underwent partial transphyseal reconstruction with either a hamstring or patella tendon autograft passed centrally through the tibial physis (6 mm) to an over-the-top position on the femur. At an average follow-up of 7.4 years, scanograms revealed no angular deformities or leg-length discrepancies.

Kennedy and associates[15] performed a biomechanical comparison of three different physeal-sparing techniques to determine which most closely restored native knee kinematics. Displacement and rotation of the tibia with respect to the femur were measured after ACL reconstruction using all-epiphyseal, partial transphyseal (transtibial over-the-top), and ITB physeal-sparing techniques. Although all physeal-sparing reconstruction techniques restored some stability to the knee, the ITB reconstruction best restored both AP and rotational stability.[15]

Transphyseal Reconstruction

Complete transphyseal reconstruction is performed with standard bone tunnels that traverse the physes of both the tibia and the femur. This technique is equivalent to conventional ACL reconstruction in adults, with the use of either autograft or allograft tissue. Aronowitz and associates[3] reported on 19 skeletally immature patients ages 11 to 15 years who underwent allograft reconstruction through tunnels in the distal femur and proximal tibia (Fig. 9-8). All patients had a skeletal age of at least 14 years. At an average of 25 months after surgery (range, 12-60 months), there were no significant leg-length discrepancies or angular deformities, as determined by scanograms and AP and lateral radiographs of the femur and tibia. The mean Lysholm knee score was 97 (range, 94-100), and the mean KT-1000 side-to-side difference was 1.7 mm (range, 0.0-3.0 mm). All patients were satisfied with the results of surgery, and 16 of 19 patients returned to the same sport they participated in before the injury.[3]

McIntosh and colleagues[28] reported on 16 patients (11 male and 5 female) who underwent transphyseal ACL reconstruction. Each patient was followed until skeletal maturity, with a mean clinical follow-up of 41.1 months (range, 24-112 months). At last follow-up, the mean leg-length discrepancy was 0.62 cm (range, 0.2-1.5 cm). Clinical or radiographic evidence of malalignment was not present in any patient. At follow-up, the mean modified Lysholm knee score was 98.8 (range, 94-100), and the majority of patients (87.5%) had returned to their previous level of activity.[28]

Shelbourne and coworkers[35] reported a series of 16 patients with open growth plates who underwent transphyseal ACL reconstruction with a patellar tendon autograft. At the time of surgery, seven patients were Tanner stage 3 and nine were Tanner stage 4. The surgical technique was meticulous for placing the bone plugs proximal to the physes and not overtensioning the graft. Clinical follow-up (mean, 3.4 years after surgery) showed that no patients had growth plate disturbances, angular deformities, or leg-length discrepancies. All patients returned to competitive sports after surgery.[35]

Most recently, Kocher and associates[18] reported on 61 knees in 59 skeletally immature pubescent adolescents (Tanner stage 3) who underwent transphyseal ACL reconstruction using hamstring

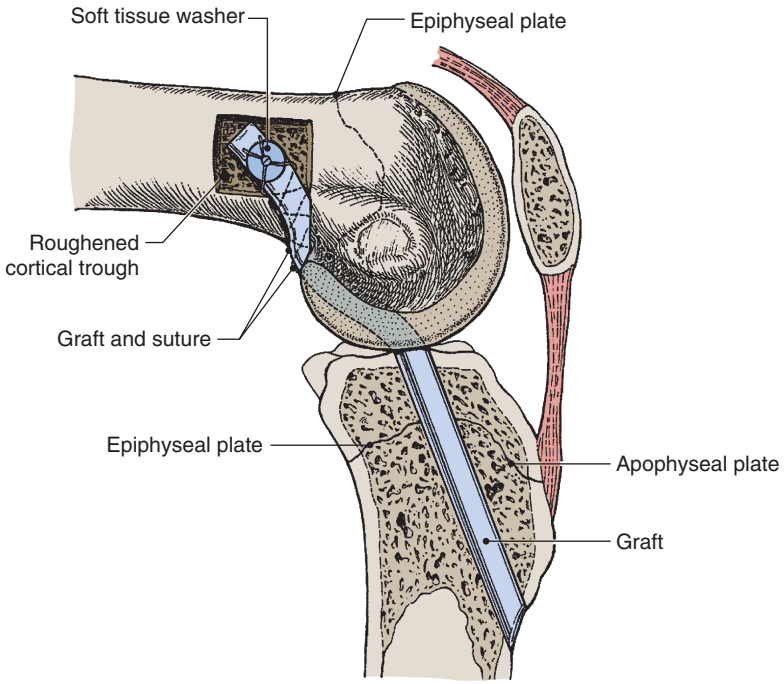


FIG 9-6 Over-the-top position in the lateral femoral condyle with elevation of periosteal H-flaps and roughening of the femoral cortical trough. (Modified from Andrews M, Noyes FR, Barber-Westin SD. Anterior cruciate ligament allograft reconstruction in the skeletally immature athlete. *Am J Sports Med.* 1994;22:48-54.)

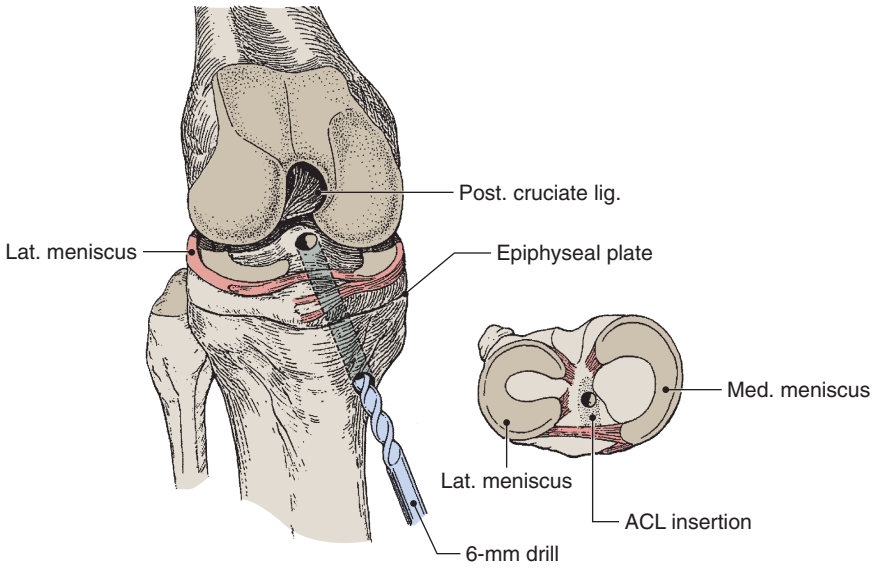


FIG 9-7 A 7-mm drill hole is made through the anteromedial aspect of the tibia (~3 cm), passing proximal to the epiphyseal plate in the center of the growth plate in a perpendicular fashion slightly posterior to the anatomic anterior cruciate ligament (ACL) insertion. (Modified from Andrews M, Noyes FR, Barber-Westin SD. Anterior cruciate ligament allograft reconstruction in the skeletally immature athlete. *Am J Sports Med.* 1994;22:48-54.)

autograft and metaphyseal fixation. Functional outcome, graft survival, and growth disturbances were evaluated at a mean of 3.6 years after surgery. Two patients required revision surgery for graft failure. The Lachman test results were normal in 51 knees and nearly normal in 8 knees, and no patient had an abnormal pivot shift test. The mean increase in height from the time of surgery was 8.2 cm (range, 1.2-25.4 cm), and no angular deformities or limb-length inequalities were detected clinically.[18]

These and other reports consistently support the use of transphyseal ACL reconstruction in pubescent (Tanner stages 3 and 4) adolescents. Overall, few growth disturbances have been reported following transphyseal reconstruction. Koman and Sanders[19] reported a case of 14-year-old boy who developed a distal femoral valgus deformity requiring osteotomy and contralateral epiphysiodesis following transphyseal reconstruction with a semitendinosus autograft. The skeletal age of the patient was unknown. The tibial tunnel diameter was

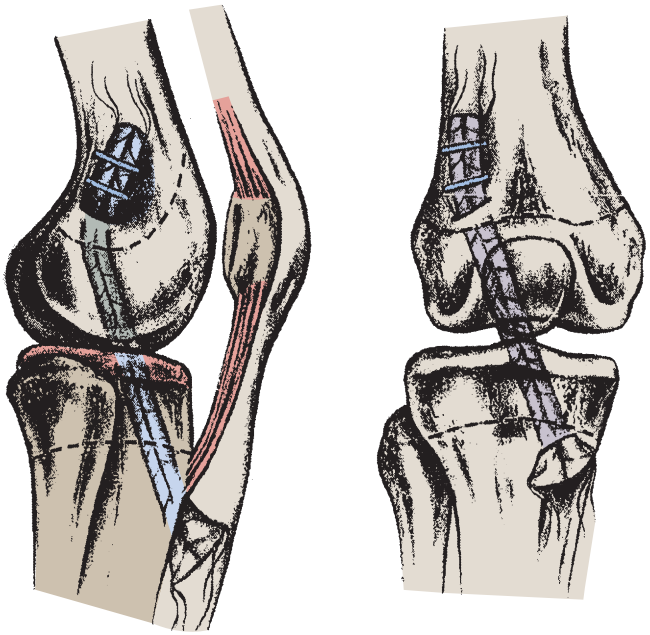


FIG 9-8 Lateral (*left*) and anteroposterior (*right*) views illustrating the technique of passing an Achilles tendon allograft through drill holes across the open physis of both the proximal tibia and distal femur. The graft is press-fitted on the tibial side before fixation with two staples on the femoral side. (From Aronowitz, E, Ganley TJ, Goode JR, et al. Anterior cruciate ligament reconstruction in adolescents with open physes. *Am J Sports Med.* 2000;28:168-175.)

unknown, but a 9-mm femoral tunnel was drilled. Cancellous bone plugs were inserted into both tunnels, and the tendon was fixed with a cannulated screw across the lateral femoral condyle.[19]

Transphyseal tunnels in the skeletally immature patient are more vertical, particularly on the femoral side. Shea and colleagues[34] used a computer-aided 3-dimensional model to incorporate the drilling of an anatomic ACL femoral tunnel in 10 pediatric knees using a variety of drill-hole diameters. They demonstrated that, with this technique, the average physeal volume removed was between 3.7% and 6.5%. Anatomic tunnel placement during ACL reconstruction produces an unacceptably large zone of physeal injury to the distal femoral physis.[34]

Graft Selection

The use of autograft versus allograft tissue in ACL reconstruction remains a source of controversy. A recent study was conducted to evaluate graft choice as well as the risks associated with graft failure.[14] Patients between ages 10 and 19 years had the highest rate of graft failure, regardless of whether autograft or allograft was used. In addition, the rate of graft failure was four times higher with allograft than with autograft reconstruction.[14]

Despite the numerous reports describing ACL reconstruction using extraarticular techniques, intraarticular physeal-sparing surgery, and transphyseal reconstruction of the ACL, there are no prospective, randomized studies comparing the clinical success of graft type, graft placement, or graft fixation in skeletally immature patients. The existing literature includes studies with relatively small sample sizes and use of a variety of outcome measures, making comparisons among studies difficult. Unfortunately, some of the reports do not clearly note the patients' sex, chronologic or skeletal age, or the level of skeletal maturity at the time of surgery. These studies also combine patients in different age groups (i.e., 8-15 years), making it difficult to interpret the results. Despite these limitations, the available studies in the literature do not support any trend or significant pattern of growth disturbance (leg-length inequality or angular deformity) following ACL reconstruction with or without physeal violation in patients with open physes.

RECOMMENDATIONS

A recent systematic review confirms the benefits and safety profile of ACL reconstruction in the skeletally immature patient.[41] The current treatment algorithm is predicated on the patient's skeletal, chronologic, and physiologic age, as well as on the extent of the ACL tear. Patients with partial tears involving less than 50% of the entire ACL diameter are treated nonsurgically with activity modification, physical therapy, and bracing. A patient with a clinically stable knee on examination and stress maneuvers typically can return to sports activity approximately 3 to 6 months following the initial injury. Complete ACL ruptures are managed surgically even in the very young patient. In prepubescent patients (i.e., Tanner stages 1 and 2) (bone age: boys, ≤12 years; girls, ≤11 years), a physeal-sparing combined intraarticular and extraarticular reconstruction using an autogenous ITB graft is preferred.[29] In the pubescent patient with open growth plates and more than 1 year of growth remaining, a partial transphyseal reconstruction (vertical tibial tunnel across the physis and over the top on the femur) using a hamstring autograft is preferred. Adolescent patients with minimal growth remaining (i.e., Tanner stages 3 and 4; bone age: boys, 13-16 years; girls, 12-14 years) are treated with complete transphyseal reconstruction using autogenous quadrupled hamstring or quadriceps tendons with smaller, more vertical tunnels and metaphyseal fixation. In older adolescent patients with closing physes (i.e., Tanner stage 5) (bone age: males, >16 years; females, >14 years), an anatomic adult-type ACL reconstruction with an autogenous quadrupled hamstring or bone-patellar tendon graft and interference screw or aperture fixation is preferred.

Patients are placed in a range-of-motion (ROM) brace for 6 weeks postoperatively. Patients treated with ITB ACL reconstruction are restricted to toe-touch weight-bearing for 6 weeks, whereas patients treated with a transphyseal technique are restricted to toe-touch weight-bearing until muscle control of the limb is achieved. Progressive rehabilitation consisting of ROM, closed-chain quadriceps and hamstring strengthening, patellar mobilization, and modalities are used for the first 3 months postoperatively. Initiation of straight-line jogging and plyometrics may begin as early as 3 to 5 months after reconstruction, depending on ROM and strength or functional progression. A full return to cutting and pivoting activities and sports is considered at 6 to 8 months postoperatively if all strength and functional parameters, including symmetry, are met.

CRITICAL POINTS Recommendations

- Prepubescent patients: physeal sparing, combined intraarticular and extraarticular reconstruction of autogenous ITB
- Pubescent patients, open growth plates, more than 1 year of growth remaining: partial transphyseal reconstruction hamstring autograft
- Adolescents, minimal growth remaining: complete transphyseal reconstruction autogenous quadrupled hamstring or quadriceps tendon graft with smaller, more vertical tunnels and metaphyseal fixation
- Older adolescents with closing physes: anatomic adult-type ACL reconstruction with autogenous quadrupled hamstring or bone–patellar tendon graft and interference screw or aperture fixation

INJURY PREVENTION

Neuromuscular Training

Well-designed injury prevention programs reduce the risk of ACL injuries for athletes, particularly females. These programs attempt to alter dynamic loading of the tibiofemoral joint through neuromuscular and proprioceptive training. They emphasize proper landing and cutting techniques. This includes landing softly on the forefoot and rolling back to the rearfoot, engaging knee and hip flexion, and, whenever possible, landing on two feet. Players are also trained to avoid excessive dynamic valgus of the knee and to focus on the "knee-over-toe position" when cutting.

Studies have shown reductions in lower-extremity injury rates with the use of training protocols that focus on landing mechanics, balance training, strength training, and/or agility training. Implementation of injury prevention training was effective in limiting the loss of knee control in female athletes during puberty, suggesting that it might be possible to lower the risk of ACL injury in this population.[32] Preventive programs should be implemented during ACL rehabilitation, followed by a maintenance program.

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Video Content

Video 7-5

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10

Scientific Basis of Rehabilitation After Anterior Cruciate Ligament Autogenous Reconstruction

Sue D. Barber-Westin, Frank R. Noyes

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VIDEO CONTENT

Video 7-5 ACL Reconstruction Panel: Graft Selection, Techniques, Rehabilitation, and Clinical Outcomes

Video 10-1 ACL Postoperative Rehabilitation Techniques: Returning Patients to Normal Activities

INTRODUCTION

Considerable advances have been made in the treatment of complete anterior cruciate ligament (ACL) ruptures and reconstruction methods. These include the appropriate selection of patient candidates and criteria for goals that should be achieved before surgery, such as resolving limitations of knee motion, muscle atrophy, gait abnormalities, pain, and joint effusion.[24,58,65,66,170,171,229,244,255,284] Appropriate graft selection, harvest, implantation, tensioning, and fixation are all paramount to achieving a reliable and desirable outcome.[8,181,286] The main goals of rehabilitation after surgery are to prevent complications such as arthrofibrosis and reinjury and eventually achieve normal knee function. Patients must regain full knee motion; normal patellar mobility; normal gait mechanics; and adequate lower-extremity muscle strength, coordination, proprioception, and neuromuscular function for their desired activities. Importantly, the exercise program should not produce undue forces on the healing ACL graft, patellofemoral or tibiofemoral compartments, or precipitate chronic joint effusions. The opposite extremity must be rehabilitated as well so that symmetries in strength and neuromuscular function are restored.

There are many factors that may impact both the initial and long-term recovery after ACL reconstruction (Table 10-1).[58] Few ACL ruptures are truly isolated in nature because approximately 80% of patients sustain concomitant bone bruises[78,138] and 60% sustain meniscus tears.[204,207] Investigators have noted no benefit[34,187] and, in some cases, deleterious outcomes[229,248,285] when ACL reconstruction is performed before the resolution of limitations in knee motion, muscle atrophy, swelling, and pain. Investigators have heavily emphasized the need to restore normal knee motion when possible before surgical intervention.[229,238,249,291] The exception is the presence of a mechanical block to extension, such as a bucket-handle meniscus tear.[246] In these cases, early surgical intervention is warranted to repair the meniscus tear, rehabilitate the knee to regain full extension and flexion, and then proceed with ACL reconstruction. In certain cases, the ACL reconstruction may be performed at the same time as the meniscus repair. Communication between the surgeon and therapist is essential so that the therapist understands what was done at surgery (especially any concomitant procedures) and the condition of the menisci and articular cartilage surfaces.

An important issue is whether the postoperative rehabilitation process should be governed and progressed according to the amount of time that has elapsed or by well-defined and measurable criteria. Although some programs allow a return to full activities according to a certain amount of time, such as 6 months postsurgery, others (including these authors) will not release patients until specific muscle and function objectives have been achieved, regardless of the amount of time that has passed since surgery.[11,12] There is no consensus among investigators regarding which factors are the most important to measure to determine when patients may safely return to athletic

TABLE 10-1 Factors Affecting Recovery After Anterior Cruciate Ligament Reconstruction

- Resolution of limitations in knee motion, muscle atrophy, gait abnormalities, pain, and knee joint effusion *before* surgery
- Anterior cruciate ligament (ACL) graft selection, harvest, placement, fixation, healing, and remodeling
- Initial patient response to surgery, including pain, effusion, and muscle inhibition
- Patient psychological factors, such as motivation, beliefs, compliance, self-efficacy, and fear of reinjury
- The condition of the articular cartilage
- The presence and severity of bone bruising
- Concomitant major operative procedures: meniscus repairs or transplants, other ligament reconstructions, patellofemoral realignment procedures, and articular cartilage restorative procedures
- Lingering postoperative deficits in muscle strength and neuromuscular function
- Patellofemoral pain or tendinitis
- Restoration of normal knee stability
- Previous ACL reconstruction that failed

activities.[246] This is concerning when one understands the risks of reinjury to either the ACL-reconstructed knee or contralateral ACL.[12]

Modern studies of ACL autograft reconstruction typically report failure rates ranging from 5% to 15%.[35,47,126,152,203] Failure is defined as an increase in anteroposterior (AP) displacement of 6 mm or more compared with the normal contralateral limb or a fully positive (grade 2 or 3) pivot shift test. However, the percentage of grafts that undergo some amount of elongation, resulting in 3 to 5 mm of increased AP displacement or a mildly positive (grade 1) pivot shift test, is quite variable and ranges from 5% to 50%.[80,89,106,110,142,267] Therefore although the overall rate of failure is usually acceptable, some authors express concern that any amount of abnormal anterior tibial translation may be detrimental to the knee joint over the long term.[26,222] Graft elongation may occur as a result of technical aspects of the operative procedure, inconsistencies in maturation of the collagenous and bony components of the construct, the rehabilitation program, or a combination of these factors.

Many modern studies have identified problems with altered gait biomechanics, muscle strength, and neuromuscular function many months or years following ACL reconstruction.* Although deficits in proprioception following ACL reconstruction were reported by investigators several years ago,[15,31,166,174] several recent studies refuted these findings.[4,28,123,168,194,218,232] Even so, altered muscle and neuromuscular function are especially concerning when patients resume sports activities, and investigators have hypothesized that these problems may result in serious reinjuries.[11,240,289]

The purpose of this chapter is to review the current knowledge regarding rehabilitation after ACL autogenous reconstruction. The scientific basis for immediate knee motion, early weight bearing, methods to regain muscle strength and neuromuscular function, and evaluation criteria for return to activity are reviewed. Our ACL postoperative rehabilitation programs, formulated from the scientific literature and over 3 decades of empirical clinical experience, are detailed in Chapter 11.

*References 41, 55, 125, 156, 164, 176, 202, 217, 235, 236, 279, 287.

CRITICAL POINTS Immediate Knee Motion, Early Weight Bearing, Bracing

- Scientific basis supporting immediate range of motion exercises after ACL reconstruction is well established. Include patellar mobilization.
- Treat limitations of knee motion early postoperatively with overpressure program.
- Immediate partial weight bearing safe, not harmful to ACL graft.
- No high-quality evidence supports postoperative bracing. Helpful in select patients for protection and comfort.

IMMEDIATE KNEE MOTION, EARLY WEIGHT BEARING, AND BRACING

The scientific basis supporting immediate range-of-motion (ROM) exercises after ACL reconstruction is well established.[25,118,131,132,154,205] Early knee joint motion decreases pain and postoperative joint effusions, aids in the prevention of scar tissue formation and capsular contractions that can result in arthrofibrosis, decreases muscle disuse effects, maintains articular cartilage nutrition, and benefits the healing ACL graft.[46,229,257] There is a consensus in the medical community that immobilization is detrimental to the knee joint structures and may result in a permanent limitation of knee motion, prolonged muscle atrophy, patella infera, and articular cartilage deterioration.[46,208-210,224] Failure to achieve full knee motion may cause abnormal joint arthrokinematics, increased contact pressures in the patellofemoral and/or tibiofemoral joints, patellofemoral osteoarthritis, and a poor outcome.[48,199,250,291] Shelbourne and Gray[250] noted a significant association between the loss of 3 to 5 degrees of knee extension and radiographic arthritis (abnormal or severely abnormal International Knee Documentation Committee [IKDC] rating).

The use of an immediate postoperative knee motion program (in the range of 0-90 degrees) after ACL reconstruction was initiated in our center in 1981.[206] Patellar mobilization is an important component of this program to help prevent the formation of excessive scar tissues around the patella, the medial and lateral retinaculum, and the fat pad. An investigation was later conducted in our center on 443 knees that had an arthroscopy-assisted ACL bone-patellar tendon-bone (B-PT-B) autograft reconstruction to determine the effectiveness of this program in restoring normal knee motion.[205] The protocol included the early recognition and treatment of limitations of flexion and extension according to goals established before surgery. Patients who did not achieve 0 to 90 degrees of flexion by the end of the first postoperative week were placed into an overpressure protocol initially (Fig. 10-1). This was followed, if required, by a serial extension cast program (Fig. 10-2) and, in rare instances, by arthroscopic debridement of scar tissues (Fig. 10-3). Treatment intervention was performed in 23 knees, all of which achieved normal knee motion. At follow-up (mean, 25 months postoperatively), a normal ROM was detected in 436 knees (98%) and a mild limitation of extension of 5 degrees was found in 7 patients who refused additional treatment intervention. Only three knees required an arthroscopic lysis of adhesions that, combined with an inpatient epidural program, resulted in successful resolution of the motion limitations. The incidence of knee motion problems based on concomitant surgical procedures with the ACL reconstruction was 22% for medial collateral ligament repairs, 18% for patellar realignment procedures, 8% for meniscus repairs, and 6% for isolated ACL reconstructions.

Although many authors have recommended early partial or full weight bearing immediately following ACL reconstruction, few studies have examined this factor and its potential effect on both short- and



FIG 10-1 Knee overpressure exercises for limitation of extension **(A)** and flexion (**B** to **D**).

long-term recovery.[282,295] The effect of immediate full weight bearing on the outcome in knees with noteworthy articular cartilage damage or those in which major concomitant operative procedures were required is unknown. In addition, gait abnormalities that may ensue from immediate full weight bearing owing to pain, knee joint effusion, and muscle weakness have not been examined. It does appear, based on the literature[28,90,107,243] and our experience,[14] that immediate partial weight bearing is safe and not deleterious to the healing ACL graft.

Ohkoshi and associates[212] recommended early weight bearing after ACL reconstruction many years ago. These investigators used an analytical model to calculate shear forces placed on the tibia during standing at various trunk and knee flexion angles (Fig. 10-4). The shear forces were posteriorly directed in all positions, which increased as trunk flexion angles increased (at knee flexion angles of 30 and 60 degrees). Cocontraction of the quadriceps and hamstrings was observed at all knee and trunk flexion angle positions, with increasing hamstring activity measured with increasing trunk flexion angles. Exercises performed in the standing position with the knees flexed and the trunk anteriorly flexed, such as half-squatting, were believed to not only be safe but also to have the potential advantages of increasing muscle strength, endurance, and proprioception and decreasing bone atrophy.

The effects of postoperative and functional braces on pain, return of normal knee motion, complications, sports activity performance, balance, and proprioception have been assessed by many investigators.[154,169,183,294] Most studies report that braces do not provide significant benefit in achievement of normal (1) knee motion, (2) isokinetic lower-extremity muscle strength, (3) stability, (4) lower limb symmetry on single-leg hop tests, and (5) functional knee rating and activity level scores.[30,107,119,131,132,185,237,294] In addition, in systematic reviews[24,154,169,183,294]

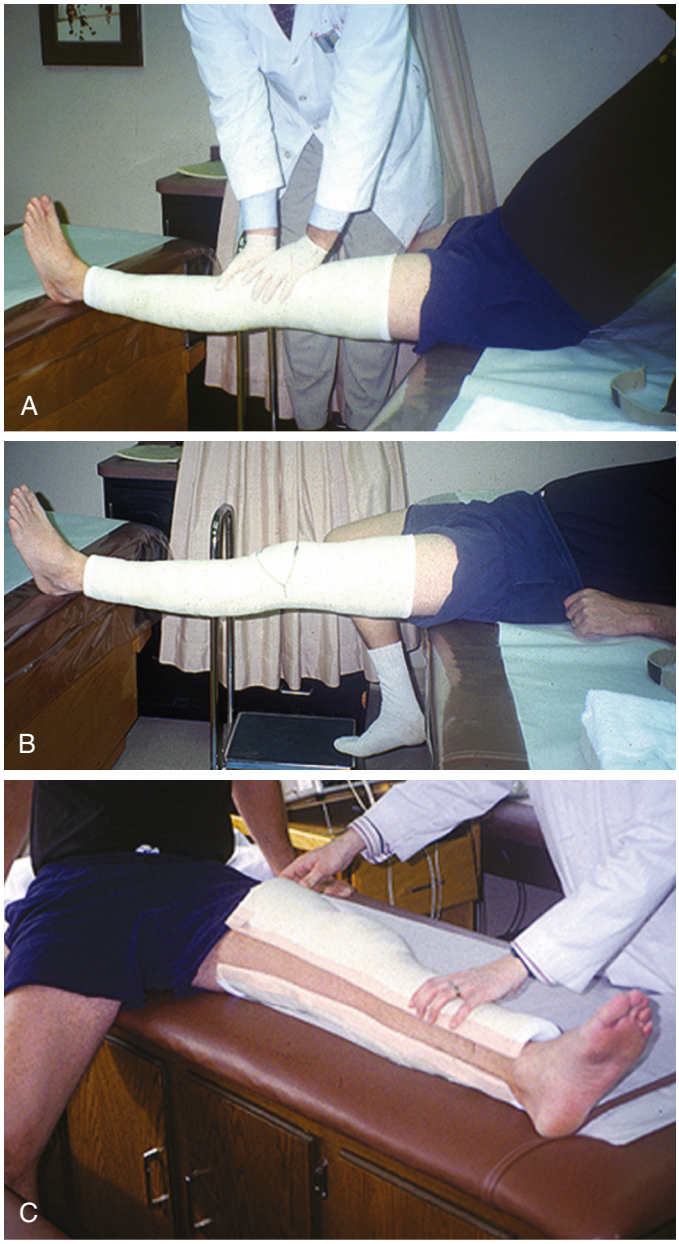


FIG 10-2 Extension cast application requires overpressure initially **(A)**. The cast is worn for 48 hours **(B)** and is then split **(C)** and converted into a night splint.

and consensus statements,[246] high-quality evidence has not been found to support the routine use of functional or rehabilitative bracing after ACL reconstruction. In our experience, a postoperative brace is beneficial in select patients early after surgery for protection and comfort, as discussed in Chapter 11.

LOWER-EXTREMITY MUSCLE ATROPHY AND WEAKNESS AFTER SURGERY

Lower-extremity muscle atrophy and weakness after ACL reconstruction represents a difficult and unresolved problem.[54,109,125,144,221,242,273] Investigators have reported postoperative strength deficits ranging from 5% to 40% for the quadriceps[54,63,120,141,148,150,191,273] and from 9% to 27% for the hamstrings.[54,120,141,146] Unresolved postoperative muscle strength deficits may be associated with knee osteoarthritis that is present either at baseline or years after surgery.[49,145,214,220,279] A recent study[227] found that quadriceps strength predicted 61% the variance in self-reported disability (according to the IKDC Subjective Knee Form) an average of 4.5 years postoperatively in a small group of 15 patients.

CRITICAL POINTS Lower-Extremity Muscle Atrophy and Weakness After Surgery

- Unresolved problem, studies report deficits ranging from 5%-40% for quadriceps, 9%-27% for hamstrings.
- Several theories for atrophy and strength deficits; may occur bilaterally.
- Changes in muscle fiber composition, abnormal gamma loop function; arthrogenic muscle inhibition commonly cited.

The factors related to the loss of muscle size and strength after ACL reconstruction remain unclear. Studies vary considerably in terms of patient age, preoperative and postoperative activity levels, time elapsed since surgery, ACL grafts, rehabilitation programs, concurrent operative procedures, and methods used to determine muscle size and function. For instance, in one recent study, researchers compared 15 patients who underwent ACL reconstruction (who were 2-15 years postreconstruction) with 15 controls, all of whom were "active" people (Tegner activity scale score ≥4), between 19 and 38 years of age.[153] Problems with muscle atrophy appear to occur regardless of the type of graft used to reconstruct the ACL and frequently occur bilaterally.[221] The proposed reasons for quadriceps muscle strength deficits that persist after surgery include:

- Selective atrophy of type 1 fibers.[105]
- A reduction in muscle fiber size.[299]
- Hypertrophy of fast-twitch muscle fibers.[17,68]
- Nonoptimal activation of muscles during voluntary contractions.[172]
- Loss of native ACL mechanoreceptors that result in abnormal (decreased) gamma loop function.[135-137,147,149,259,263,264]
- Arthrogenic muscle inhibition: Inhibition of muscle tissue from joint effusion and soft tissue damage leads to altered afferent output from knee joint and muscle atrophy.[109,122,221,261]
- Peripheral changes in muscle-tendon units of the quadriceps muscle, including chronic atrophy, changes in the compliance of the series elastic components of the muscle-tendon units, and alterations in structure and fiber type.[153]
- Elevated levels of atrophy-inducing signaling cytokines such as myostatin and transforming growth factor-β.[188]
- Alterations in neural pathways.[167]
- A combination of the above.

Regardless of the cause of muscle atrophy and weakness, it is paramount that the rehabilitation program correct the deficits in a controlled, effective, and safe manner. There are several principles the therapist must use to achieve this goal, which change as the patient progresses through the program. Modifications will be required based on the factors addressed in Table 10-1. Adequate muscle strength is required to initiate more advanced neuromuscular exercises and, eventually, sports-specific activities. At our center, patients are seen 24 hours after surgery to begin initial muscle-strengthening and knee motion exercises.

OPTIONS TO REGAIN MUSCLE STRENGTH

Patellofemoral Joint Protection

It is critical as one attempts to make gains in strength to avoid placing high forces on the patellofemoral joint throughout the rehabilitation process. Anterior knee pain that develops after ACL reconstruction is a difficult complication,[91,142] and it is essential that the therapist

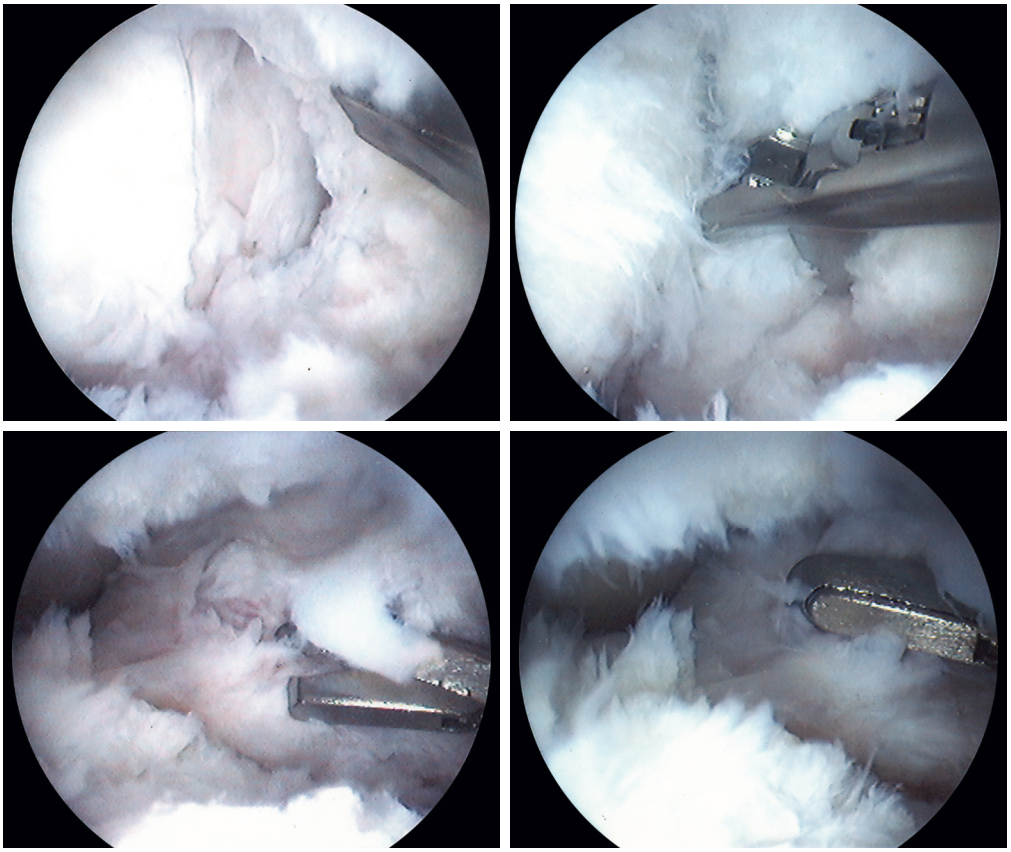


FIG 10-3 Arthroscopic debridement of scar tissues.

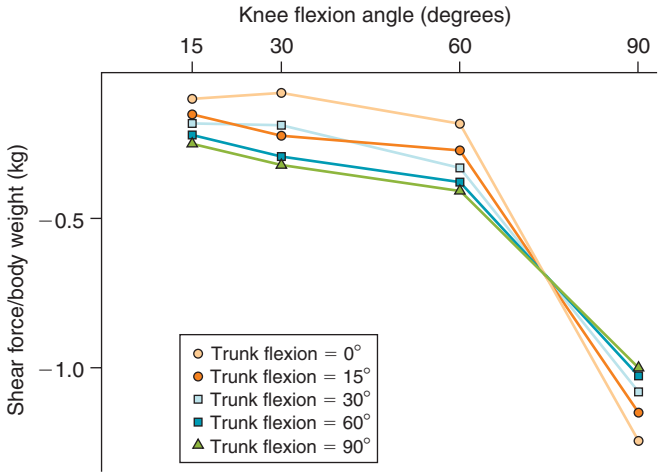


FIG 10-4 Shear force (kilograms) per body weight (kilograms) while standing on both legs at various flexion angles of the knee and the trunk. (From Ohkoshi Y, Yasuda K, Kaneda K, et al. Biomechanical analysis of rehabilitation in the standing position. *Am J Sports Med.* 1991;19:605–611.)

CRITICAL POINTS Options to Regain Muscle Strength

- Protect patellofemoral joint, avoid leg extension 0-30 degrees, exercises involving high knee flexion angles (deep squats, stairs).
- Prefer closed kinetic chain exercises 0- to 50-degree range to minimize patellofemoral forces.
- Control joint effusion to prevent reflex inhibition of quadriceps.
- Electrical muscle stimulation, biofeedback are good adjuncts early postoperatively.
- Use knee extension 50-100 degrees, single-leg and two-legged squats, wall squats, lunges, leg press machine, stationary bicycle initial postoperative phase.
- Single-leg squat, straight-leg raise, heel raises, single-leg stance safe for healing anterior cruciate ligament graft.
- Eccentric training appears advantageous, further studies required to determine safety.
- Motor imagery should be explored early postoperatively to enhance muscle activation.

understand the impact that exercises have on the patellofemoral joint. Patients who develop patellofemoral symptoms postoperatively must be carefully followed and the rehabilitation program altered as required to avoid activities that place high forces on the patella. We recommend avoidance of the leg extension machine (an open kinetic chain [OKC] exercise) in the range of 30 to 0 degrees of knee flexion, as well as exercises that involve high knee flexion angles such as deep squatting, kneeling (past 50 degrees) and extensive stair climbing, in the first 3 months after surgery. The advice to avoid leg extensions in low knee flexion angles was first given many years ago in a cadaveric study conducted in our laboratory that measured the forces incurred on the extensor mechanism that developed during an OKC knee extension simulated exercise.[104] The investigation demonstrated that the quadriceps force required to extend the knee remained at a constant value between 60 and 15 degrees of knee flexion and then rose rapidly. The addition of a small amount of resistance (31 N) doubled the quadriceps force that was required to extend the knee, resulting in large forces on the patellofemoral joint.

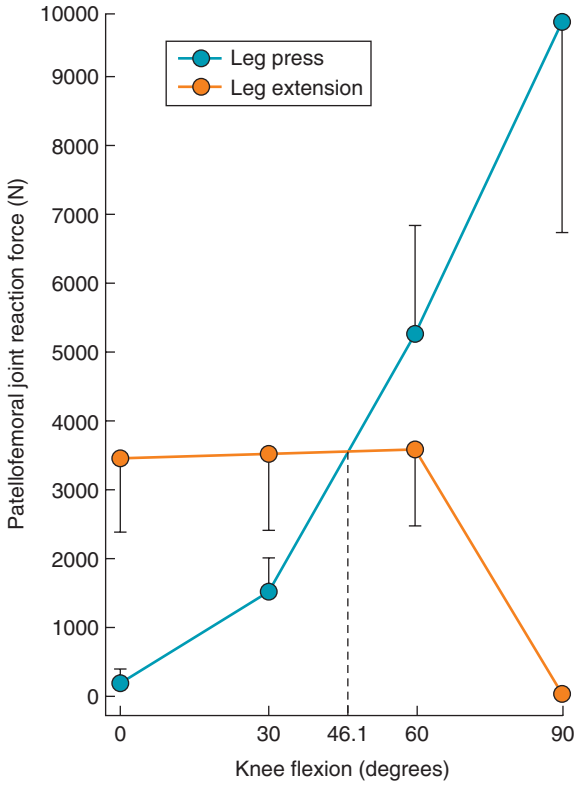


FIG 10-5 Mean ± standard deviation of patellofemoral joint reaction force at four flexion angles. (From Steinkamp LA, Dillingham MF, Markel MD, et al. Biomechanical considerations in patellofemoral joint rehabilitation. *Am J Sports Med.* 1993;21:438–444.)

Steinkamp and associates[266] calculated patellofemoral joint reaction forces in 20 healthy subjects at 0, 30, 60, and 90 degrees of knee flexion during a closed kinetic chain (CKC) leg press exercise and an OKC leg extension exercise. Reaction forces were significantly greater ($P < .001$) at 0 and 30 degrees in the OKC leg extension exercise than during the leg press exercise (Fig. 10-5). The opposite was true at the high knee flexion angles, for which forces were significantly greater in the leg press exercise. The authors concluded that the leg press placed minimal stress on the patellofemoral joint in the functional ROM (low knee flexion angles).

The stress on the patellofemoral joint depends not only on the load applied but also on the surface areas of the patella and femur that may be in contact at any given point in time. At 0 degrees of knee flexion, no or only minimal contact occurs between the patella and trochlear groove (Fig. 10-6).[33,88] With small amounts of knee flexion (20 degrees), contact occurs first on the distal portion of the patella with the proximal trochlea. As the knee flexes, the contact area moves proximally on the patella, whereas at 45 degrees, contact is on the central portion of the patella. Borotikar and Sheehan[33] measured the in vivo contact area between the femur and patella using dynamic magnetic resonance imaging during knee flexion-extension and reported a mean of 125 mm^2 at 10 degrees of flexion, which increased to 229 mm^2 at 40 degrees of flexion. At 90 degrees, the superior portion of the patella is in contact with the trochlea. The greatest compressive forces occur in 60 to 90 degrees of flexion.[103,300] Investigators have estimated that the loads on the patellofemoral joint range from 3 times body weight (BW) with stair climbing to 7 times BW with squatting to up to 20 times BW with jumping.[233,258]

In regard to stair climbing, Goudakos and colleagues[100] reported that, compared with level walking, this activity resulted in greater

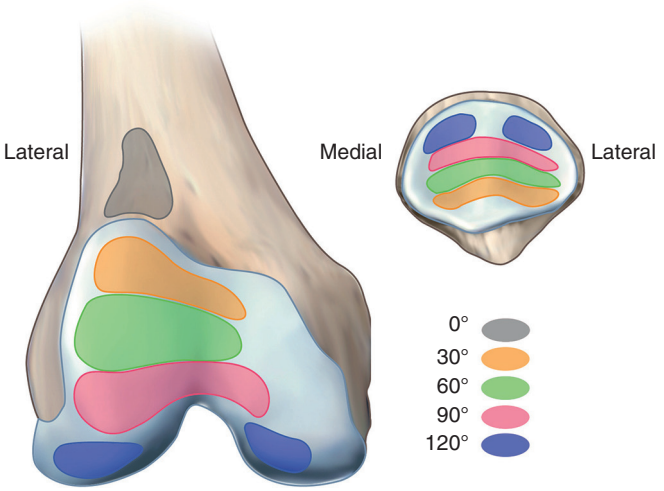


FIG 10-6 Contact surface areas on the patella and trochlea/femoral condyles at various degrees of knee flexion.

patellofemoral mean and peak pressures ($P = .01$), patellar contact area ($P = .02$), and patellar tilt ($P = .02$). These differences were recorded when the knee reached 30 degrees of flexion. At a lower knee flexion angle of 12 degrees, stair climbing resulted in a significantly higher peak patellofemoral pressure, lateral patellar tilt, and amount of lateral force distribution on the trochlea ($P = .01$). These authors concluded that their findings explained the association of stair climbing with patellofemoral pain.

Doucette and Child[60] measured patellar congruence in patients with symptomatic lateral patellar compression syndrome with the lower extremity relaxed, holding an OKC knee extension position, and holding a CKC exercise position. During all three conditions, patellar congruence progressively improved with knee flexion. The authors concluded that a quadriceps contraction had less influence on patellar tracking at 30 degrees of flexion than at 0 degrees of flexion owing to the increased stability of the patella as it moved into the intercondylar groove as the knee was flexed. In low ranges of knee motion, CKC exercises were recommended owing to the improved patellar positioning and decreased joint irritation in symptomatic patellofemoral patients. This advice was more recently supported in a systematic review of exercises for patellofemoral pain by Harvie and associates.[113] Some examples include minisquats (to 45 degrees of knee flexion), wall sits (to 50 degrees of flexion), lateral step-ups, and forward step-ups.[42] Escamilla and associates[74] measured patellofemoral compressive forces during a CKC wall squat exercise in healthy subjects. The forces ranged from approximately 75 to 1400 N between 0 and 50 degrees of knee flexion and then rose to approximately 2100 to 3650 N between 60 and 90 degrees of knee flexion. This compares to compressive forces incurred on the patellofemoral joint during walking of approximately 900 N. A series of studies led Escamilla and colleagues[70,71] to recommend CKC training within 0 to 50 degrees of knee flexion to minimize patellofemoral and cruciate ligament forces.

Control Effusion

A knee joint effusion may precipitate reflex inhibition of the quadriceps, leading to weakness and atrophy.[53] Several investigators documented that quadriceps muscle inhibition occurred following an experimentally induced knee joint effusion and produced alterations in normal function during walking, jogging, and landing from a jump.[134,219,277,278] Therefore it is imperative that knee joint effusions be avoided or treated immediately to lessen deleterious impact on

quadriceps function. Joint aspiration, cryotherapy, transcutaneous electrical nerve stimulation, and compression are effective therapeutic measures.[155,221] Prudent, short-term use of nonsteroidal antiinflammatory medications may also be required.

Electrical Muscle Stimulation and Biofeedback

Neuromuscular electrical muscle stimulation (EMS) and biofeedback are recommended early after surgery in modern ACL rehabilitation protocols (see Chapter 11).[114,221,291] Studies conducted several years ago demonstrated that EMS combined with active exercise was more effective than active exercise alone in recovery of quadriceps strength and normal gait mechanics.[56,260,262] Fitzgerald and associates[82] reported modest (effect size, 0.48) improvements in quadriceps isometric peak torque 16 weeks after ACL reconstruction when an EMS training protocol was incorporated into the postoperative rehabilitation program of 21 patients. Twelve weeks postoperatively, the experimental group demonstrated significantly greater quadriceps isometric peak torque index compared with that of a matched group of patients who did not receive EMS training (75.9 ± 16.8 and 67.0 ± 19.9, respectively; $P < .05$). However, no significant differences were measured at 16 weeks postoperatively between these groups. A greater proportion of the EMS-trained subjects initiated agility training at 16 weeks compared with the control group (62% and 32%, respectively; $P < .05$). Although high-level modern quality studies are lacking, Wright and associates[296] concluded on the basis of a systematic review that high-intensity EMS may help achieve improved quadriceps strength after ACL reconstruction. In a more recent review, Imoto and colleagues[128] concluded that EMS added to conventional exercises may be effective in improving muscle strength and recovery 2 months after surgery.

Biofeedback therapy has been suggested as a useful therapeutic technique in overcoming muscle inhibition early postoperatively.[221] This therapy helps patients develop and increase their voluntary control over muscle contractions.[45,61,62] However, no high-level studies have been conducted to ascertain the effectiveness of biofeedback following ACL reconstruction in regard to increases in muscle strength and/or reduced quadriceps atrophy.

Open Versus Closed Kinetic Chain Exercises

The process of ACL graft maturation and healing is assumed to be influenced by strains and forces applied to the lower limb during weight bearing and exercises. Although a general consensus exists that some strain is necessary to promote the process of ligamentization,[26] questions remain regarding the amount of load that is safe and the amount that may produce graft elongation. Over the past two decades, investigations have attempted to measure, through either analytical or direct means, force and strain incurred on the ACL during common OKC and CKC exercises used in rehabilitation. During CKC exercises, the foot is fixed to a platform or surface, the motion at the knee joint is accompanied by predictable motions at the hip and ankle joints, and the entire limb is loaded such as during a leg press or squat. In OKC exercises, the foot is mobile and not fixed to a surface, and motion at the knee joint occurs independent of motion at the hip and ankle joints. Common examples include the leg extension and hamstring curl exercises.

Calculated ACL Forces, in Vivo ACL Strain

Several years ago, 2-dimensional mathematical models were used to calculate muscle forces, tibiofemoral shear, and compressive forces during isometric and isokinetic exercises.[10,129,143,173,200,201,212,280,297] These analytical models did not allow the authors to determine the magnitude of the ligament forces incurred during various exercises. Experimental biomechanical models have also been used to estimate ACL strain or tensile forces during a variety of OKC and CKC exercises.[70,71,73,75,76,79,226,252,253,290]

Direct in vivo measurement of ACL strain incurred during activities in human subjects has been conducted by several investigators.[21-23,27,84,85,87,117] Beynnon and associates[23,27,84,86,115] conducted a series of studies in which a Hall effect transducer was arthroscopically implanted into the anteromedial fibers of the normal ACL in volunteers undergoing surgical procedures under local anesthesia. Patients performed several OKC and CKC exercises at different knee flexion angles, including isometric contractions,[23] squatting,[27] bicycling,[85] stair climbing,[84] and lunging.[115] The mean peak ACL strains reported in these studies are shown in Table 10-2.[26] The magnitude of ACL strain produced by the exercises assessed in these studies was *lowest* in those that involved (1) isometric contractions of the hamstring muscles; (2) cocontractions of the quadriceps and hamstrings at 30, 60, and 90 degrees of knee flexion; (3) isometric quadriceps contractions at 60 and 90 degrees of knee flexion; and (4) passive flexion and extension of the knee. The activities that produced the *highest* ACL strain included (1) isometric quadriceps contractions at 15 degrees of knee flexion with 30 N-m of extension torque, (2) squatting without and with resistance, and (3) active flexion and extension of the knee with a 45-N weight boot. The authors emphasized that the limits of ACL strain that are safe and not deleterious to healing ACL grafts remain unknown. Although excessive loading must be avoided early postoperatively, controlled loading is required to enhance graft healing and ligamentization.

Escamilla and associates[72] recently summarized data from multiple experimental biomechanical models and in vivo measurements of ACL strain and tensile forces. These investigators concluded that the OKC knee extension exercise performed between 50 and 100 degrees of knee flexion, as well as isometric and isokinetic knee flexion exercises, appear to be safe to the healing graft early postoperatively. In addition, CKC exercises of single-leg and two-legged squats (with and without resistance), forward and side lunges, leg press machine, and stationary bicycle were recommended in the initial recovery phase after surgery.

Anterior Tibial Translation

Studies have reported that the early incorporation of certain OKC exercises after surgery does not adversely affect anterior tibial translation compared with the later initiation of these exercises.[28,29,90,131,225] These exercises include (1) leg extensions in the range of 45 to 90 degrees,[28,29,90,116,189] (2) short arc quadriceps sets from 0 to 30 degrees,[29] (3) quadriceps isometrics at 0 degrees,[28,29,245] and (4) quadriceps-hamstrings cocontraction isometrics at 0 degrees.[28,29,131,245] Beynnon and associates[28] performed a roentgen stereophotogrammetric analysis of tibiofemoral joint displacements and rotations that occurred in 24 patients who began early OKC exercises and compared them with 18 patients who participated in a nonaccelerated program. Significant increases in anterior tibial displacement ($P < .0001$) and internal-external and varus-valgus rotations ($P = .03$) were measured in both groups between the baseline (immediately after surgery) and at the 2-year follow-up evaluation. The investigators concluded that "the entire envelope of knee laxity increases for participants of both rehabilitation programs" and that these increases occur over the first 6 months of graft healing.

Tagesson and colleagues[271] conducted analyses of dynamic anterior tibial translation that occurred during the Lachman test and seven exercises done 5 weeks after ACL reconstruction with a computerized electrogoniometric measuring system. Exercises performed with a straight knee (heel raises, single-leg stance, straight-leg raises) produced significantly less anterior tibial translation than those that

TABLE 10-2 Rank Comparison of Mean Peak Anterior Cruciate Ligament Strain Values Measured in Vivo in Subjects With Uninjured Knees

Exercise	OKC or CKC	Peak ACL Strain (%)
Isometric quadriceps contraction at 15 degrees (30 N-m extension torque)	OKC	4.4
Squat with SportCord	CKC	4
Active flexion and extension (45 N weight boot)	OKC	3.8
Lachman test at 30 degrees (150 N anterior shear load)		3.7
Squat, no resistance	CKC	3.6
Isometric gastrocnemius contraction at 15 degrees (15 N-m plantar flexion torque)	OKC	3.5
Active flexion and extension, no resistance	OKC	2.8
Cocontraction quadriceps and hamstrings at 15 degrees	OKC	2.8
Isometric gastrocnemius contraction at 5 degrees (15 N-m plantar flexion torque)	OKC	2.8
Single-legged sit-to-stand exercise	CKC	2.8
Isometric quadriceps contraction at 30 degrees (30 N-m extension torque)	OKC	2.7
Stair climbing	CKC	2.7
Step-up and step-down	CKC	2.5
Weight bearing at 20 degrees		2.1
Leg press at 20 degrees (40% body weight)	CKC	2.1
Anterior drawer test at 90 degrees (150-N anterior shear load)		1.8
Lunge	CKC	1.8
Stationary bicycling	CKC	1.7
Isometric hamstrings contraction at 15 degrees (10 N-m flexion torque)	OKC	<1.0
Cocontraction quadriceps and hamstrings at 30 degrees	OKC	<1.0
Isometric gastrocnemius contraction at 30 degrees (15 N-m plantar flexion torque)	OKC	<1.0
Passive flexion and extension	OKC	<1.0
Isometric quadriceps contraction at 60 and 90 degrees (30 N-m extension torque)	OKC	0
Isometric gastrocnemius contraction at 45 degrees (15 N-m plantar flexion torque)	OKC	0
Cocontraction quadriceps and hamstrings at 60 and 90 degrees	OKC	0
Isometric hamstrings contraction at 30, 60, and 90 degrees (10 N-m flexion torque)	OKC	0

ACL, Anterior cruciate ligament; *CKC,* closed kinetic chain; *OKC,* open kinetic chain.

required greater motion in the knee joint (Table 10-3). However, when these exercises were evaluated only at the same knee flexion angle as that performed in the Lachman test, they produced less anterior tibial translation ($P < .001$). The authors concluded that all exercises evaluated could be recommended early after ACL reconstruction, but they believed the single-leg squat and straight-leg raise were the safest in terms of ACL graft forces. It is important to note that the cyclic effect on anterior tibial displacement produced from OKC or CKC exercises after ACL reconstruction in the usually prescribed manner performed (e.g., 30-50 sets of an exercise) has not been explored in clinical studies.

Muscle Activation Patterns

Muscle electromyographic (EMG) activation patterns that occur during OKC and CKC exercises have been measured in several studies in uninjured subjects (Table 10-4).[9,19,20,67,79,158,159,184,268,271,290] Notable findings included (1) high and balanced levels of quadriceps activation occurred during CKC single-leg squat, step-ups, and leg press tasks[20,268,271] (see also Table 10-5); (2) the single-leg wall squat had the highest muscle efficiency compared with other single-leg CKC exercises[9]; (3) trunk position affected muscle activity patterns during the forward lunge exercise[79]; and (4) balanced quadriceps-hamstrings cocontractions occurred during the single-leg dead lift, single-leg transverse (rotational) hop, single-leg lateral hop, and lateral band walking exercises (Table 10-6).[19]

The issue of muscle activation patterns that occur after ACL reconstruction was addressed by Tagesson and associates[271] in 11 men and 8 women who underwent preoperative and postoperative (5-week) EMG testing during several exercises. None of the patients had knee pain before the postoperative test; however, there were deficits in knee flexion (mean, 16 degrees; range, 3-55 degrees) and extension (mean, 6 degrees; range, 0-13 degrees). Compared with the preoperative values of the uninjured legs, EMG activation in the reconstructed extremity's hamstrings and gastrocnemius was greater during many of the activities evaluated (Table 10-7). The investigators concluded that patients incorporated greater hamstring muscle activity to enhance joint stiffness to protect the ACL graft.

There are conflicting data regarding the effect of early OKC exercises on the time to restore quadriceps and hamstrings strength. In addition, some studies showed no beneficial effect of early OKC exercises for limb symmetry on hop tests, final muscle strength, proprioception, and functional knee outcome rating scores.[28,29,90,116,131,225] Even so, some investigators recommend the use of early OKC exercises owing to the potential for early postoperative increases in quadriceps strength.[28,90]

Eccentric Muscle Training

Eccentric training has been proposed to enhance increases in muscle cross-sectional area (CSA), volume, and strength after ACL reconstruction.[37,93-96,161] This type of training is believed by some to be superior to concentric training owing to its potential to overload the muscle and produce greater increases in muscle size and strength. Gerber and colleagues[93] used a progressive, gradual eccentric training protocol from 3 to 15 weeks after ACL reconstruction in 16 patients. These investigators reported that patients who completed this program had

TABLE 10-3 Maximal Anterior Tibial Translation During Seven Exercises 5 Weeks After Anterior Cruciate Ligament Reconstruction

Exercise	Uninjured Leg (mm)	ACL-Reconstructed Leg (mm)
Lachman test 90 N	5.3 ± 1.3	5.6 ± 1.4
Seated knee extension 0-100 degrees	5.4 ± 2.7*†‡	5.2 ± 1.3†‡
Level walking	5.0 ± 2.2‡	5.0 ± 1.8
Single-leg squat to 60 degrees	6.0 ± 2.9*†‡	4.9 ± 1.8
Two-legged squat to 75 degrees	5.5 ± 3.0*†‡	4.6 ± 1.6
Heel raise	3.8 ± 2.1§‖¶	4.3 ± 1.6**
Single-leg stance	3.4 ± 2.9§‖¶	4.1 ± 1.9§**
Straight-leg raise	3.2 ± 2.0§‖¶††	4.0 ± 1.3§**

From Tagesson S, Oberg B, Kvist J. Tibial translation and muscle activation during rehabilitation exercises 5 weeks after anterior cruciate ligament reconstruction. *Scand J Med Sci Sports.* 2010;20(1):154-164.
*Exercise significantly different from heel raise ($P < .05$).
†Exercise significantly different from single-leg stance ($P < .05$).
‡Exercise significantly different from straight-leg raise ($P < .05$).
§Exercise significantly different from seated knee extension ($P < .05$).
‖Exercise significantly different from single-leg squat ($P < .05$).
¶Exercise significantly different from two-legged squat ($P < .05$).
**Exercise significantly different from Lachman test ($P < .05$).
††Exercise significantly different from gait ($P < .05$).

a twofold greater increase in quadriceps CSA, volume, and strength compared with patients who followed a standard rehabilitation program only. There were no significant differences between groups in the improvement in volume and CSA of the hamstring muscles. Brasileiro and associates[37] reported significant improvement in isokinetic peak torque and quadriceps CSA following 6 weeks of eccentric training in nine subjects who underwent ACL reconstruction. The training was conducted on an isokinetic dynamometer 9 to 10 months postoperatively. There are concerns with high-force eccentric training after ACL reconstruction, including the potential for inducing damage to the muscle and healing graft. Further high-level research is required to determine the efficacy of this type of training.

Motor Imagery

A few investigators have explored the potential efficacy of the use of motor imagery (MI) as a part of the rehabilitation process early after ACL reconstruction.[50,163] MI is a cognitive process whereby the patient is asked to mentally visualize certain motions, but not to actually perform them, thus not resulting in any measurable outflow from spinal motor neurons. The primary motor cortex is engaged, which may involve contralateral as well as bilateral cortex activity. MI strategies are classified as either kinesthetic motor imagery (KMI) or visual motor imagery (VMI).[269] KMI indicates imaging the *feeling* that the task indicated produces, whereas VMI involves mentally *visualizing* performing the task. In a study involving these concepts in the upper extremity, researchers found that KMI, not VMI, modulated corticomotor excitability.[269]

Cupal and Brewer[50] conducted a randomized trial in which 10 patients were treated with standard physical therapy and a program involving relaxation and MI beginning approximately 2 weeks after ACL reconstruction. This group participated in 10 sessions, each 2 weeks apart, all of which began with breath-assisted relaxation techniques and then progressed to VI. At 24 weeks postsurgery, the treatment group had significantly greater knee isokinetic strength and less reinjury anxiety and pain ($P < .001$) than the placebo and control groups. Lebon and associates[163] studied the effectiveness of MI in a group of seven patients with ACL reconstruction who completed 12 MI sessions beginning 7 to 12 days postoperatively. The sessions were conducted every 2 days and were done along with traditional rehabilitation. At the conclusion of the last session, EMG analysis of the quadriceps showed that, compared with a control group, the MI group elicited greater muscle activation ($P < .05$). There were no significant differences between groups in pain or range of knee motion. In addition, quadriceps muscle size decreased in a similar manner in both groups. These findings led the authors to conclude that MI influences neural, but not structural, modulations and should be considered as a reliable and cost-effective adjunct to standard rehabilitation. Further research is required to determine the short- and long-term potential effects of MI.

RESTORATION OF NEUROMUSCULAR FUNCTION

Proprioception and Postural Stability

Restoration of normal neuromuscular function after ACL reconstruction is paramount for the eventual implementation of sports-specific exercises and release to full activities. Knee joint proprioception is considered by many to be a crucial element of neuromuscular function and its recovery essential for a successful outcome.[194,291] Proprioception is altered after ACL rupture owing to damage incurred to the joint mechanoreceptors and muscle afferents and may be further impaired with a concurrent meniscus tear.[178,180] Years ago, several investigators reported deficits in proprioception 1 to 2 years after ACL reconstruction.[15,31,166,174]

Interestingly, more recent studies[4,28,142,168,194,218,254] have refuted previous findings regarding deficits in proprioception after ACL reconstruction. The authors of a recent systematic review questioned the tests commonly used to measure proprioception and the clinical relevance of prior studies.[98] Littmann and associates[168] found no difference in dynamic position sense accuracy and central nervous system processing time between ACL-reconstructed knees (that were at least 1 year postoperative) and healthy controls. These results conflicted with the patients' perception of knee function and impairment, which was significantly inferior compared with controls. These and other authors[98,174] have suggested that variables other than proprioception

CRITICAL POINTS Restoration of Neuromuscular Function

- Knee joint proprioception and dynamic postural control may be altered from ACL rupture and require restoration early after surgery.
- Joint repositioning, weight shifting, cup and/or cone walking, mini-squats, single-leg stance, lunges, progress from stable to unstable surfaces.
- Normal neuromuscular function may not be restored many months or years postoperatively.
- Front step-downs, lateral step-downs, single-leg balance drills, progressive perturbation training with the therapist, lunge exercises in various directions using a resistance cord onto an unstable surface. Progress to running, plyometrics.
- Patient must be taught correct form and posture during all exercises.

TABLE 10-4 Muscle Activation and Recruitment During Open and Closed Kinetic Chain Exercises

Study	No. of Healthy Subjects	Methods, Muscles Tested	Results	Comments
Wilk et al[290] (1996)	10 men	Knee extension, leg press, squat RF, VMO, VL, BF, ST, SM, gastrocnemius	Maximum quadriceps activation occurred during knee extension from 56-70 degrees. Cocontraction of quadriceps-hamstrings was greatest during squat from 0-30 degrees	Squat best exercise evaluated for quadriceps: hamstring cocontraction; leg press: quadriceps activation 39%-52% MVC, minimal hamstring activity
Beutler et al[20] (2002)	11 men, 7 women	Single-leg squat, step-up RF, VMO, VL	Peak quadriceps activation of MVC: 201 ± 66% squats, 207 ± 50% step-ups	High, sustained levels of quadriceps activation indicated these exercises would be effective for strengthening
Stensdotter et al[262] (2003)	3 men, 7 women	Isometric knee extension at 30 degrees flexion, simulated OKC, CKC activities RF, VMO, VML, VL	Onset activity for all quadriceps muscles was simultaneous during CKC exercise; OKC, onset of VL occurred before all other muscles	CKC more balanced initial quadriceps activation
Ayotte et al[9] (2007)	16 men, 7 women	Single-leg wall squat, single-leg minisquat; forward step-up, lateral step-up, retro step-up GMAX, GMED, VMO, BF	Statistically significant differences in mean normalized EMG signal for 4 muscles among all exercises; wall squat had highest levels of activation	All exercises sufficient for strengthening; wall squat most efficient
Ekstrom et al[67] (2007)	19 men, 11 women	Lateral step-up, lunge VMO, ST, SM, GMAX, GMED	Both exercises >75% MVC of VMO	Both exercises sufficient for quadriceps strengthening
Farrokhi et al[79] (2008)	5 men, 5 women	Forward lunge: trunk erect, trunk forward, trunk extended GMAX, BF, VL, gastrocnemius	Trunk forward position produced significant increases in peak hip flexion angle, hip extensor and ankle plantar flexor impulse, % MVC of GMAX and BF	Trunk position affected exercise; forward position increased hip extensor muscle actions; other positions did not change EMG findings
Tagesson et al[271] (2010)	11 men, 8 women	7 exercises VMO, VL, hamstrings, gastrocnemius, soleus	Highest quadriceps activation: single-leg squat, seated knee extension; no exercise produced enough hamstring activation to promote strengthening	Seated knee extension also produced greatest amount of anterior tibial translation compared with other exercises
Begalle et al[19] (2012)	12 men, 15 women	9 CKC exercises VMO, VL, ST, SM, BF	Most balanced coactivation ratios: single-leg dead lift, single-leg transverse hop, single-leg lateral hop, lateral band walk; no exercise produced enough hamstring activation to promote strengthening	Quadriceps-dominant exercises: single-limb squat, transverse lunge, lateral lunge, forward lunge (see also Table 10-4)

BF, Biceps femoris; *CKC,* closed kinetic chain; *EMG,* electromyographic; *GMAX,* gluteus maximus; *GMED,* gluteus medius; *MVC,* maximum voluntary contraction; *OKC,* open kinetic chain; *RF,* rectus femoris; *SM,* semimembranosus; *ST,* semitendinosus; *VL,* vastus lateralis; *VML,* vastus medialis longus; *VMO,* vastus medialis obliquus.

affect the perception of knee function after ACL reconstruction. Gokeler and colleagues,[98] in a review of 24 studies, found no association between proprioception and (1) quadriceps isokinetic muscle strength, (2) knee joint laxity, (3) limb symmetry on single-leg hop tests, and (4) patient-reported outcome. It may be that modern rehabilitation programs are effective in eliminating proprioceptive deficits as measured by the standard joint position sense and threshold to detect passive motion tests.

Dynamic postural control or stability is another important neuromuscular factor that must be restored after ACL reconstruction. Balance requires constant adjustment to the body's muscular activity and positioning and is influenced by the integration of sensorimotor information into the central nervous system and the resultant motor response. Impairment in postural stability is believed to be related, in part, to deficiencies in proprioception.[1,97] Postural control may be measured using a *static* test on a fixed force platform by assessing the displacement (in centimeters) of the patient's center of gravity in the sagittal and frontal planes. A *dynamic* test may also be used with a tilting or translating platform in which the deviation from the level position is indicated in degrees, or with an even simpler clinical method such as the Star Excursion Balance Test (SEBT). The SEBT requires a patient to maintain a stable base by balancing on one leg

TABLE 10-5 Normalized Electromyographic Signal Amplitudes (% MVIC) for Seven Exercises in Uninjured Legs

Exercise	Vastus Medialis	Vastus Lateralis	Hamstrings	Gastrocnemius	Soleus
Level walking	114 ± 212[a,b]	25 ± 13[c,d,e,f]	26 ± 24[b,e]	59 ± 47[b,c,d,e,f]	78 ± 30[b,c,d,e,f]
Single-leg squat to 60 degrees	110 ± 83[b]	61 ± 38[a,b,g]	16 ± 13	32 ± 26[a,f,g]	47 ± 24[c,e,f,g]
Seated knee extension 0-100 degrees	94 ± 53	82 ± 50[a,b,e,g]	18 ± 12	12 ± 12[a,g]	16 ± 23[a,b,d,g]
Straight-leg raise	90 ± 49	78 ± 33[a,b,g]	20 ± 14[b]	7 ± 4[a,d,g]	13 ± 11[a,b,d,g]
Two-legged squat to 75 degrees	73 ± 32	54 ± 31[a,b,c,g]	12 ± 6[g]	19 ± 24[a,f]	19 ± 17[a,d,g]
Heel raise	28 ± 22[g]	20 ± 11[c,d,e,f]	20 ± 14[d]	74 ± 28[b,c,d,e,f]	61 ± 36[b,c,e,f]
Single-leg stance	12 ± 8[d,g]	10 ± 5[b,c,d,f]	7 ± 8[a,f,g]	21 ± 18[a,g]	36 ± 18[a,c,f,g]

From Tagesson S, Oberg B, Kvist J. Tibial translation and muscle activation during rehabilitation exercises 5 weeks after anterior cruciate ligament reconstruction. *Scand J Med Sci Sports*. 2010;20(1):154-164.
[a]Exercise significantly different from heel raise ($P < .05$).
[b]Exercise significantly different from single-leg stance ($P < .05$).
[c]Exercise significantly different from seated knee extension ($P < .05$).
[d]Exercise significantly different from single-leg squat ($P < .05$).
[e]Exercise significantly different from two-legged squat ($P < .05$).
[f]Exercise significantly different from straight-leg raise ($P < .05$).
[g]Exercise significantly different from gait ($P < .05$).
MVIC, maximum voluntary isometric contraction.

TABLE 10-6 Quadriceps and Hamstrings Normalized Electromyographic Signal Amplitudes (% MVIC) and Quadriceps-Hamstrings Coactivation Ratios for Nine Exercises in Uninjured Legs

Exercise	Quadriceps	Hamstrings	Quadriceps-Hamstrings Coactivation Ratio
Forward lunge	128.42 ± 57.32*	15.20 ± 7.98	9.70 ± 5.90†
Lateral lunge	141.42 ± 55.07*	15.08 ± 7.37	9.30 ± 5.53†
Transverse (rotational) lunge	123.73 ± 51.06*	20.99 ± 9.09‡	7.78 ± 5.51
Single-leg squat	113.27 ± 38.49*	22.24 ± 8.42‡	5.52 ± 2.89
Single-leg forward hop	75.87 ± 58.77	14.66 ± 7.58	5.26 ± 4.43
Lateral band walk	45.27 ± 19.01	10.69 ± 6.05	3.64 ± 1.57§
Single-leg lateral hop	67.84 ± 42.18	17.97 ± 8.79	3.83 ± 3.51§
Single-leg transverse (rotational) hop	48.46 ± 40.04	16.47 ± 10.29	3.77 ± 3.51§
Single-leg dead lift	65.71 ± 29.40	24.15 ± 8.51‡‖	2.87 ± 1.77§

From Begalle RL, Distefano LJ, Blackburn T, Padua DA. Quadriceps and hamstrings coactivation during common therapeutic exercises. *J Athl Train*. 2012;47(4):396-405.
*Exercise uses significantly greater quadriceps activation than lateral band walk, single-leg dead lift, all hopping exercises ($P < .01$).
†Ratio significantly greater than all other exercises ($P < .01$).
‡Exercise uses significantly greater hamstrings activation than lateral band walk ($P < .001$).
§Ratio significantly smaller than all three lunge exercises ($P < .01$).
‖Exercise uses significantly greater hamstrings activation than lateral band walk, forward hop, lateral lunge, forward lunge ($P < .01$).
MVIC, maximum voluntary isometric contraction.

while reaching out with the other leg and touching the ground as far as possible in various directions.[13]

Howells and associates[124] reviewed 10 studies of ACL reconstruction and concluded that subjects appeared to have impaired postural control, especially in dynamic tasks that were more relevant to actual sports activities. Subsequently, other studies demonstrated impairments in dynamic postural stability in athletes.[55,190,198,287] The clinical significance of these deficits in regard to risk of reinjury and poor outcomes is unclear and requires further study. Even so, investigators encouraged the continuation of supervised neuromuscular training before[190,198] and after[55] the patient has returned to athletics in an effort to correct this problem.

A general consensus exists that the ACL postoperative rehabilitation program should include exercises believed to improve proprioception and postural stability as soon as possible after surgery and gradually progress in difficulty. Some examples of these exercises are joint repositioning (with the therapist),[139] weight shifting, cup and/or cone walking, mini-squats (to 25 to 30 degrees of knee flexion) on a stable and unstable surface, single-leg stance on even and then unstable surfaces,[90] and lateral and/or diagonal lunge drills. Recently, Cappellino and associates[40] devised a unique neurocognitive exercise protocol that included MI initially to assist in recovery of motor skills. A pilot study showed promise in improvements in gait and lower limb symmetry while standing. Brunetti and associates[39] conducted vibration muscle stimulation (low amplitude, high frequency with simultaneous muscle voluntary contraction) to the quadriceps 1 month postoperatively in 15 patients. When compared with 15 other patients who did not receive the therapy, single-leg standing balance and

TABLE 10-7 Normalized Electromyographic Signal Amplitudes (% MVIC) for Seven Exercises 5 Weeks After Anterior Cruciate Ligament Reconstruction*

	VASTUS MEDIALIS		VASTUS LATERALIS		HAMSTRINGS		GASTROCNEMIUS		SOLEUS	
EXERCISE	% MVIC	*P* Uninj	% MVIC	*P* Uninj	% MVIC	*P* Uninj	% MVIC	*P* Uninj	% MVIC	*P* Uninj
Level walking	73 ± 83[a]	NS	38 ± 22[b,c]	.05	115 ± 132[a,b,d,e,g]	.003	67 ± 59[a,b,d,e,g]	NS	98 ± 64[a,b,d,g]	NS
Single-leg squat to 60 degrees	85 ± 39[a,e]	NS	70 ± 31[a,e,g]	NS	68 ± 45	.001	56 ± 40[a,e,d,g]	.02	75 ± 50[a,b,d,g]	.003
Seated knee extension 0-100 degrees	75 ± 89[a,e]	NS	74 ± 49[a,e,g]	NS	39 ± 29[g]	.003	40 ± 30[a,e,g]	.001	12 ± 6[c,e,g]	NS
Straight-leg raise	49 ± 37	.001	55 ± 24[a,e]	NS	19 ± 10[g]	NS	13 ± 9[b,c,e,g]	.004	11 ± 9[c,e,g]	NS
Two-legged squat to 75 degrees	58 ± 31	NS	54 ± 23[a,e]	NS	28 ± 23[g]	.001	24 ± 15[c,e,g]	NS	28 ± 19[c,e,g]	.02
Heel raise	28 ± 22[b,c]	NS	29 ± 17[b,c,d,g]	NS	41 ± 30[g]	.001	96 ± 30[a-d,f,g]	NS	71 ± 27[a,b,d,g]	NS
Single-leg stance	17 ± 13[b,c,g]	NS	18 ± 11[b,c,d,g]	.002	34 ± 3[g]	.001	28 ± 13[c,e,g]	NS	38 ± 15[c,e,g]	NS

From Tagesson S, Oberg B, Kvist J. Tibial translation and muscle activation during rehabilitation exercises 5 weeks after anterior cruciate ligament reconstruction. *Scand J Med Sci Sports.* 2010;20(1):154-164.
*See Table 10-4 for values of uninjured legs.
[a]Exercise significantly different from seated knee extension ($P < .05$).
[b]Exercise significantly different from gait ($P < .05$).
[c]Exercise significantly different from single-leg squat ($P < .05$).
[d]Exercise significantly different from two-legged squat ($P < .05$).
[e]Exercise significantly different from heel raise ($P < .05$).
[f]Exercise significantly different from single-leg stance ($P < .05$).
[g]Exercise significantly different from straight-leg raise ($P < .05$).
MVIC, maximum voluntary isometric contraction; *NS,* not significant; *Uninj,* uninjured.

extensor muscle torque of the treated subjects was significantly improved immediately after the 3-day treatment and remained so 9 months later ($P < .05$).

Advanced Neuromuscular Activities

The restoration of normal neuromuscular function and correction of limb-to-limb asymmetry during complex athletic tasks is the final goal of ACL reconstruction and postoperative rehabilitation. Unfortunately, several recent investigations demonstrated this goal was not achieved in young athletic populations before or after sports were resumed (Table 10-8).[41,52,55,57,99,176,211,216,217,235,272,298] Because of these relatively new findings, we can only speculate on rehabilitation concepts that may correct continued neuromuscular impairments. For instance, Delahunt and colleagues[55] concluded, "Based on our findings, we would advocate the use of dynamic stabilization training, with emphasis placed on the correct execution of sports applicable techniques incorporating tri-planar hip and knee joint control." Nyland and associates[211] demonstrated long-term (5 years postoperatively) compensatory neuromuscular and biomechanical adaptations in 70 patients during a single-leg countermovement jump, even though knee extensor muscle strength and limb symmetry on a single-leg hop test were within normal limits. The findings included decreased lower-extremity landing forces, decreased vastus medialis activation, and increased gluteus maximus activation. The investigators suggested the need to continue neuromuscular training for as long as patients continue to participate in high-risk athletic activities.

Exercises to promote neuromuscular function are detailed in Chapters 11 and 12. Examples include front step-downs, lateral step-downs, single-leg balance drills, progressive perturbation training with the therapist, and lunge exercises in various directions using a resistance cord onto an unstable surface. It is crucial that the patient be taught correct posture and form while performing these exercises. This includes avoiding varus or valgus lower limb alignment, maintaining knee flexion to prevent knee hyperextension, avoiding hip adduction and internal rotation, maintaining balance and control throughout the exercise, and landing softly to decrease ground reaction forces. The progression of exercises to running, pivoting and/or cutting, plyometrics, and return to full activities is based on specific criteria to be discussed next.

CRITERIA TO BEGIN SPORTS TRAINING, RETURN TO FULL ACTIVITIES

Published Criteria

A lack of consensus exists among medical professionals regarding the objective and subjective criteria patients should achieve before clearance is given to progress to strenuous training and, eventually, release to full sports activities.[51,69,133,246,276] We conducted a systematic review to determine when return to unrestricted athletics was deemed appropriate following ACL reconstruction.[11] Literature published between

CRITICAL POINTS Criteria to Begin Sports Training, Return to Full Activities

- Systematic review of 264 articles revealed only 13% listed objective criteria for return to activities.
- Use knee examination, isokinetic muscle test, single-leg hop test, knee arthrometer test, completion of each phase before progression to next phase allowed (see Table 10-9).
- Most of the rehabilitation program is done at home, but therapist must be actively involved during all phases.

2001 and 2011 was searched, and 264 articles were identified that were original research reports (all levels of evidence) involving primary ACL reconstructions in skeletally mature patients who had a minimum of 12 months of follow-up. Of these, 105 (40%) failed to provide any criteria for return to sports postoperatively. In 84 studies (32%), the amount of time postoperatively that patients were allowed to return to sports activities was the only criterion provided. In 40 other studies (15%), the amount of time along with subjective criteria (that could not be measured) were provided.

Only 35 studies (13%) in the review listed objective criteria required for return to athletics. These included muscle strength (25 studies), knee effusion and/or ROM (15 studies), limb symmetry on single-leg

TABLE 10-8 Impairments in Advanced Neuromuscular Activities After Anterior Cruciate Ligament Reconstruction

Study	Subjects	Testing Protocol	Results	Comments
Dai et al[52] (2013)	23 ACLR adolescents, 5-7.6 mo postoperative before return to sports	Vertical approach jump, preplanned side-cut 35 degrees, involved-noninvolved limb GRF, knee kinetics in sagittal plane	24%-34% asymmetries in peak knee extension moment, average knee moment, total knee work 11%-23% asymmetries in GRF on vertical jump, <11% on side-cut Asymmetry index of peak knee moments correlated with GRF asymmetry indexes	Asymmetries in vertical GRF significantly predicted knee kinetic asymmetries (11%-19% estimation errors) during both tasks No control group
Roos et al[235] (2014)	21 ACLD, 3-240 mo postinjury 23 ACLR, 7-36 mo postoperative 20 controls	Single-leg hop, involved leg only onto force platform, isokinetic knee extension-flexor 90 degrees/sec, hip abductor-adductor 45 degrees/sec	ACLR significantly reduced hop distance, peak knee extensor moment compared with controls ($P < .001$) Hop distance correlated with strength ($P < .01$).	Fluency (mediolateral knee control) in coronal plane was reduced in ACLR and ACLD
Delahunt et al[55] (2012)	14 ACLR, avg. 4.4 yr postoperative 14 controls, all female athletes	Vertical two-legged drop-jump 35 cm	ACLR increased peak hip adduction ($P = .01$) and internal rotation ($P < .05$), decreased peak knee adduction ($P < .05$) and flexion ($P < .01$) angles At IC, ACLR valgus knee position, controls varus knee position	ACLR multiplanar kinematic deficits
Castanharo et al[41] (2011)	12 ACLR, avg. 37 mo postoperative 12 controls, all male, all participating in sports	Countermovement jump, squats	ACLR 13% lower peak knee joint power involved-noninvolved side on jump task ($P < .05$) ACLR 15% greater hip/knee power ratio on involved side on squat task ($P < .05$)	ACLR asymmetries suggest need for improved rehabilitation
Madhavan et al[176] (2011)	12 ACLR, avg. 3.7 yr postoperative 12 physically active controls, all female	LLRs in quadriceps-hamstrings in response to unexpected perturbation during single-leg squat to 30 degrees flexion	ACLR greater overshoot error, knee velocity, increased LLR responses, reduced absolute anticipatory, short-latency reflex, voluntary quadriceps activity	ACLR impaired response of decreased quadriceps activity and enhanced LLR
Ortiz et al[217] (2011)	13 ACLR, 1-16 yr postoperative 15 physically active controls, all female	Single-leg side-to-side hop, hip and knee joint angles/moments, EMG quadriceps/hamstrings	ACLR greater knee abduction moments	Landing mechanics, muscle activation similar with exception of knee abduction moments
Yosmaoglu et al[298] (2011)	20 ACLR, 6 and 12 mo postoperative	Target-tracking ability, isokinetic strength 60 degrees/sec, 180 degrees/sec, single-leg hop	Significant deficits in isokinetic strength and hop test 6 mo postoperative improved 12 mo postoperative Significant deficits in concentric and eccentric motor coordination tracking ability 6 and 12 mo postoperative	Significant coordination deficits remained at 12 months postoperative, even though muscle and hop performance improved
Deneweth et al[57] (2010)	9 ACLR (6 male, 3 female), 4 mo postoperative	Single-leg forward hop landing	At IC, reconstructed side had significantly greater knee extension, external tibial rotation, and medial tibial translation than contralateral side ($P < .05$)	Patients had different tibiofemoral joint motion on reconstructed knee; caution warranted in performing this task 4 mo postoperative

TABLE 10-8 Impairments in Advanced Neuromuscular Activities After Anterior Cruciate Ligament Reconstruction—cont'd

Study	Subjects	Testing Protocol	Results	Comments
Gokeler et al[99] (2010)	9 ACLR (6 male, 3 female), 6 mo postoperative 11 controls	Single-leg hop, EMG	ACLR significantly earlier onset times for all muscles except vastus medialis compared with noninvolved side ($P < .05$) Significantly reduced knee flexion during takeoff, increased plantar flexion at IC ($P < .05$) Significantly lower knee extension moment ($P < .05$)	Muscle onset times earlier and movements patterns altered on ACLR side compared with contralateral side 6 mo postoperative
Nyland et al[211] (2010)	70 ACLR (35 male, 35 female), avg. 5.3 yr postoperative	Single-leg countermovement vertical jump	ACLR decreased lower-extremity landing forces ($P < .01$), decreased vastus medialis activation ($P = .01$), increased gluteus maximus ($P < .0001$) and gastrocnemius activation ($P < .0001$)	Patients demonstrated protective mechanisms to minimize knee loads
Orishimo et al[216] (2010)	13 ACLR (9 male, 4 female), 4-12 mo postoperative	Single-leg hop	Takeoff: degrees of knee motion of reconstructed side significantly smaller than noninvolved side ($P < .01$), peak knee extensor moment 40% lower ($P = .01$), peak power generated at knee 38% lower ($P < .01$)	During takeoff, decreased knee moment and power production compensated for by higher moments and power at the hip During landing, decreased knee power compensated for by greater power absorption at the ankle

ACLD, Anterior cruciate ligament deficient; *ACLR,* anterior cruciate ligament reconstructed; *avg.,* average; *EMG,* electromyographic; *GRF,* ground reaction force; *IC,* initial contact; *LLR,* long latency reflex.

hop tests (10 studies), and knee stability (8 studies). In regard to muscle strength, recommendations ranged from more than 80% to more than 90% for isokinetic testing of the quadriceps and hamstrings compared with the contralateral side. There were no data regarding requirements for the hamstring/quadriceps ratio or other muscle groups.

A multifactorial analysis of knee function was determined by two studies[111,182] in which three to four categories were included for release to sports activities. Hartigan and associates[111] required 90% or greater scores on the quadriceps strength index, four single-leg hop tests (single hop, triple hop, triple crossover hop, time hop), the Knee Outcome Survey activities of daily living scale, and a global rating of overall knee function. Mascarenhas and colleagues[182] proposed at least 90% on a weighted leg extension test and hop and/or jump tests (although the specific tests were not provided), full knee motion, and no effusion for return to athletics.

Van Grinsven and coworkers[284] conducted a systematic review of the rehabilitation literature to develop an evidence-based postoperative ACL program that would allow a return to athletics within 6 months. These authors recommended the following for return to sports criteria: full knee motion, at least 85% on strength (quadriceps and hamstrings) and single-leg hop tests compared with the opposite leg, no more than a 15% deficit on the hamstrings/quadriceps strength ratio, no pain or swelling with sport-specific activities, and a stable knee in active situations.

Our Recommendations

We recommend the criteria shown in Table 10-9 for progression to advanced training and release to unrestricted sports activities.[114] Other tests to consider include the multistage fitness test to determine maximal oxygen consumption[230] and the 60-second sit-up test or other core strength measures.[215] If isokinetic test equipment is not available, a one-repetition maximum bench press and leg press is recommended if weight room equipment is available, along with an experienced test administrator and a sufficient amount of time to safely conduct these tests.[151,234] If the athlete desires to return to high-risk activities, the medical professional should watch the athlete's pivoting and cutting techniques, which should demonstrate the ability to maintain the upper body over the knees and toes, adequate knee and hip flexion, and symmetry with the technique compared with the uninvolved leg.

Home-Based Versus Supervised Therapy

In several investigations, researchers have compared home-based rehabilitation with supervised clinic-based physical therapy programs.[18,81,101,102,121,241] The studies found similar outcomes among programs, and most authors agree that essential components required for a successful home-based protocol are preoperative patient education sessions, a comprehensive written and visual description of the exercises, and periodic monitoring of the patient's progress by a therapist. However, the investigations did not provide a rigorous analysis of the sports activities to which patients returned (both asymptomatically and symptomatically), details regarding the end-stage functional progression of their programs (e.g., plyometric training), or long-term outcomes. There were several methodologic problems, such as small sample sizes and inadequate randomization, making conclusions difficult.[3] It remains unclear if patients participating in a home-based program are able to achieve the same final goals as those in a supervised situation in terms of restoration of normal neuromuscular

TABLE 10-9 Recommendations for Progression of Advanced Training and Return to Sports After Anterior Cruciate Ligament Autogenous Reconstruction

Approximate Time Postoperative	Activity Permitted	Requirements
Weeks 9-12	Straight running	Isokinetic test isometric mode quadriceps, hamstrings: ≤30% deficit No pain, swelling, patellofemoral crepitus Lachman, KT-2000 (MEDmetric) arthrometer test: <3-mm increase over opposite side
Weeks 13-26	Cutting, basic plyometrics	Isokinetic test 300 degrees/sec quadriceps, hamstrings: ≤25% deficit No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test: <3-mm increase over opposite side Single-leg hop tests: ≤25% deficit
Week 27 and beyond	Advanced plyometrics	Isokinetic test 180 degrees/sec and 300 degrees/sec quadriceps, hamstrings: <15% deficit No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test: <3-mm increase over opposite side Single-leg hop tests: <15% deficit Successful completion of running program Successful completion beginning plyometric training with therapist
As indicated	Release unrestricted to sports	Isokinetic test 180 degrees/sec and 300 degrees/sec quadriceps, hamstrings: ≤10% deficit No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test: <3-mm increase over opposite side Single-leg hop tests: <15% deficit Successful completion of advanced plyometric training >60% normalized knee separation distance on video drop-jump test No valgus motion or mediolateral movement of knee on single-leg squat test

indices. One recent study found that although patient compliance in completing home exercises after ACL reconstruction was acceptable, it was affected by fluctuations in pain, negative mood, and stress.[38] In addition, the term *home-based* may be misleading because the therapists in the investigations were actively involved in the patients' care. We acknowledge that a great deal of the rehabilitation program must be done outside the clinic setting owing to insurance and financial issues. However, in light of the potential for reinjury in younger, highly active patients, to be discussed next, it is believed critical that the therapist remain actively involved in the patient's care throughout advanced neuromuscular and plyometric training.

REINJURY RISK FACTORS

An important component of the surgery and rehabilitation process is an understanding of the risks of reinjury upon return to activity. In both long-term[35,64,126,130,144,162,196,213,228,240,292] and short-term investigations,[140,177,223] researchers have reported concern regarding reinjury rates after ACL reconstruction (Table 10-10); however, the factors most responsible for this problem remain unclear. The contralateral knee is also at risk for ACL rupture, and many studies have documented a higher rate of this injury than that to the ACL-reconstructed knee.[35,126,162,196,213,223,228,240,270]

CRITICAL POINTS Reinjury Risk Factors

- Concerning reinjury rates published, involve both knees.
- Factors that may influence reinjury rates: patient age, activity level, family history, use of allografts.
- Possibility exists that many athletes have not regained normal neuromuscular indices in both lower limbs, and premature release to unrestricted activities is a potential factor for reinjuries.

Investigators have analyzed potential risk factors for reinjury rates, including patient age, sex, sports activity level, type of graft, and genetic predisposition.[32,35,126,140,177,197,228,240,251,283] Younger patient age is the factor most frequently associated with an increased risk of reinjury.[126,140,177,228,240,251,283] Shelbourne and colleagues[251] reported a reinjury rate (to either knee) of 17% for patients younger than 18 years of age, 7% for those aged 18 to 25 years, and 4% for those older than 25 years of age. A total of 72% of patients younger than 18 years of age returned to sports and did so an average of 4.6 months postoperatively. Although not always related to patient age, return to high-level[239] or high-risk sports such as soccer,[251] basketball,[251] and team handball[197] has also been associated with increased injury rates.

Bourke and colleagues[35] reported that female sex and a family history of ACL ruptures (to either sex) were significantly associated with subsequent ACL reinjuries. Borchers and associates,[32] in a case-control study, reported that the use of allografts and a return to high levels of sports activities were significant risk factors for ACL graft failure in 21 of 322 patients followed 2 years postoperatively. High failure rates and an increased risk for revision after ACL allograft reconstruction have been reported by other investigators, especially in young active cohorts.[16,186,231,256,286] Paterno and colleagues[223] reported that alterations in neuromuscular control of the hip and knee on a drop-jump task and postural stability predicted ACL injury upon return to activities after reconstruction in 43 athletes followed for 1 year postoperatively. In this investigation, 10 of the 13 patients who sustained a reinjury did so to the contralateral knee. Studies in which researchers have specifically analyzed patients who sustained contralateral ACL rupture have noted return to high activity levels, age younger than 21 years, small intercondylar notch width, generalized joint laxity, and a family history of ACL injuries as potential risk factors for this problem.[2,108,193,228,239,247,265]

Unfortunately, studies in which investigators assessed factors that might have been responsible for reinjury rates did not always take into

TABLE 10-10 Rates of Reinjury/Graft Failure in the Reconstructed Knee and Injury to the Contralateral Anterior Cruciate Ligament

Study	Follow-up	*N*, ACL Graft*	ACL Graft Reinjured/ Failed	Fully Positive Pivot Shift, Lachman, IKDC Grade C-D	Contralateral ACL Injured	Factors Associated With Reinjuries, Failures
Inderhaug et al[130] (2013)	10 yr	83 STG	4%	20%	NA	None
Kamien et al[140] (2013)	2 yr	98 STG	15%	NA	NA	Age ≤25 yr
Bourke et al[35] (2012)	15 yr	314 BPTB, 359 STG	11%	NA	14%	Female sex, family history of ACL rupture, BPTB graft for contralateral knee
Magnussen et al[177] (2012)	6-47 mo	256 STG	7%	NA	NA	Age <20 yr, small graft size
Murray et al[196] (2012)	13 yr	96 BPTB	4%	15%	7%	None
Hui et al[126] (2011)	15 yr	90 BPTB	8%	8%	24%	Coronal graft inclination angle <17 degrees (vertical graft placement) for ACL-reconstructed knee Age <18 yr for contralateral knee
Wipfler et al[292] (2011)	8.8 yr	29 BPTB, 25 STG	11%	NA	NA	NA
Oiestad et al[213] (2010)	10-15 yr	181 BPTB	8%	25%	14%	NA
Borchers et al[32] (2009)	2 yr	135 autografts	3.7%	NA	NA	
		187 allografts	8.6%	NA	NA	Allograft, high activity level
Shelbourne et al[251] (2009)	5 yr	1415 BPTB	4.3%	NA	5.3%	Age <18 yr, Female sex for contralateral knee
Lebel et al[162] (2008)	10 yr	101 BPTB	9%	9%	14%	None
Pinczewski et al[228] (2007)	10 yr	90 BPTB	8%	8%	22%	Increased laxity for ACL-reconstructed knees
		90 STG	13%	13%	10%	Age <21 yr for contralateral knee
Keays et al[144] (2007)	6 yr	29 BPTB	0%	0%	7%	None
		27 STG	7%	7%	11%	
Salmon et al[240] (2006)	5-13 yr	67 BPTB	13%	7%	22%	Age <21 yr and meniscectomy for ACL-reconstructed knee
Drogset et al[64] (2006)	16 yr	45 primary repair	NA	51%	2%	None
		42 repair + LAD	NA	36%	12%	
		42 BPTB	NA	8%	12%	

ACL, Anterior cruciate ligament; *BPTB,* bone-patellar tendon-bone; *ITB EA,* iliotibial band extra-articular; *LAD,* ligament augmentation device; *NA,* not available; *STG,* semitendinosus-gracilis.
*Grafts are autografts unless otherwise indicated.

account the status of the athletes' strength, stability, neuromuscular control, and general knee condition upon return to sports. The possibility exists that many athletes had not regained normal indices in both lower limbs and that the premature release to unrestricted activities may have been a factor in the subsequent reinjuries. The effect of advanced neuromuscular retraining following ACL reconstruction on the reduction of reinjury rates remains unknown.

Note that ACL grafts may fail for reasons other than obvious reinjuries. These include improper graft placement,[181] failure of the graft to complete the healing (revascularization) process, failure to correct lower-limb malalignment, and failure to restore deficiency to other ligaments in the knee joint. These problems are discussed in detail in Chapter 8.

PSYCHOLOGICAL FACTORS THAT MAY AFFECT OUTCOMES

An important consideration regarding factors that may affect patient outcomes for the rehabilitation team are patient psychological traits

Critical Points Psychological Factors That May Affect Outcomes

- Fear of reinjury one of most common reasons for failure to return to preinjury activity levels.
- Measures of self-motivation, self-efficacy, and optimism predict compliance with rehabilitation, return to sport, and self-rated knee function.
- Self-efficacy influenced by patient's preinjury activity level, age, chronicity of injury, and sex.
- Modeling techniques may be effective in increasing early postoperative levels of self-efficacy and motivation to comply with rehabilitation.
- Further work highly warranted to improve postoperative self-efficacy and investigate appropriate preoperative psychological screening methods to determine patients who require additional support and counseling.

TABLE 10-11 Knee Self-Efficacy Scale

Category	Items
Daily activities	*Right now, despite pain or discomfort, how certain are you about:* • Walking in the forest • Climbing up and down a hill/stairs • Going out dancing • Jumping ashore from a boat • Running after small children • Running for the tram/bus • Working in the garden
Sports and leisure activities	• Cycling a long distance • Cross-country skiing • Riding a horse • Swimming • Hiking in the mountains
Physical activities	• Squatting • Jumping sideways from one leg to the other • Working out hard • Doing one-leg hops on the injured leg • Moving around in a rocking small boat • Doing fast twisting
Knee function in the future	*How certain are you that:* • You can return to the same physical activity level as before the injury? • You would not suffer any new injuries to your knee? • Your knee will not "break"? • Your knee will not get worse than before surgery?

From Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. A new instrument for measuring self-efficacy in patients with an anterior cruciate ligament injury. *Scand J Med Sci Sports*. 2006;16(3):181-187.
Responses to all items are done on an 11-grade Likert scale from 0 (not at all certain) to 10 (very certain).

TABLE 10-12 Tampa Scale of Kinesiophobia for Anterior Cruciate Ligament Injury Studies

1. I'm afraid that I might injure myself if I exercise.
2. If I were to overcome it, my pain would increase.
3. My body is telling me I have something dangerously wrong.
4. My knee trouble would probably be relieved if I were to exercise.
5. People aren't taking my medical condition seriously enough.
6. My accident has put my body at risk for the rest of my life.
7. Pain always means I have injured my body.
8. Just because something aggravates my knee trouble does not mean it is dangerous.
9. I am afraid that I might injure myself accidentally.
10. Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my injured leg from worsening.
11. I wouldn't have this much knee trouble if there wasn't something potentially dangerous going on in my body.
12. Although my knee condition is painful, I would be better off if I were physically active.
13. Pain lets me know when to stop exercising so that I don't injure myself.
14. It's really not safe for a person with a condition like mine to be physically active.
15. I can't do all the things normal people do because it's too easy for me to get injured again.
16. Even though my injured knee is causing me a lot of pain, I don't think it's actually dangerous.
17. No one should have to exercise when he/she is gets injured.

From Kvist J, Ek A, Sporrstedt K, Good L. Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2005;13(5):393-397.
Responses to all items are done on a 4-point Likert scale from 1 (strongly disagree) to 4 (strongly agree). On a scale from 0 to 51, a higher score indicates more fear.

and behavioral responses to injury and pain.[6,7,36,59,77,83,112,157,160,165,179] Researchers have tested basic psychological theories of the fear-avoidance model and self-efficacy. Fear of reinjury is one of the most common reasons patients fail to return to preinjury sports activity levels.[5,7,43,59,83,157,281] *Self-efficacy* refers to the judgment of one's potential ability to complete a task. Following ACL surgery, an individual with a high level of self-efficacy will devote considerable effort and have greater resolve to return to their desired level of activity than will a patient with low self-efficacy.

Available scales for ACL studies related to psychology include (1) the Anterior Cruciate Ligament-Return to Sport After Injury scale (12 items)[288]; (2) the Knee Self-Efficacy Scale (22 items, Table 10-11)[274]; (3) the Tampa Scale of Kinesiophobia, adapted by Kvist and associates[157] for ACL injury studies (17 items, Table 10-12); (4) the shortened version of the Tampa Scale of Kinesiophobia[92,293]; (5) the Emotional Responses of Athletes to Injury Questionnaire (28 items)[192]; and (6) the Sport Rehabilitation Locus of Control scale (9 items).[195]

A recent systematic review by Everhart and associates[77] noted that measures of self-motivation, self-efficacy, and optimism were predictive of compliance with rehabilitation, return to sport, and self-rated knee function. Ardern and colleagues[6] found that preoperative psychological responses predicted return to preinjury sports by 12 months after surgery. Factors included readiness to return to sport, the subject's estimate of how long it would take to return, and locus of control. Locus of control indicates whether patients believe their health is controlled by their own behavior and beliefs or by fate or chance.[36] Chmielewski and coworkers[44] studied longitudinal changes in the psychosocial factors of self-efficacy and fear of movement or reinjury during the first 12 weeks after ACL reconstruction in 77 patients. Compared with baseline, all factors improved in a positive manner. Importantly, an association was found between high self-efficacy scores for rehabilitation exercises and higher knee pain improvements. High self-efficacy scores combined with low scores for fear of movement or reinjury were associated with improved knee function.

Brand and Nyland[36] suggested that self-efficacy is one of the most important psychological factors affecting outcomes of ACL reconstruction. This trait is influenced by the patient's preinjury activity level, age, chronicity of injury, and sex. Men, younger patients, patients with acute injuries, and patients with high activity levels tend to have higher self-efficacy levels.[275] Modeling techniques may be effective in increasing early postoperative levels of self-efficacy and motivation to comply with rehabilitation.[175] Maddison and associates[175] successfully used two modeling videos in an effort to reduce preoperative anxiety and pain and increase postoperative self-efficacy and functional outcomes after ACL surgery. The first video was watched preoperatively and addressed the first 2-week rehabilitation period. The second video focused on the 2- to 6-week time period and consisted of interviews and various action sequences of models performing the same time-matched rehabilitation

exercises that the patient was currently performing. Further work is highly warranted in this area to improve postoperative self-efficacy in patients with (measured) low levels and to investigate appropriate preoperative psychological screening methods to determine patients who require additional support and counseling.

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Video Content

Video 7-5
Video 10-1

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11

Rehabilitation of Primary and Revision Anterior Cruciate Ligament Reconstruction

Timothy P. Heckmann, Frank R. Noyes, Sue D. Barber-Westin

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CLINICAL CONCEPTS

The two anterior cruciate ligament (ACL) postoperative rehabilitation protocols described in this chapter consist of a careful incorporation of exercise concepts supported by the scientific data presented in Chapter 10. The protocols are evaluation based; that is, progression through the program is based on continual evaluation using the principles of anatomy, physiology, biomechanics, and surgery,[4,5,20,44,55] with an understanding that the overall goals of the reconstruction and rehabilitation are to:

- Regain normal knee stability: less than 3 mm of increased anteroposterior (AP) displacement on knee arthrometer testing, negative or trace pivot shift
- Control joint pain, swelling, and hemarthrosis
- Regain a normal range of knee motion
- Restore a normal gait pattern and neuromuscular control for ambulation
- Recover normal lower limb muscle strength
- Regain normal proprioception, balance, coordination, and neuromuscular control for desired activities
- Achieve optimal functional outcome based on orthopedic and patient goals

Each patient is taken through the appropriate program at a rate that takes into account sports and occupational goals; the condition of the articular surfaces, menisci, and other knee ligaments; concomitant operative procedures performed with the ACL reconstruction; the type of graft used; postoperative healing and response to surgery; and biologic principles of graft healing and remodeling. The protocols are divided into seven phases according to the time period postoperatively (e.g., phase I comprises postoperative weeks 1 and 2). Each phase has

CRITICAL POINTS Clinical Concepts

Protocols are evaluation based: Progression is based on continual evaluation using the principles of anatomy, physiology, biomechanics, and surgery.

Goals

- Regain normal knee stability
- Control joint pain, swelling, and hemarthrosis
- Regain normal range of knee motion
- Restore normal gait pattern
- Recover normal lower limb muscle strength
- Regain normal proprioception, balance, coordination, and neuromuscular control
- Achieve optimal functional outcome based on orthopedic and patient goals

The protocols are divided into seven phases according to the time period postoperatively. Each phase has four categories:

- General observation of the patient's condition
- Evaluation and measurement of specific variables, with goals identified for each variable
- Treatment and exercise program according to frequency and duration
- Rehabilitation goals that must be achieved to enter into the next phase

One protocol for patients who undergo primary ACL bone-patellar tendon-bone (autogenous reconstruction and desire to return to strenuous sports or work activities as soon as possible after surgery)

Second protocol for ACL revision reconstruction, primary ACL allograft or semitendinosus-gracilis autograft reconstruction, complex reconstruction in which major concomitant operative procedures were performed, or in whom significant articular cartilage lesions were found during the operation

Both protocols incorporate home self-management program.

Neuromuscular retraining program (e.g., Sportsmetrics) advocated for all patients returning to high-risk activities

First postoperative week critical for all patients: control pain and swelling, demonstrate adequate quadriceps muscle contraction, immediate knee motion, and adequate limb elevation

four main categories that describe the factors evaluated by the therapist and exercises performed by the patient:

- General observation of the patient's condition
- Evaluation and measurement of specific variables, with goals identified for each variable
- Treatment and exercise program according to frequency and duration
- Rehabilitation goals that must be achieved to enter into the next phase

The first protocol is designed for patients who undergo primary ACL bone-patellar tendon-bone (B-PT-B) autogenous reconstruction and desire to return to strenuous sports or work activities as soon as possible after surgery. All patients are warned that the return to strenuous activities early postoperatively carries a risk of either a reinjury to the ACL-reconstructed knee or a new injury to the contralateral knee. These risks cannot be scientifically predicted, and patients are cautioned to return to strenuous activities carefully and avoid any activity in which pain, swelling, or a feeling of instability develops. Patients who develop postoperative problems, such as knee motion complications, chronic effusion, patellofemoral pain, or patellar tendinitis, are advised to slow the rate of progression until the problems are resolved. The following criteria exclude a patient from this protocol:

- Concomitant major operative procedures, such as complex meniscal repair or transplantation,[19] other ligament reconstruction, patellofemoral realignment, articular cartilage restorative procedure, and osteotomy

TABLE 11-1 Estimated Supervised Physical Therapy Visits After Anterior Cruciate Ligament Reconstruction

Phase	Postoperative Weeks	Minimum Visits (*n*)	Maximum Visits (*n*)
1	1-2	2	4
2	3-4	2	4
3	5-6	1	2
4	7-8	1	2
5	9-12	1	2
6	13-26	2	3
7	27-52	2	4
Total		11	21

- Prior ACL reconstruction that failed
- Residual muscular atrophy with chronic instability
- Magnetic resonance imaging (MRI) or arthroscopic evidence of major bone bruising or articular cartilage damage

A second protocol, designed to delay or diminish knee joint and graft loading, is used for patients who undergo ACL revision reconstruction (with either allogeneic or autogenic tissue), primary ACL allograft or semitendinosus and gracilis autograft reconstruction, or complex B-PT-B autogenous reconstruction in which major concomitant operative procedures were performed or in whom significant articular cartilage lesions were found during the operation. Delays in return of full weight bearing, initiation of certain strengthening and conditioning exercises, initiation of running and agility drills, and return to full sports activities are incorporated. This protocol is designed to protect healing concomitant meniscal or ligament repairs or allograft tissues and avoid exacerbating articular cartilage deterioration or symptoms.

Specific criteria are evaluated throughout both rehabilitation programs to determine if the patient is ready to progress from one phase to the next. Both protocols incorporate a home self-management program, along with an estimated number of formal physical therapy visits (Table 11-1). For most patients, a total of 11 to 21 postoperative visits is expected to produce a desirable result. A few more supervised sessions may be required between the sixth and twelfth postoperative months for patients who undergo advanced training to return to strenuous activities. A specific neuromuscular retraining program (e.g., Sportsmetrics) is advocated for all patients returning to high-risk activities (see Chapter 14). For all patients, the following signs are continually monitored postoperatively: joint swelling, pain, gait pattern, knee motion, patellar mobility, muscle strength, flexibility, and AP displacement. Any individual who experiences difficulty progressing through the protocol or who develops a complication is expected to require additional supervision in the formal clinic setting.

The first postoperative week represents a critical time period for all patients in regard to control of knee joint pain and swelling, demonstration of adequate quadriceps muscle contraction, initiation of immediate knee motion exercises, and maintenance of adequate limb elevation. A bulky compression dressing is used for 48 hours and then converted to compression stockings with an additional Ace bandage if necessary. Patients are encouraged to remain recumbent and elevate the limb above the heart for the first 5 to 7 days, rising only to perform exercises and attend to personal bathing issues. Prophylaxis against deep venous thrombosis includes one aspirin daily for 10 days, ambulation (with crutch support) six to eight times daily for short periods of time, ankle-pumping every hour that the patient is awake, and close observation of the lower limb by the therapist and surgeon. Knee joint

hemarthroses require aspiration. Nonsteroidal antiinflammatory drugs are used for at least 5 days postoperatively. Appropriate pain medication is prescribed to provide relief and allow the immediate exercise protocol described below to be performed.

REHABILITATION PROTOCOL FOR PRIMARY ACL B-PT-B AUTOGENOUS RECONSTRUCTION: EARLY RETURN TO STRENUOUS ACTIVITIES

Modalities

In the immediate postoperative period (1-3 days), knee effusion must be controlled to avoid the quadriceps inhibition phenomenon.[14] Electrogalvanic stimulation or high-voltage electrical muscle stimulation (EMS) may be used to augment the ice, compression, and elevation program to control swelling.[31,59,75] This treatment uses the concept of like charges repelling. The effusion or swelling has a negative electrical charge, so using the negative electrodes at the knee and the positive (dispersive) electrode on either the low back or opposite thigh will assist the body in removing the fluid from the joint to be reabsorbed. The treatment duration is approximately 30 minutes; the intensity is set to patient tolerance; and the treatment frequency is three to six times per day. Once the joint effusion is controlled, functional EMS is begun for muscle reeducation and quadriceps facilitation (Table 11-2).

The use of EMS to facilitate and enhance an adequate quadriceps contraction is based on the evaluation of quadriceps and vastus medialis oblique (VMO) muscle tone. One electrode is placed over the VMO, and the second electrode is placed on the central to lateral aspect of the upper third of the quadriceps muscle belly (Fig. 11-1). The treatment duration is 15 to 20 minutes. The patient actively contracts the quadriceps muscle simultaneously with the machine's stimulation. A portable EMS machine for home use may be required in individuals whose muscle rating is poor. EMS is continued until the muscle grade is rated as good.[10,59] Biofeedback is also useful in enhancing hamstring relaxation if the patient experiences difficulty achieving full knee extension secondary to knee pain or muscle spasm. The surface electrode may be placed over the selected muscle component to provide positive feedback to the patient and clinician regarding the quality of active or voluntary quadriceps contraction (Fig. 11-2). The electrode may also be placed over the belly of the hamstring muscle while the patient performs range-of-motion (ROM) exercises.



FIG 11-1 Electrical muscle stimulation is used to facilitate and enhance an adequate quadriceps contraction early postoperatively.

The most widely used modality after ACL reconstruction is cryotherapy, which is begun in the recovery room after surgery. The cost of various cryotherapy options and patient compliance are two major factors in the successful control of postoperative pain and swelling. The standard method of cold therapy is an ice bag or commercial cold pack, which is kept in the freezer until required. Empirically, patients prefer motorized cooler units (Fig. 11-3). These units maintain a constant temperature and circulation of ice water through a pad, which provides excellent pain control. Gravity flow units are also effective; however, temperature maintenance is more difficult with these devices than with the motorized cooler units. The temperature can be controlled by using gravity to backflow and drain the water, refilling the cuff with fresh ice water as required. Cryotherapy is used for 20 minutes at a time from three times per day to every waking hour, depending upon the extent of pain and swelling. In some cases, the treatment time is extended owing to the thickness of the buffer used between the skin and the device. The motorized units contain a thermostat, which is

Text continued on p. 304



FIG 11-2 Biofeedback therapy is implemented to facilitate an adequate quadriceps muscle contraction early postoperatively.



FIG 11-3 A motorized cooler unit is used to provide cryotherapy.

TABLE 11-2 Cincinnati SportsMedicine & Orthopaedic Center Rehabilitation Protocol for Primary Anterior Cruciate Ligament Reconstruction: Early Return to Strenuous Activities

	POSTOPERATIVE WEEKS					POSTOPERATIVE MONTHS			
	1-2	3-4	5-6	7-8	9-12	4	5	6	7-12
Brace: immobilizer for patient comfort	X	(X)							
Range-of-motion minimum goals:									
0-110 degrees	X								
0-120 degrees		X							
0-135 degrees			X						
Weight bearing:									
50% body weight	X								
100% body weight		X							
Patella mobilization	X	X	X						
Modalities:									
EMS	X	X	X						
Pain/edema management (cryotherapy)	X	X	X	X	X	X	X	X	X
Stretching: hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X	X
Strengthening:									
Quadriceps isometrics, straight-leg raises, active knee extension	X	X	X	X					
Closed-chain: gait retraining, toe raises, wall-sits, mini-squats	X	X	X	X	X				
Knee flexion hamstring curls (90 degrees)	X	X	X	X	X	X	X	X	X
Knee extension quadriceps (90-30 degrees)	X	X	X	X	X	X	X	X	X
Hip abduction-adduction, multihip	X	X	X	X	X	X	X	X	X
Leg press (70-10 degrees)	X	X	X	X	X	X	X	X	X
Balance/proprioceptive training:									
Weight shifting, cup walking, Biodex Balance System	X	X	X	X					
Biodex Balance System, Biomechanical Ankle Platform System, perturbation training, balance board, minitrampoline				X	X	X	X	X	
Conditioning:									
UBC	X	X	X						
Bike (stationary)		X	X	X	X	X	X	X	X
Aquatic program		X	X	X	X	X	X	X	X
Swimming (kicking)				X	X	X	X	X	X
Walking				X	X	X	X	X	X
Stair-climbing machine			X	X	X	X	X	X	X
Ski machine			X	X	X	X	X	X	X
Elliptical machine				X	X	X	X	X	X
Running: straight					X	X	X	X	X
Cutting: lateral carioca, figure-eights						X	X	X	X
Plyometric training						X	X	X	X
Full sports							X	X	X

PHASE 1: WEEKS 1-2

General Observation

50% weight bearing with two crutches when:

- Postoperative pain controlled
- Hemarthrosis controlled
- Voluntary quadriceps contraction achieved

Factors Evaluated (Goal)

Pain (controlled)
Hemarthrosis (mild)
Patellar mobility (good)
ROM (minimum, 0-110 degrees)
Quadriceps contraction and patella migration (good)
Soft tissue contracture (none)
Joint arthrometry day 14 (<3 mm)

TABLE 11-2 Cincinnati SportsMedicine & Orthopaedic Center Rehabilitation Protocol for Primary Anterior Cruciate Ligament Reconstruction: Early Return to Strenuous Activities—cont'd

PHASE 1: WEEKS 1-2

Activity	Frequency	Duration
ROM	3-4 ×/day, 10 min	
Passive (0-90 degrees)		
Patella mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec each
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion, extension, abduction, adduction)		3 sets × 10 reps
Active quadriceps isometrics (full extension)		1 set × 10 reps
Knee flexion (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (active assisted, 90-30 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain: minisquats (0-45 degrees, 50% weight bearing)		3 sets × 20 reps
Balance Training	3 ×/day, 5 min	
Weight shift side-side and forward-back		5 sets × 10 reps
Aerobic Conditioning		
UBC	1-2 ×/day, 5 min	
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
Goals	• ROM 0-110 degrees • Adequate quadriceps contraction • Control inflammation and effusion • 50% weight bearing	

PHASE 2: WEEKS 3-4

General Observation	Full weight bearing with one crutch when: • Pain controlled without narcotics • Effusion controlled • ROM 0-100 degrees • Muscle control throughout ROM
Factors Evaluated (Goal)	Pain (mild) Effusion (mild) Patellar mobility (good) ROM (minimum, 0-120 degrees) Muscle control (3/5) Inflammatory response (none) Joint arthrometry, day 28, 20 lb (<3 mm)

Activity	Frequency	Duration
ROM	3-4 ×/day, 10 min	
Passive (0-120 degrees)		
Patella mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec each

Continued

TABLE 11-2 Cincinnati SportsMedicine & Orthopaedic Center Rehabilitation Protocol for Primary Anterior Cruciate Ligament Reconstruction: Early Return to Strenuous Activities—cont'd

PHASE 2: WEEKS 3-4

Activity	Frequency	Duration
Strengthening	2-3 ×/day, 20 min	
Straight-leg raises (flexion, extension, adduction, abduction)		3 sets × 10 reps
Isometric training, multiangle (90, 60, 30 degrees)		1 set × 10 reps
Heel raise/toe raise		3 sets × 10 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (active, 90-30 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		5 reps
Minisquats		3 sets × 20 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Balance Training	3×/day, 5 min	
Weight shift side-side, forward-back		5 sets × 10 reps
Balance board, two legged		
Cup walking		
Single-leg stance (level surface)		5 reps
Aerobic Conditioning	2×/day, 5 min	
UBC		
Water walking		
Stationary bicycling (patellofemoral precautions)		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
Goals	• ROM 0-125 degrees • Muscle control • Arthrometer within 3 mm • Control inflammation, effusion • 100% weight bearing	

PHASE 3: WEEKS 5-6

General Observation	Independent ambulation when: • Pain controlled • Effusion controlled • ROM 0-120 degrees • Muscle control throughout ROM
Factors Evaluated (Goal)	Pain (no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-135 degrees) Muscle control (4/5) Inflammatory response (none) Gait, symmetric

Activity	Frequency	Duration
ROM	3 ×/day, 10 min	
ROM passive (0-135 degrees)		
Patella mobilization		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec

TABLE 11-2 Cincinnati SportsMedicine & Orthopaedic Center Rehabilitation Protocol for Primary Anterior Cruciate Ligament Reconstruction: Early Return to Strenuous Activities—cont'd

PHASE 3: WEEKS 5-6

Activity	Frequency	Duration
Strengthening	1-2 ×/day, 20 min	
Straight-leg raises (ankle weight, <10% of body weight)		3 sets × 10 reps
Straight-leg raises with rubber tubing		3 sets × 10 reps
Isometric training, multiangle (90, 60, 30 degrees)		2 sets × 10 reps
Heel raise/toe raise		3 sets × 20 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (90-30 degrees, with resistance)		3 sets × 10 reps
Closed-chain:		
Wall-sits		5 reps
Minisquats		3 sets × 20 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Balance board, two legged		
Lateral step-ups, 2- to 4-inch block		
Aerobic Conditioning (Patellofemoral Precautions)	2 ×/day, 10 min	
UBC		
Water walking		
Stationary bicycling		
Stair machine (low resistance and stroke)		
Ski machine (short strike and level, low resistance)		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
Goals	• ROM 0-135 degrees • Control inflammation and effusion • Recognition of complications (motion loss, CRPS, increased anteroposterior displacement) • Muscle endurance • Recognition of patellofemoral changes • Full weight bearing, normal gait	

PHASE 4: WEEKS 7-8

General Observation	• No effusion • Painless ROM (0-135 degrees) • Joint stability • Performs activities of daily living • Full weight bearing • Can walk 20 min without pain
Factors Evaluated (Goal)	Manual muscle test (hamstrings, quadriceps, all hip muscles; 4/5) Swelling (none) Joint arthrometry, 8 weeks (<3 mm) Patellar mobility (good) Crepitus (none/slight)

Continued

TABLE 11-2 Cincinnati SportsMedicine & Orthopaedic Center Rehabilitation Protocol for Primary Anterior Cruciate Ligament Reconstruction: Early Return to Strenuous Activities—cont'd

PHASE 4: WEEKS 7-8

Activity	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	1-2 ×/day, 20 min	
Straight-leg raises, rubber tubing		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension with resistance (90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Closed-chain:		
Wall-sits		5 reps
Minisquats		3 sets × 20 reps
Dynamic hip and core program		
Balance Training	3 ×/day, 5 min	
Balance board, two legged		
Single-leg stance		
Resistance band walking		
PlyoBack ball toss		
Perturbation training		
Aerobic Conditioning (Patellofemoral Precautions)	1-2 ×/day, 15-20 min	
Stationary bicycling		
Water walking		
Swimming (straight-leg kicking)		
Walking		
Stair machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Elliptical machine (low resistance)		
Modalities	As required	
Cryotherapy		20 min
Goals	Increase strength and endurance	

PHASE 5: WEEKS 9-12

General Observation	• No effusion, painless ROM (0-135 degrees), joint stability • Performs ADLs, can walk 20 min without pain • Full weight bearing
Factors Evaluated (Goal)	Manual muscle test (4/5) Isometric test, 12 weeks, mean average torque/% deficit in quadriceps and hamstrings (30%) Swelling (none) Joint arthrometry, 12 weeks (<3 mm) Patellar mobility (good) Crepitus (none/slight)

TABLE 11-2 Cincinnati SportsMedicine & Orthopaedic Center Rehabilitation Protocol for Primary Anterior Cruciate Ligament Reconstruction: Early Return to Strenuous Activities—cont'd

PHASE 5: WEEKS 9-12

Activity	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises with rubber tubing		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension with resistance (90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Closed-chain:		
Wall-sits		5 reps
Minisquats		3 sets × 20 reps
Lateral step-ups (2- to 4-inch block)		3 sets × 10 reps
Dynamic hip and core program		
Balance Training	3 ×/day, 5 min	
Balance board, two legged		
Single-leg stance		
Resistance band walking		
PlyoBack ball toss		
Perturbation training		
Aerobic Conditioning (Patellofemoral Precautions)	3 ×/wk, 15-20 min	
Stationary bicycling		
Walter walking		
Swimming (kicking)		
Walking		
Stair machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Elliptical machine (low resistance)		
Running Program (Straight)	3 ×/wk, 10 min	
Jog		¼ mile
Walk		⅛ mile
Backward walk		20 yards
Modalities	As required	
Cryotherapy		20 min
Goals	Increase strength and resistance	

PHASE 6: WEEKS 13-26

General Observation	• No effusion • Painless ROM • Joint stability • Performs ADLs • Can walk 20 min without pain

Continued

TABLE 11-2 Cincinnati SportsMedicine & Orthopaedic Center Rehabilitation Protocol for Primary Anterior Cruciate Ligament Reconstruction: Early Return to Strenuous Activities—cont'd

PHASE 6: WEEKS 13-26

Factors Evaluated (Goal)	Isokinetic test (isometric + torque 300 degrees/sec, % difference in quadriceps and hamstrings, tested monthly) Swelling (none) Joint arthrometry (<3 mm) Patellar mobility (good) Crepitus (none/slight) Single-leg function tests (hop distance, timed hop, % difference between involved and noninvolved side)

Activity	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	1 ×/day, 20-30 min	
Straight-leg raises, rubber tubing (high speed)		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension with resistance (90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		
Dynamic hip and core program		
Balance Training	3 ×/day, 5 min	
Balance board, two legged to single legged		
Single-leg stance on unstable platform		
Aerobic Conditioning (Patellofemoral Cautions)	3 ×/wk, 20-30 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Stair machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Elliptical machine (low resistance)		
Running Program (Straight)	3 ×/wk, 15-20 min	
Jog (progress speed from ½ to ¾ to full)		¼ to 1 mile
Walk		⅛ mile
Backward run		20 yards
Cutting Program (Lateral, Carioca, Figure-Eights)	3 ×/wk	20 yards
Functional Training	3 ×/wk	
Plyometric training (box hops, level, double leg)		15 sec, 4-6 sets
Sport-specific drills		
Modalities	As required	
Cryotherapy		20 min
Goals	Increase strength and endurance	

PHASE 7: WEEKS 27-52

General Observation	• No effusion • Painless ROM • Joint stability • Performs ADLs • Can walk 20 min without pain

TABLE 11-2 Cincinnati SportsMedicine & Orthopaedic Center Rehabilitation Protocol for Primary Anterior Cruciate Ligament Reconstruction: Early Return to Strenuous Activities—cont'd

PHASE 7: WEEKS 27-52

Factors Evaluated (Goal)	Isokinetic test (torque at 180 and 300 degrees/sec, % difference in quadriceps and hamstrings, tested quarterly; isometric if symptomatic patellofemoral joint) (10%-15%) Swelling (none) Joint arthrometry (<3 mm) Patellar mobility (good) Crepitus (none/slight) Single-leg functional test (hop distance, timed hop, % difference between noninvolved and involved side) (≤15%)	
Activity	**Frequency**	**Duration**
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening		
Straight-leg raises, rubber tubing (high speed)	3-4 ×/wk, 20-30 min	3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		1-2 sets × 8-12 reps
Knee extension with resistance (90-30 degrees)		1-2 sets × 8-12 reps
Leg press (70-10 degrees)		1-2 sets × 8-12 reps
Multihip machine (flexion, extension, abduction, adduction)		1-2 sets × 8-12 reps
Dynamic hip and core program		
Balance Training	3 ×/day, 5 min	
Balance board, two legged to single legged		
Single-leg stance on unstable platform with secondary activity		
Aerobic Conditioning (Patellofemoral Precautions)	3 ×/wk, 20-30 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Stair machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Running Program (Straight)	3 ×/wk, 20 min	
Interval training		20, 40, 60, 100 yards
Walk/rest phase (3 : 1 rest/work)		20 yards
Backward run		20 yards
Cutting Program (Lateral, Carioca, Figure-Eights)	3 ×/wk	20 yards
Functional Training	3 ×/wk	
Plyometric training (box hops, level, double leg)		15 sec, 4-6 sets
Sport-specific drills		
Modalities	As required	
Cryotherapy		20 min
Goals	• Increase function, strength, and endurance • Return to previous activity level	

ADLs, Activities of daily living; *CRPS,* complex regional pain syndrome; *EMS*, electrical muscle stimulation; *ITB*, iliotibial band; *ROM*, range of motion; *UBC*, upper body cycle; values in parentheses indicate when exercises are to be performed.

helpful when cold therapy is used for an extended treatment time. Vasopneumatic devices offer another option for cold therapy. The Game Ready device (Game Ready) allows the clinician to set the temperature as well as one of four different compression levels, depending on patient tolerance. Although this is primarily a clinical treatment tool, it may be used at home. Cryotherapy is typically done after exercise or when required for pain and swelling control and is maintained throughout the entire postoperative rehabilitation protocol.

Postoperative Bracing

The use of postoperative braces after ACL reconstruction is controversial.[7,30,34,37,74] Screening patients for personality type, pain tolerance, and program compliance may provide insight into the individual who will require brace protection postoperatively. The primary indication for the use of a brace, in our opinion, is protection of the patient during weight bearing in the event of a fall and to initiate early, more comfortable weight bearing during the first few postoperative weeks. The brace should be rigid in nature and the knee held initially at 0 degrees (Fig. 11-4). The brace is opened based on the protocol to allow normal knee flexion during ambulation. Periodic evaluation of the brace and its position on the leg must be done to ensure maximal benefit is achieved. We do not routinely prescribe a derotation or functional knee brace upon return to full activities after ACL reconstruction for patients treated according to this protocol.

Range of Knee Motion

The goal in the first postoperative week is to obtain a ROM of 0 to 90 degrees. We do not require or routinely use continuous passive motion machines. Patients perform passive and active ROM exercises in a seated position for 10 minutes per session, approximately four to six times per day (Fig. 11-5).



FIG 11-4 A long-leg postoperative brace protects the patient during weight bearing in the event of a fall and promotes early, comfortable weight bearing during the first few postoperative weeks.



FIG 11-5 Passive (**A**) and active (**B**) range-of-motion exercises in a seated position.

Full passive knee extension must be obtained immediately to avoid excessive scarring in the intercondylar notch and posterior capsular tissues. If the patient has difficulty regaining at least 0 degrees ROM by the seventh postoperative day, he or she begins an overpressure program. The foot and ankle are propped on a towel or other device to elevate the hamstrings and gastrocnemius that allows the knee to drop into full extension (Fig. 11-6, *A*). This position is maintained for 10 minutes and repeated four to six times per day. A 10-pound weight may be added to the distal thigh and knee to provide overpressure to stretch the posterior capsule. Full knee extension should be obtained by the second postoperative week. If this is not accomplished, or if the clinician notes a firm end feel, then an extension board (see Fig. 11-6, *B*) or additional weight of 15 to 20 pounds is used six times per day. If this is still not effective, a dropout cast (see Fig. 11-6, *C*) is implemented for 24 to 36 hours for continuous extension overpressure. The goal is to obtain 0 to 2 to 3 degrees of hyperextension, which is within the normal knee motion limit. In patients with physiologic bilateral knee hyperextension, we recommend the gradual return of 3 to 5 degrees of hyperextension in the reconstructed knee to more closely resemble the amount of hyperextension present in the contralateral knee. However, we do not recommend that the patient regain more than 5 degrees of hyperextension, owing to potentially deleterious forces that may be placed on the healing graft.

Knee flexion is gradually increased to 120 degrees by the third to fourth postoperative week and 135 degrees by the fifth to sixth postoperative week. Passive knee flexion exercises are performed initially in the traditional seated position, using the opposite lower extremity to provide overpressure. Other methods to assist in achieving flexion greater than 90 degrees include chair-rolling (Fig. 11-7, *A*), wall slides (see Fig. 11-7, *B,* and 11-7, *C*), knee flexion devices (see Fig. 11-7, *D*), and passive quadriceps-stretching exercises. Patients who have difficulty achieving 0 to 90 degrees of flexion by the fourth week require additional treatment interventions to relieve pain during joint motion, such as appropriate medications, local nerve blocks, and possibly a gentle ranging of the knee under anesthesia (not a forceful manipulation), as described in Chapter 38, Prevention and Treatment of Knee Arthrofibrosis.

Patellar Mobilization

Restoring normal patellar mobility is critical to regain a normal range of knee motion. The loss of patellar mobility is often associated with arthrofibrosis and, in extreme cases, the development of patella infera.[56,57,60] Patellar glides are begun the first postoperative day in all four planes (superior, inferior, medial, and lateral) with sustained pressure applied to the appropriate patellar border for at least 10 seconds (Fig. 11-8). This exercise is performed for 5 minutes before ROM exercises. Caution is warranted if an extensor lag is detected, because this may be associated with poor superior migration of the patella, indicating the need for additional emphasis on this exercise. Patellar mobilization is performed for approximately 6 weeks postoperatively.

Weight Bearing

Partial weight bearing is permitted immediately postoperatively as long as pain and swelling are controlled and a voluntary quadriceps contraction is demonstrated. Initially, bilateral crutches may be used, and 50% body weight is placed on the involved foot. The amount of weight the patient is allowed to place on the involved limb is progressed as tolerated to allow full weight by the third to fourth postoperative week. Importantly, a normal gait pattern is advocated that avoids a locked knee position and encourages normal knee flexion throughout the gait cycle. This technique allows for normal patterning of heel-to-toe ambulation, quadriceps contraction during midstance, and hip and knee flexion during the gait cycle. The locked-knee position is avoided owing to the potential of the development of a quadriceps-avoidance gait pattern.



FIG 11-6 Overpressure program for extension. **A,** Hanging-weight exercise. **B,** Extension board (ERMI Knee Extensionater). **C,** Dropout cast.

Flexibility

Hamstring and gastrocnemius-soleus flexibility exercises are begun the first day after ACL reconstruction. A sustained static stretch is held for 30 seconds and repeated five times. The most common hamstring stretch is the modified hurdler stretch (Fig. 11-9), whereas the most common gastrocnemius-soleus stretch is the towel pull (Fig. 11-10). These exercises help control pain owing to the reflex response created in the hamstrings when the knee is kept in the flexed position. As well,



FIG 11-7 Overpressure program for flexion. **A,** Rolling-stool exercise. **B** and **C,** Wall slides. **D,** Overpressure flexion device (E Knee Flexionater).

the towel-pulling exercise can help lessen discomfort in the calf, Achilles tendon, and ankle. These stretches represent critical components of the knee extension ROM program, because the ability to relax these two muscle groups is imperative to achieve full passive knee extension.

Quadriceps (Fig. 11-11) and iliotibial band (Fig. 11-12) flexibility exercises are performed to assist in achieving full knee flexion and controlling lateral hip and thigh tightness. A complete evaluation of the lower extremity will reveal deficit areas in flexibility that should be corrected. When designing a flexibility program, the therapist should take into account the particular sport or activity to which the patient wishes to return, as well as the position or physical requirements of that activity. Flexibility is incorporated in the maintenance program the patient performs once discharged.

Strengthening

Lower extremity muscle atrophy and weakness after ACL reconstruction represents a difficult and unresolved problem.[15,17,23,28,59,67,70] Therefore our strengthening program begins at the first postoperative visit. Early emphasis on the generation of a good voluntary quadriceps contraction is critical for a successful and safe return to functional activity. Isometric quadriceps contractions are completed on an hourly basis following the repetition rules of 10-second holds, 10 repetitions, 10 times per day. Adequate evaluation of the quadriceps contraction by both the therapist and patient is critical. The patient can monitor contractions by visual or manual means, comparing the quality of the contractions with those achieved by the contralateral limb. The patient can also assess the superior migration of the patella during the contraction, which should be approximately 1 cm, and the inferior migration of the patella during the initial relaxation of the contraction. The patient must not let the knee go into hyperextension during isometric contractions but instead hold the knee flexion position throughout the exercise. If necessary, biofeedback can also be used to reinforce a good quadriceps contraction.

Straight-leg raises are initiated on the first postoperative day in the four planes of hip movement. The adduction straight-leg raise has a beneficial effect on the VMO. Supine straight-leg raises must include a sufficient isometric quadriceps contraction to benefit the quadriceps. Straight-leg raises in the other two planes are also important for proximal stabilization. As these exercises become easy to perform, ankle weights are added to progress muscle strengthening. Initially, 1 to 2 pounds of weight are used, and eventually up to 10 pounds is added



FIG 11-8 Patellar glides are begun on the first postoperative day in all four planes. **A,** Superior and inferior. **B,** Medial and lateral.



FIG 11-9 Hamstring modified hurdler stretch.

as long as this is not more than 10% of the patient's body weight. Active assisted ROM can also be used to facilitate the quadriceps muscle if poor tone is observed during isometric contractions. These exercises are used primarily during the first 8 postoperative weeks, when emphasis is placed on controlling pain and swelling, regaining full ROM,



FIG 11-10 Gastrocnemius-soleus towel-pull stretch.



FIG 11-11 Quadriceps stretch.

achieving early quadriceps control and proximal stabilization, and resuming a normal gait pattern.

Closed kinetic chain exercises are initiated in the first postoperative week. Minisquats from 0 to 45 degrees (Fig. 11-13, *A*) are begun when tolerated by the patient. Initially, the patient's body weight is used as resistance, and TheraBand (see Fig. 11-13, *B*) or surgical tubing is gradually used as resistance mechanisms. Quick, smooth, rhythmic squats are performed to a high-set/high-repetition cadence to promote muscle fatigue. Hip position should be monitored to promote a quadriceps contraction.

Toe raises for gastrocnemius-soleus strengthening and wall-sitting isometrics for quadriceps control are begun in the second postoperative week. The goal of wall-sitting is to improve quadriceps contraction by performing the exercise to muscle exhaustion (Fig. 11-14, *A*). If anterior knee pain is experienced, it may be decreased by either altering the knee flexion angle of the sit or by subtly changing the toe-out/toe-in angle by no more than 10 degrees. The exercise may also be modified to produce greater challenge to the quadriceps. The patient may voluntarily set the quadriceps muscle once he or she reaches the maximum knee flexion angle, which is typically between 30 and 45 degrees. This contraction and knee flexion position is held until muscle fatigue occurs, and the exercise is repeated three to five times. The patient may squeeze a ball between the distal thighs, inducing a hip adduction contraction and a stronger VMO contraction (see Fig. 11-14, *B*). In a third variation, the patient holds dumbbell weights in the hands to increase body weight, which promotes an even stronger quadriceps contraction (see Fig. 11-14, *C*). Finally, the patient can shift the body weight over the involved side to stimulate a single-leg contraction. This exercise is promoted as an excellent one for the patient to perform at home four to six times daily to achieve quadriceps fatigue in a safe knee flexion angle that does not induce an abnormal anterior tibial translation.



FIG 11-12 Iliotibial band stretch.

Lateral step-ups are begun when the patient has achieved full weight bearing (Fig. 11-15). The height of the step is gradually increased based on patient tolerance.

Hamstring curls are begun with Velcro ankle weights within the first few weeks and eventually advanced to weight machines (Fig. 11-16). Weight machines are advantageous owing to the muscle isolation obtained, as the machine provides stability to the knee joint. The patient exercises the involved limb alone as well as both limbs together. If the lightest amount of weight on the machine is too heavy to be lifted by the involved limb alone, the exercise may be performed as an eccentric contraction in which the patient lifts the weight with both legs and lowers the weight with the involved side. Eccentric contractions may also be used in the advanced stages of strength training. Hamstring strength is critical to the overall success of the rehabilitation program because of the role that this musculature plays in the dynamic stabilization of the knee joint. Weight training is used throughout the advanced program and continues in the return-to-activity and maintenance phases of rehabilitation.

Open kinetic chain extension exercises are incorporated within the first few weeks to further develop quadriceps muscle strength. Caution is warranted because of the potential problems these exercises may create for the healing graft and the patellofemoral joint. Resisted knee extension is begun with Velcro ankle weights in the first week from 90 to 30 degrees. The terminal phase of extension is avoided because of the forces placed on the patellofemoral joint and ACL graft. The patellofemoral joint must be monitored for changes in pain, swelling, and



FIG 11-13 Minisquats from 0 to 45 degrees using the patient's body weight **(A)** and a TheraBand for increased resistance **(B)**.



FIG 11-14 **A,** Wall-sitting to muscle exhaustion. **B,** Squeezing a ball between the distal thighs induces a hip adduction contraction and a stronger vastus medialis obliquus contraction. **C,** Use of dumbbell weights to increase body weight promotes an even stronger quadriceps contraction.

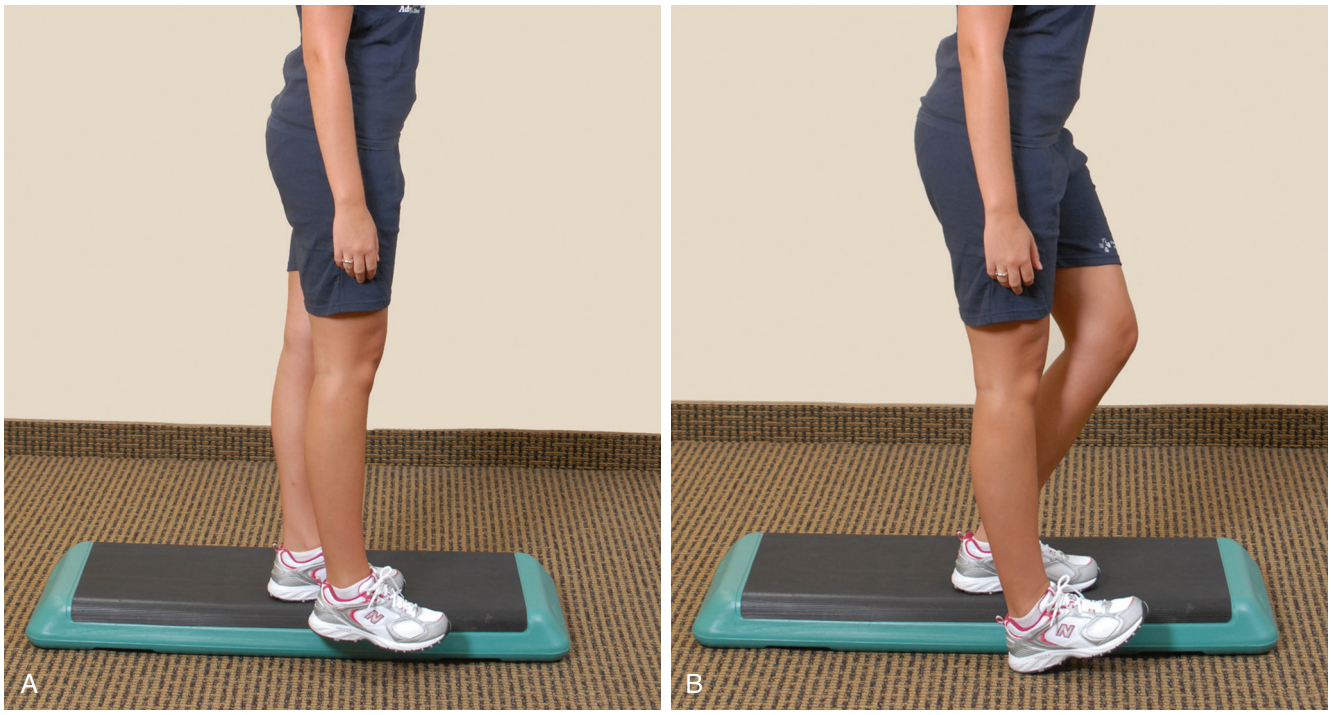


FIG 11-15 The step-up exercise.



FIG 11-16 Hamstring curls.

crepitus to avoid a patellar conversion in which painful patellofemoral crepitus develops with articular cartilage damage. The surgeon should advise the therapist if there are abnormal patellofemoral findings of joint damage.

A full lower extremity–strengthening program is critical for the early and long-term success of the rehabilitation program. Other muscle groups included in this routine are the hip abductors, hip adductors, hip flexors, and hip extensors. These muscle groups can be exercised on either a multihip or cable system machine (Fig. 11-17) or a hip abductor/adductor machine. Gastrocnemius-soleus strength is a key component for both early ambulation and the running program. In addition, upper extremity and core strengthening are important for a safe and effective return to work or sports. Sport and position specificity are taken into account when devising the strengthening program to maximize its benefits. In 2009, the American College of Sports Medicine (ACSM)[2] updated their recommendations for progression of muscle strength, hypertrophy, power, and endurance training (Tables 11-3 to 11-6). Specific strengthening and sport-specific timing drills are beyond the scope of this chapter; the therapist should work with the patient and appropriate coaches to determine the individual patient's program.

Balance, Proprioceptive, and Perturbation Training

Restoration of normal neuromuscular function after ACL reconstruction is paramount for the eventual implementation of sport-specific exercises and release to full activities. Knee joint proprioception is a crucial element of neuromuscular function, and its recovery is essential for a successful outcome.[16,22,38,40,42,73] Balance and proprioceptive training are begun the first postoperative week. Initially, the patient simply stands and shifts weight from side to side and from front to back. This activity encourages confidence in the leg's ability to withstand the pressures of weight bearing and initiates the stimulus to knee joint position sense.

Cup walking is begun when the patient achieves full weight bearing (Fig. 11-18) to promote symmetry between the surgical and uninvolved limbs. This exercise helps develop hip and knee flexion and quadriceps control during midstance of gait to prevent knee hyperextension. In addition, cup walking controls hip and pelvic motion during midstance, gastrocnemius-soleus activity during push-off, and excessive hip hiking. These components of gait control are critical in the early phases of rehabilitation to decrease forces on the healing graft.

Double- and single-leg balance exercises in the stance position are beneficial early postoperatively. During the single-leg exercise, the foot is pointed straight ahead, the knee flexed 20 to 30 degrees, the arms extended outward to horizontal, and the torso positioned upright with the shoulders above the hips and the hips above the ankles (Fig. 11-19, *A*). The objective is to remain in this position until balance is disturbed. A minitrampoline or unstable platform may be used to make this exercise more challenging, because these devices promote greater dynamic limb control than that required to stand on a stable surface (see Fig. 11-19B). To provide a greater challenge, patients may assume the single-leg stance position and throw and catch a weighted ball against an inverted minitrampoline (Fig. 11-20) until fatigue occurs.

Perturbation training techniques are initiated at approximately the seventh to eighth postoperative week during balance exercises. The therapist stands behind the patient and disrupts her or his body posture and position periodically to enhance dynamic knee



FIG 11-17 Multihip cable system machine.

TABLE 11-3 American College of Sports Medicine Recommendations for Progression During Strength Training

	Novice	Intermediate	Advanced
Muscle action	Eccentric, concentric, isometric	Eccentric, concentric, isometric	Eccentric, concentric, isometric
Exercise selection	Unilateral and bilateral; single and multiple joint	Unilateral and bilateral; single and multiple joint	Unilateral and bilateral; single and multiple joint
Exercise order	Large then small muscles Multiple then single High then low intensity	Large then small muscles Multiple then single High then low intensity	Large then small muscles Multiple then single High then low intensity
Loading	60%-70% 1 RM	60%-70% 1 RM	80%-100% 1 RM
Volume	1-3 sets × 8-12 reps	Multiple sets × 8-12 reps	Multiple sets × 8-12 reps
Rest intervals	1-2 min core, 2-3 min all other	1-2 min core, 2-3 min all other	1-2 min core, 2-3 min all other
Velocity	Slow to moderate	Moderate	Unintentionally slow to fast
Frequency	2-3 days/wk	3-4 days/wk	4-6 days/wk

From American College of Sports Medicine: Progression models in resistance training for healthy adults. *Med Sci Sports Exerc.* 2009;41:687-708.
1 RM, 1 repetition maximum.

TABLE 11-4 American College of Sports Medicine Recommendations for Progression During Hypertrophy Training

	Novice	Intermediate	Advanced
Muscle action	Eccentric, concentric, isometric	Eccentric, concentric, isometric	Eccentric, concentric, isometric
Exercise selection	Single and multiple joint	Single and multiple joint	Single and multiple joint
Exercise order	Large then small muscles Multiple then single High then low intensity	Large then small muscles Multiple then single High then low intensity	Large then small muscles Multiple then single High then low intensity
Loading	70%-85% 1 RM	70%-85% 1 RM	70%-100% 1 RM, with emphasis on 70%-85%
Volume	1-3 sets × 8-12 reps	1-3 sets × 8-12 reps	3-6 sets × 1-12 reps with emphasis on 6-12
Rest intervals	1-2 min	1-2 min	2-3 min: heavy core 1-2 min for others
Velocity	Slow to moderate	Slow to moderate	Slow, moderate, and fast
Frequency	2-3 days/wk	4 days/wk	4-6 days/wk

From American College of Sports Medicine: Progression models in resistance training for healthy adults. *Med Sci Sports Exerc.* 2009;41:687-708.
1 RM, 1 repetition maximum.

TABLE 11-5 American College of Sports Medicine Recommendations for Progression During Power Training

	Novice	Intermediate	Advanced
Muscle action	Eccentric and concentric	Eccentric and concentric	Eccentric and concentric
Exercise selection	Multiple joint	Multiple joint	Multiple joint
Exercise order	Large then small muscles Most then least complex High then low intensity	Large then small muscles Most then least complex High then low intensity	Large then small muscles Most then least complex High then low intensity
Loading	30%-60% 1 RM: upper body 0%-60% 1 RM: lower body	70%-80% 1 RM: strength 30%-60% 1 RM: velocity/technique	>85% 1 RM: strength 30%-60% 1 RM: velocity
Volume	1-3 sets × 3-6 reps	1-3 sets × 3-6 reps	3-6 sets × 1-6 reps
Rest intervals	2-3 min: core 1-2 min others	2-3 min: core 1-2 min others	2-3 min: core 1-2 min others
Velocity	Moderate	Fast	Fast
Frequency	2-3 days/wk	3-4 days/wk	4-5 days/wk

From American College of Sports Medicine: Progression models in resistance training for healthy adults. *Med Sci Sports Exerc.* 2009;41:687-708.
1 RM, 1 Repetition maximum.

TABLE 11-6 American College of Sports Medicine Recommendations for Progression During Endurance Training

	Novice	Intermediate	Advanced
Muscle action	Eccentric and concentric	Eccentric and concentric	Eccentric and concentric
Exercise selection	Unilateral and bilateral; single and multiple joint	Unilateral and bilateral; single and multiple joint	Unilateral and bilateral; single and multiple joint
Exercise order	Variety	Variety	Variety
Loading	50%-70% 1 RM	50%-70% 1 RM	30%-80% 1 RM
Volume	10-15 reps	10-15 reps	Multiple sets × 10-25 reps or more
Rest intervals	1-2 min for high reps <1 min for moderate reps	1-2 min for high reps <1 min for moderate reps	1-2 min for high reps <1 min for moderate reps
Velocity	Slow for moderate reps Moderate for high reps	Slow for moderate reps Moderate for high reps	Slow for moderate reps Moderate for high reps
Frequency	2-3 days/wk	3-4 days/wk	4-6 days/wk

From American College of Sports Medicine: Progression models in resistance training for healthy adults. *Med Sci Sports Exerc.* 2009;41:687-708.
1 RM, 1 Repetition maximum.



FIG 11-18 Cup walking to promote symmetry between the reconstructed and uninvolved limbs.

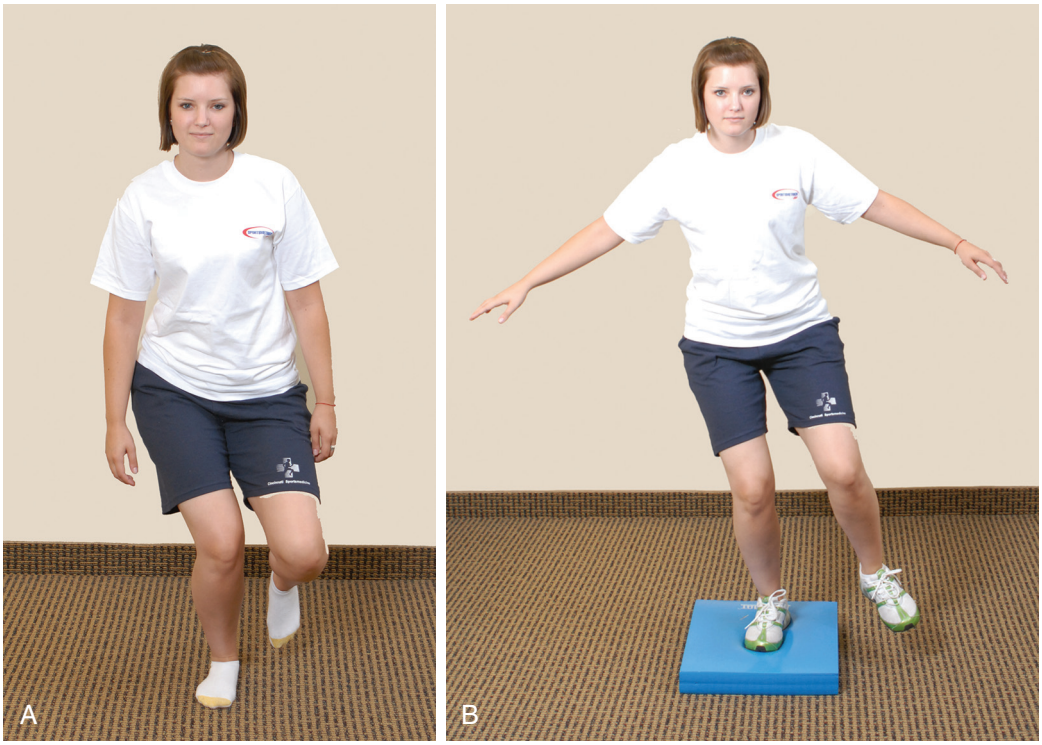


FIG 11-19 Single-leg balance exercise performed first on a stable surface **(A)** and then on an unstable surface **(B)**.



FIG 11-20 Single-leg balance exercise in which the patient throws and catches a weighted ball against an inverted minitrampoline.

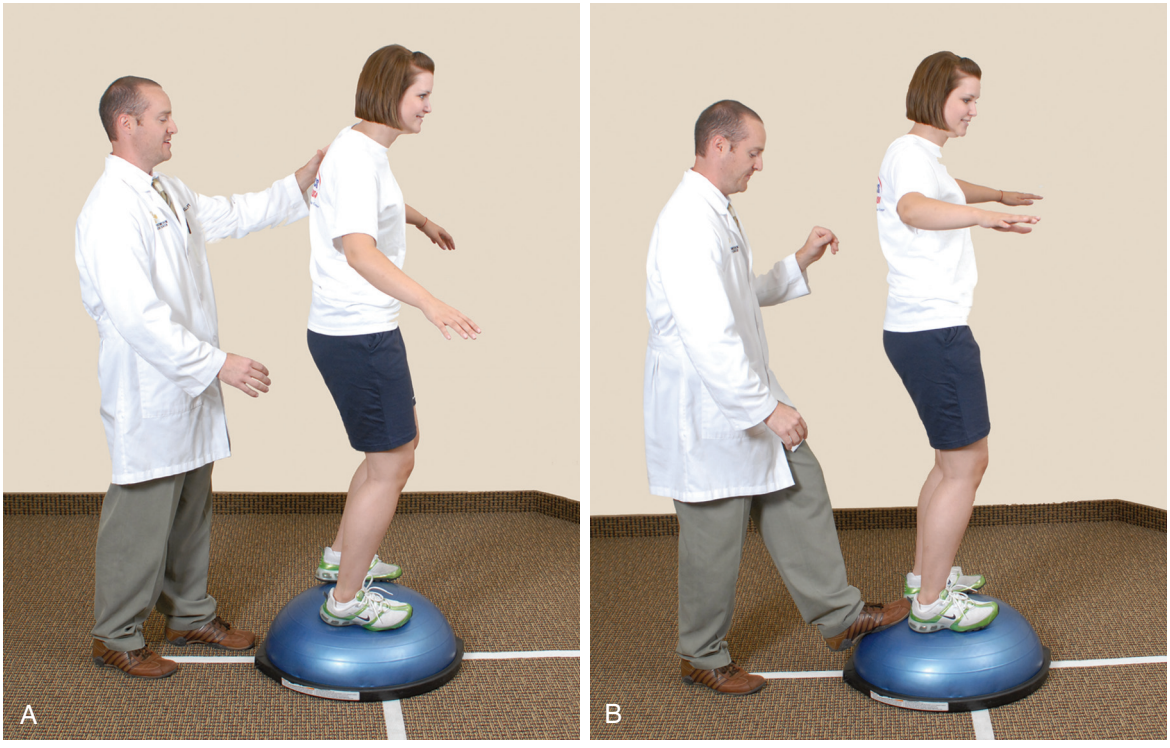


FIG 11-21 Perturbation training involving direct contact with the patient **(A)** and disruption of the platform the patient is standing on **(B)**.

stability. The techniques involve either direct contact with the patient (Fig. 11-21, *A*) or disruption of the platform the patient is standing on (Fig. 11-21, *B*).

Half round foam rolls are also used in this time period as part of the gait retraining and balance program (Fig. 11-22). This exercise helps the patient develop balance and dynamic muscular control required to maintain an upright position and be able to walk from one end of the roll to the other. Developing a center of balance, limb symmetry, quadriceps control in midstance, and postural positioning are benefits developed from this type of training. Use of the Biomechanical Ankle Platform System (BAPS [AliMed]) in double-leg and single-leg stances is another effective balance and proprioceptive exercise (Fig. 11-23).

The use of more expensive devices adds another dimension to the proprioception program, because certain units objectively attempt to document balance and dynamic control. Two of the more common units include balance systems from Biodex Medical Systems (Fig. 11-24) and NeuroCom (Natus Balance & Mobility).



FIG 11-22 Gait and balance retraining using half round foam rolls.



FIG 11-24 The Biodex Balance System (Biodex Medical Systems) may be used for balance training and to objectively measure balance and dynamic control.



FIG 11-23 The Biomechanical Ankle Platform System (BAPS [AliMed]) is used in double-leg and single-leg stances.

Conditioning

The primary consideration for a conditioning program throughout the rehabilitation period is to stress the cardiovascular system without compromising the knee joint. Depending on accessibility, a cardiovascular program is begun as soon as the patient can sufficiently tolerate the upright position with an upper extremity ergometer. The surgical limb should be elevated to minimize lower extremity swelling. This exercise is performed as tolerated. Stationary bicycling is begun in the third postoperative week. Water walking may be initiated when the surgical wound has healed. Early goals of these programs include facilitation of full ROM, gait retraining, and cardiovascular reconditioning. To improve cardiovascular endurance, the program should be performed at least three times per week for 20 to 30 minutes, and the exercise should be performed to at least 60% to 85% of maximal heart rate. It is generally regarded that performing in the higher levels of percentage of maximal heart rate achieves greater cardiovascular efficiency and endurance.

Use of cross-country skiing and stair-climbing machines is permitted during the fifth to sixth postoperative weeks. Protection against high stresses to the patellofemoral joint is strongly advocated. During bicycling, the seat height is adjusted to its highest level based on patient body size, and a low resistance level is used initially. Stair-climbing machines are adjusted to produce a short step and low resistance.

An effective cardiovascular exercise program is an important component of the latter phases of rehabilitation. In addition to the previously described exercises, an aquatic program that includes lap work using freestyle or flutter kicking, water walking, water aerobics, and deep-water running is encouraged. The determination of which cardiovascular exercises are appropriate is based on each patient's access to and preference for specific equipment.

Running and Agility Program

To initiate the running program, the patient must demonstrate no more than a 30% deficit in average torque for the quadriceps and hamstrings on isokinetic testing, have no more than a 3-mm increase in AP displacement on arthrometer testing, and be at least 9 weeks postoperative. It is important to note that the majority of patients initiate running at approximately 16 to 20 weeks after surgery. Only in exceptional cases does this program begin before this time period when muscle strength has returned to normal, no pain of joint effusion is present, and no concurrent operative procedures were performed, such as a complex meniscus repair or other ligament reconstruction.

The running program is designed based on the patient's athletic goals, particularly the position or physical requirements of the activity. For instance, an individual returning to short-duration, high-intensity activities should participate in a sprinting program rather than a long-distance endurance program. The running program is performed three times per week on opposite days of the strength program. Because the running program may not reach aerobic levels initially, a cross-training program is used to facilitate cardiovascular fitness. The cross-training program is performed on the same day as the strength workout.

The first level consists of straight-ahead walk-run combinations. Running distances are 20, 40, 60, and 100 yards (18, 37, 55, and 91 m) in both forward and backward directions. The initial running speed is approximately one-fourth to one-half of the patient's normal speed, which gradually progresses to three-fourths to full speed. An interval training-rest approach is applied in which the rest phase is two to three times the length of the training phase. After the patient is able to run straight ahead at full speed, lateral running and crossover maneuvers are begun. Short distances, such as 20 yards (18 m), are used to work on speed and agility. Side-to-side running over cups may be used to facilitate proprioception. At this time, sport-specific equipment is introduced to enhance skill development (e.g., a soccer ball for a soccer player to work on dribbling and passing activities). These variations are useful to motivate the patient and minimize training boredom.

The third level of the running program incorporates figure-eight running drills. Long and wide movement patterns over 20 yards (18 m) are initially used to encourage subtle cutting. As speed and confidence improve, the distance is decreased to approximately 10 yards (9 m). Progression through this phase is similar to that used in the lateral side-to-side program just described. Speed and agility are emphasized and equipment is introduced to develop sport-specific skills.

The fourth phase in the running program introduces cutting patterns. These patterns include directional changes at 45- and 90-degree angles, which allow the patient to progress from subtle to sharp cuts.

Plyometric Training

Plyometric training is begun upon successful completion of the running program to minimize bilateral alterations in neuromuscular function and proprioception. Plyometric training in combination with resistance training is recommended by the ACSM to improve vertical jump height.[2] Important parameters to consider when performing plyometric exercises include surface, footwear, and warmup. The jump training should be done on a firm yet forgiving surface such as a wooden gym floor. Very hard surfaces such as concrete should be avoided. A cross-training or running shoe should be worn to provide adequate shock absorption as well as adequate stability to the foot. Checking wear patterns and outer sole wear will help avoid overuse injuries. Beginning plyometric training is done in individual sessions performed in a manner similar to interval training. Initially, a rest period is incorporated that lasts two to three times the length of the exercise period; this is gradually decreased to one to two times the length of the exercise period. As well, plyometrics are performed two to three times each week, along with strength and cardiovascular endurance exercises.

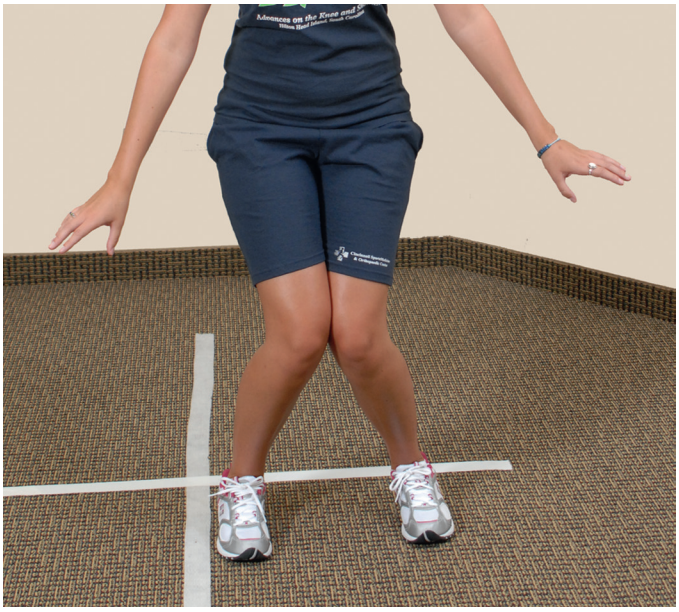


FIG 11-25 During plyometric training, the patient is instructed to keep the body weight on the balls of the feet and to jump and land with the knees flexed and shoulder-width apart to avoid knee hyperextension and an overall valgus lower limb position, as shown here.

During the various jumps, the patient is instructed to keep the body weight on the balls of the feet and to jump and land with the knees flexed and shoulder-width apart to avoid knee hyperextension and an overall valgus lower limb position (Fig. 11-25). The patient should understand that the exercises are reaction and agility drills and that, though speed is emphasized, correct body posture must be maintained throughout the drills.

The first exercise is level-surface box-hopping using both legs. A four-square grid of four equally sized boxes is created with tape on the floor. The patient is instructed to first hop from box 1 to box 3 (front to back) and then from box 1 box 2 (side to side) (Fig. 11-26). The second level incorporates both of these directions into one sequence and also includes hopping in both right and left directions (e.g., box 1 to box 2 to box 4 to box 2 to box 1). Level three progresses to diagonal hops (Fig. 11-27), and level four includes pivot hops in 90- and 180-degree directions (Fig. 11-28). Once the patient can perform level four double-leg hops, the same exercises are done on a single leg. The next phase incorporates vertical box hops.

Improvement is measured by counting the number of hops in a defined time period. The initial exercise time period is 15 seconds. The patient is asked to complete as many hops between the squares as possible in 15 seconds. Three sets are performed for both directions, and the number of hops is recorded. The program is progressed as the number of hops increases, as does the patient's confidence.

We recommend that patients complete a course of Sportsmetrics training to reduce the risk of a noncontact reinjury before return to strenuous athletics.[53] This training program teaches athletes to control the upper body, trunk, and lower body position; lower the center of gravity by increasing hip and knee flexion during activities; and develop muscular strength and techniques to land with decreased ground reaction forces. In addition, athletes are instructed to preposition the body and lower extremity before initial ground contact to



FIG 11-26 Initial plyometric training involves jumping front to back (**A** to **C**) and side to side (**D** to **F**) on a level surface using both legs.

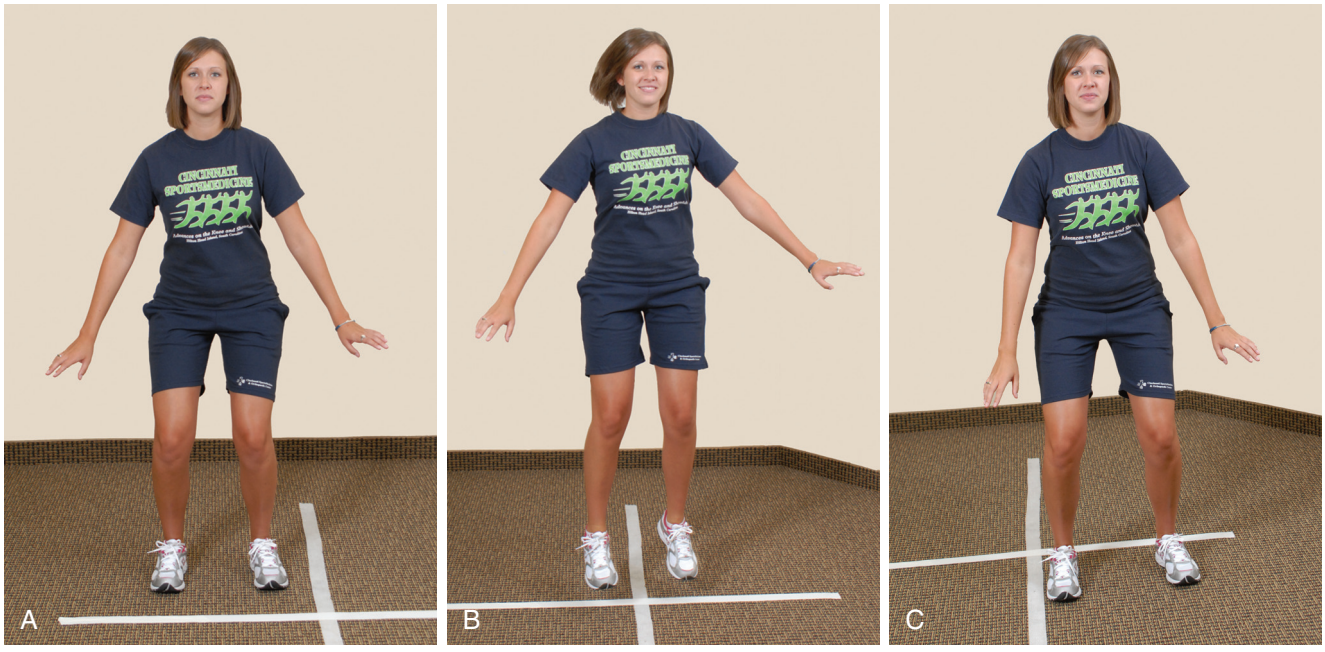


FIG 11-27 Plyometric training using diagonal hops forward and backward.



FIG 11-28 Plyometric training using pivot hops in 90- and 180-degree directions.

obtain the position of greatest knee joint stability and stiffness. The program consists of a dynamic warmup, plyometric jump training, strengthening exercises, aerobic conditioning, agility, and risk awareness training. The training is conducted three times per week on alternating days for 6 weeks. It is described in detail in Chapter 14.

Return to Sports Activities

Return to sports activities is based on successful completion of the running and functional training and plyometric programs as well as the following criteria:[4,5]

1. Knee examination
   - ROM: International Knee Documentation Committee (IKDC) rating of normal or nearly normal
   - Lachman test: IKDC rating of normal or nearly normal
   - Pivot shift test: IKDC rating of normal or nearly normal
   - Patella pain: none
   - Effusion: none
2. KT-2000 (MEDmetric)[13,76]
   - Less than 3-mm reconstructed compared with contralateral knee (if normal), 134-N total AP displacement.
3. Quadriceps and hamstrings muscle strength and endurance tests: less than 10% deficit compared with contralateral side, based on equipment available:
   - Isokinetic 180 degrees/sec and 300 degrees/sec[8,9,18,21,26,32,33,39,61,66,77]
   - Isometric portable fixed or hand-held dynamometer: quadriceps 60-degree flexion, hamstrings 60- or 90-degree flexion, three repetitions each, use average[69,71,72]
   - If isokinetic or isometric equipment is not available, a one-repetition maximum bench press and leg press is recommended if weight room equipment is available, along with an experienced test administrator and a sufficient amount of time to safely conduct these tests.[29,65]
4. Single-leg hop tests: 15% or less deficit lower limb symmetry on single-hop and triple crossover hop tests[3,6,18,33,35,36,45,77] (may videotape to provide subjective analysis of balance and landing position)
3. Video drop-jump[43,54,63,68]
   - If software is available, 60% or greater normalized knee separation distance
   - If software is not available, use video for subjective analysis of landing position (varus, valgus, neutral): no valgus, knees flexed for controlled landing
5. Single-leg squat, five repetitions: no knee valgus, mediolateral movement, or pelvic tilt[1,11,24,25]
6. Video plant-and-cut drill: subjective rating of high hip and knee flexion, upright posture, and no valgus collapse[12,27,41] (This test should be done in the manner described by Pollard and associates,[62] in which the patient runs 5 meters to a spot designated on the floor with tape, plants on the reconstructed leg, and then performs a 45-degree cut. If the right leg was reconstructed, the cut should be to the left. Cones may be set up to direct the patient to perform the angle of 45 degrees.)

Other tests to consider before the patient is released to unrestricted athletic activities include the multistage fitness test to determine maximal aerobic capacity[64] and the 60-second sit-up test or other core strength measures.[58] A single-leg vertical jump test may be conducted to determine whether a deficit exists between the reconstructed and the contralateral leg.

A trial of function is encouraged in which the patient is monitored for knee swelling, pain, overuse symptoms, and giving-way episodes. Some athletes will experience transient knee swelling upon return to strenuous activities and should be educated on how to recognize this problem and the importance of reducing activities until the swelling subsides. If swelling persists, the athlete is advised to reduce athletic activities for 2 to 6 weeks, consider use of nonsteroidal antiinflammatory drugs, and use ice and elevation. Upon successful return to activity, the patient is encouraged to continue with a maintenance program. During the in-season, a conditioning program of two workouts per week is recommended. In the off-season or preseason, this program should be performed three times per week to maximize gains in flexibility, strength, and cardiovascular endurance.

REHABILITATION PROTOCOL WITH DELAYED PARAMETERS FOR REVISION ACL RECONSTRUCTION, ALLOGRAFTS, AND COMPLEX KNEES

This protocol incorporates delays in return of full weight bearing and knee flexion; initiation of certain strengthening, conditioning, running, and agility drills; and return to unrestricted activities (Table 11-7) for knees undergoing ACL revision,[48,52] allograft reconstruction,[51] major concomitant operative procedures (complex meniscus repairs or transplants, other ligament reconstructions, articular cartilage restorative procedures, patellofemoral realignment procedures, or osteotomies), or that have noteworthy articular cartilage damage.[47,49] Toe touch–only weight bearing is allowed for the first 2 postoperative weeks. The amount of weight patients are allowed after this time depends on the concomitant operative procedures performed as well as on evaluation of postoperative pain and swelling, quadriceps muscle control, and ROM. The majority of patients are weaned from crutch support between the sixth and eighth postoperative weeks.

Allowance of knee flexion of at least 135 degrees is delayed according to the concomitant procedure performed. Knees that undergo a posterolateral reconstructive procedure are placed into a bivalved long-leg cast for the first 4 weeks[50] (see Chapter 18). The patient removes the cast to perform ROM exercises several times each day and is instructed to reach 0 degrees of extension, but to avoid hyperextension. Patients who undergo a concomitant proximal patellar realignment are allowed 0 to 75 degrees of flexion for the first 2 postoperative weeks. Flexion is slowly advanced to 135 degrees by the eighth week. Knee flexion is also initially limited in knees that undergo a concomitant posterior cruciate ligament reconstruction[46] (see Chapter 18) and or complex meniscus repair (see Chapter 25).[19]

Knee extension is limited in individuals who have abnormal hyperextension (≥10 degrees) with physiologic laxity to 0 to 5 degrees for approximately 3 weeks to allow for sufficient healing before stress is applied to push for 0 degrees.

A postoperative long-leg hinged knee brace is used for approximately the first 8 weeks in patients placed in this protocol, except those who undergo a posterolateral procedure. The brace provides protection and support to the healing tissues and assists with patient comfort during this time period.

Modifications in strengthening, conditioning, and strenuous training are based on the concomitant procedures performed. Return to activity is delayed until at least the sixth postoperative month to allow for healing of all repaired and reconstructed tissues and return of joint and muscle function. It is our opinion that allografts have a delay in maturation compared with autografts (see Chapter 5) and that the resultant time constraints postoperatively in terms of release to full activity are empirical at present. Evaluation is a key component to allow initiation of the functional program, which includes the

Text continued on p. 327

TABLE 11-7 Cincinnati Sportsmedicine & Orthopaedic Center Rehabilitation Protocol for Anterior Cruciate Ligament Reconstruction: Revision Knees, Allografts, and Complex Knees

	POSTOPERATIVE WEEKS					POSTOPERATIVE MONTHS			
	1-2	3-4	5-6	7-8	9-12	4	5	6	7-12
Brace: postoperative and functional	X	X	X	X	(X)			X	X
ROM Minimum Goals									
0-90 degrees	X	X							
0-120 degrees			X						
0-135 degrees				X					
Weight Bearing									
Toe touch	X								
25%-50% body weight		X							
75%-100% body weight			X						
Patella Mobilization	X	X	X	X					
Modalities									
EMS	X	X	X	X					
Pain/edema management (cryotherapy)	X	X	X	X	X	X	X	X	X
Stretching									
Hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X	X
Strengthening									
Quad isometrics, quadriceps-hamstrings isometrics, cocontraction, straight-leg raises, active knee extension	X	X	X	X	X				
Closed-chain: gait retraining, toe raises, wall-sits, minisquats	X	X	X	X	X	X			
Knee flexion hamstring curls (90 degrees)			X	X	X	X	X	X	X
Knee extension quads (90-30 degrees)			X	X	X	X	X	X	X
Hip abduction-adduction, multihip			X	X	X	X	X	X	X
Leg press (70-10 degrees)			X	X	X	X	X	X	X
Balance/Proprioceptive Training									
Weight shifting, cup walking	X	X	X	X	X				
BBS, BAPS, perturbation training, balance board, minitrampoline					X	X	X	X	X
Conditioning									
UBC		X	X	X					
Stationary bike			X	X	X	X	X	X	X
Aquatic program			X	X	X	X	X	X	X
Elliptical machine				X	X	X	X	X	X
Swimming (kicking)					X	X	X	X	X
Walking					X	X	X	X	X
Stair-climbing machine				X	X	X	X	X	X
Ski machine				X	X	X	X	X	X
Running: straight								X	X
Cutting: lateral carioca, figure-eights									X
Plyometric training									X
Full sports activities									X

PHASE 1: WEEKS 1 TO 2

General Observation

Toe-touch weight bearing to 25% body weight when:

- Pain is controlled
- Hemarthrosis is controlled
- Voluntary quadriceps contraction is achieved
- 0 degrees extension

TABLE 11-7 Cincinnati Sportsmedicine & Orthopaedic Center Rehabilitation Protocol for Anterior Cruciate Ligament Reconstruction: Revision Knees, Allografts, and Complex Knees—cont'd

PHASE 1: WEEKS 1 TO 2		
Evaluation (Goal)	Pain (controlled) Hemarthrosis (mild) Patellar mobility (good) ROM (minimum 10-80 degrees) Quadriceps contraction and patella migration (good) Soft tissue contracture (none)	
Goals	ROM (depends on procedure) Adequate quadriceps contraction Control of inflammation, effusion	
	Frequency	**Duration**
ROM	3-4 ×/day, 10 min	
ROM passive Meniscus repair (complex), MCL, revision, EA = 0-90 degrees Patellar realignment = 0-75 degrees Posterolateral procedure = 0-90 degrees (unless examination shows hyperelastic tissue type, then hold 15-70 degrees for 2 wk postoperative) Patella mobilization Ankle pumps (plantar flexion with resistance band) Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion)		3 sets × 10 reps
Active quadriceps isometrics (based on ROM limits)		1 set × 10 reps
Knee extension (active assisted)		3 sets × 10 reps
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
PHASE 2: WEEKS 3 TO 4		
General Observation	50% weight bearing when: • Pain is controlled • Hemarthrosis is controlled • Voluntary quadriceps contraction is achieved	
Evaluation (Goal)	Pain (controlled) Effusion (mild) Patellar mobility (good) ROM (minimum 0-90 degrees) Quadriceps contraction and patella migration (good) Soft tissue contracture (none) Joint arthrometry, 3 wk, 20 lb (<3 mm)	
Goals	ROM (0-110 degrees) Control of inflammation, effusion Adequate quadriceps contraction 50% weight bearing	
	Frequency	**Duration**
ROM	3-4 ×/day, 10 min	
ROM passive (0-90 degrees) Patella mobilization Ankle pumps (plantar flexion with resistance band) Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec

Continued

TABLE 11-7 Cincinnati Sportsmedicine & Orthopaedic Center Rehabilitation Protocol for Anterior Cruciate Ligament Reconstruction: Revision Knees, Allografts, and Complex Knees—cont'd

	Frequency	Duration
PHASE 2: WEEKS 3 TO 4		
Strengthening	2-3 ×/day, 20 min	
Straight-leg raises (flexion, extension, adduction, abduction)		3 sets × 10 reps
Isometric training:		
Multiangle (0, 60 degrees)		1 set × 10 reps
Active quadriceps (full extension)		
Quadriceps/hamstring co-contraction with EMS		
Toe raises/heel raises		3 sets × 10 reps
Knee extension (90-45 degrees, no resistance)		3 sets × 10 reps
Knee flexion (active, 0-90 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain:		
Minisquats (0-45 degrees, 50% weight bearing)		3 sets × 20 reps
Wall-sits		To fatigue
Wall-sits with EMS		
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
PHASE 3: WEEKS 5 TO 6		
General Observation	Full weight bearing when: • Pain is controlled without narcotics • Effusion is controlled • ROM 0-100 degrees • Muscle control throughout ROM • Dynamic control of varus/valgus	
Evaluation (Goal)	Pain (mild) Effusion (minimal) Patellar mobility (good) ROM (0-120 degrees) Muscle control (3/5) Inflammatory response (none) Joint arthrometry, 6 wk, 30 lb (<3 mm)	
Goals	ROM (0-125 degrees) Control of inflammation, effusion Muscle control Full weight bearing Early recognition of complications (motion loss, CRPS, increased anteroposterior displacement, patellofemoral changes)	
	Frequency	**Duration**
ROM	3 ×/day, 10 min	
ROM passive (0-120 degrees)		
Patella mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec

TABLE 11-7 Cincinnati Sportsmedicine & Orthopaedic Center Rehabilitation Protocol for Anterior Cruciate Ligament Reconstruction: Revision Knees, Allografts, and Complex Knees—cont'd

PHASE 3: WEEKS 5 TO 6

	Frequency	Duration
Strengthening	1-2 ×/day, 20 min	
Straight-leg raises (ankle weight, <10% body weight)		3 sets × 10 reps
Isometric training: multiangle (90, 60, 30 degrees)		2 sets × 10 reps
Heel raise/toe raise		3 sets × 20 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (90-45 degrees, with resistance)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue, 5 sets
Minisquats		3 sets × 20 reps
Lunge (no resistance)		
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Weight shift side-side and forward-backward		5 sets × 10 reps
Balance board, two legged		
Cup walking	1-2 ×/day, 5 min	
Single-leg stance on stable platform		5 reps
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Water walking		
Stationary bicycling (patellofemoral precautions)		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

PHASE 4: WEEKS 7 TO 8

General Observation	Independent ambulation when: • Pain is controlled • Effusion is controlled • ROM 0-120 degrees • Muscle control throughout ROM • Dynamic control of varus/valgus
Evaluation (Goal)	Pain (no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-135 degrees) Muscle control (4/5) Inflammatory response (none) Gait (symmetric) Joint arthrometry, 8 wk (<3 mm)
Goals	ROM (0-135 degrees) Full weight bearing, normal gait Control of inflammation, effusion Muscle endurance Recognition of complications (motion loss, CRPS, increased anteroposterior displacement, patellofemoral changes)

Continued

TABLE 11-7 Cincinnati Sportsmedicine & Orthopaedic Center Rehabilitation Protocol for Anterior Cruciate Ligament Reconstruction: Revision Knees, Allografts, and Complex Knees—cont'd

PHASE 4: WEEKS 7 TO 8

	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (ankle weight, <10% body weight)		3 sets × 10 reps
Straight-leg raises with rubber tubing		3 sets × 30 reps
Isometric training: multiangle (90, 60, 30 degrees)		3 sets × 20 reps
Heel raise/toe raise		3 sets × 10 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (90-45 degrees, with resistance)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue ×3
Minisquats (rubber tubing, 0-30 degrees)		3 sets × 20 reps
Lunge		
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Dynamic hip and core program		
Balance Training	3 ×/day, 5 min	
Balance board, two legged		
Lateral step-ups: 2- to 4-inch block		
Aerobic Conditioning (Patellofemoral Cautions)	2 ×/day, 10 min	
UBC		
Stationary bicycling		
Water walking		
Stair machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Elliptical machine (low resistance)		
Modalities	As required	
Cryotherapy		20 min

PHASE 5: WEEKS 9 TO 12

General Observation	Full weight bearing ROM 0-135 degrees No effusion, painless ROM, joint stability Performs ADLs, can walk 20 min without pain
Evaluation (Goal)	Manual muscle test (hamstrings, quadriceps, hip abductors/adductors/flexors/extensors) (4/5) Swelling (none) Joint arthrometry, 12 wk (<3 mm) Patellar mobility (good) Crepitus (none/slight)
Goals	Increase strength and endurance

	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises with rubber tubing		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps

TABLE 11-7 Cincinnati Sportsmedicine & Orthopaedic Center Rehabilitation Protocol for Anterior Cruciate Ligament Reconstruction: Revision Knees, Allografts, and Complex Knees—cont'd

PHASE 5: WEEKS 9 TO 12

	Frequency	Duration
Knee extension (90-45 degrees, with resistance)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue ×3
Minisquats (rubber tubing, 0-40 degrees)		3 sets × 20 reps
Lunge		
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Dynamic hip and core program		
Balance Training	3 ×/day, 5 min	
Balance board, two legged		
Single-leg stance on unstable platform		
Perturbation program		
Aerobic Conditioning (Patellofemoral Cautions)	1-2 ×/day, 15-20 min	
Stationary bicycling		
Water walking		
Swimming (straight-leg kicking)		
Walking		
Stair machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Elliptical machine (low resistance)		
Modalities	As required	
Cryotherapy		20 min

PHASE 6: WEEKS 13 TO 26

General Observation	No effusion, painless ROM, joint stability Performs ADLs, can walk 20 min without pain ROM 0-135 degrees	
Evaluation (Goal)	Isometric test (% difference in quadriceps and hamstrings) (30%) Swelling (none) Joint arthrometry (<3 mm) Patellar mobility (good) Crepitus (none/slight)	
Goals	Increase strength and endurance	
	Frequency	**Duration**
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises with rubber tubing (high speed)		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (90-45 degrees, with resistance)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue ×5
Minisquats		3 sets × 20 reps
Lateral step-ups (2- to 4-inch block)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Dynamic hip and core program		

Continued

TABLE 11-7 Cincinnati Sportsmedicine & Orthopaedic Center Rehabilitation Protocol for Anterior Cruciate Ligament Reconstruction: Revision Knees, Allografts, and Complex Knees—cont'd

PHASE 6: WEEKS 13 TO 26

	Frequency	Duration
Balance Training	3 ×/day, 5 min	
Balance board, two legged		
Single-leg stance on unstable platform		
PlyoBack with ball toss		
Perturbation training		
Aerobic Conditioning (Patellofemoral Cautions)	3 ×/wk, 15-20 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Stair machine (low resistance and stroke)		
Elliptical machine (low resistance)		
Running Program (6 Months, Straight, 30% Deficit Isometric Test)	3 ×/wk, 10 min	
Jog (progress speed: ½ to ¾ to full)		¼ mile
Walk		⅛ mile
Backward run		20 yards
Modalities	As required	
Cryotherapy		20 min

PHASE 7: WEEKS 27 TO 52

General Observation	No effusion, painless ROM, joint stability Performs ADLs, can walk 20 min without pain
Evaluation (Goal)	Isometric test (isometric + torque 300 degrees/sec, % difference in quadriceps and hamstrings) (10%-15%) Swelling (none) Joint arthrometry (3 mm) Patellar mobility (good) Crepitus (none/slight) Single-leg function tests (9 mo: hop distance, timed hop, % difference between noninvolved compared with involved side) (≤15%)
Goals	Increase function, strength, and endurance Return to previous activity level

	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	1 ×/day, 20-30 min	
Straight-leg raises with rubber tubing (high speed)		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (90-45 degrees, with resistance)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Dynamic hip and core program		

TABLE 11-7 Cincinnati Sportsmedicine & Orthopaedic Center Rehabilitation Protocol for Anterior Cruciate Ligament Reconstruction: Revision Knees, Allografts, and Complex Knees—cont'd

PHASE 7: WEEKS 27 TO 52

	Frequency	Duration
Balance Training	3 ×/day, 5 min	
Balance board, two legged		
Single-leg stance on unstable platform with secondary activity		
Perturbation training		
Aerobic Conditioning (Patellofemoral Cautions)	3 ×/wk, 20-30 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Stair machine (low resistance and stroke)		
Elliptical machine (low resistance)		
Running Program (Straight)	3 ×/wk, 15-20 min	
Jog: interval training		20, 40, 60, 100 yards
Walk/rest phase (3 : 1 rest/work)		20 yards
Backward run		20 yards
Cutting Program (Lateral, Carioca, Figure-Eights, 20% Deficit Isokinetic Test)	3 ×/wk	20 yards
Functional Training (10%-15% Deficit Isokinetic Test)	3 ×/wk	
Plyometric training: box hops, level, double leg		4-6 sets
Sports-specific drills (10%-15% deficit isokinetic test)		
Modalities	As required	
Cryotherapy		20 min

BAPS, Biomechanical Ankle Platform System (Patterson Medical); *BBS,* Biodex Balance System (Biodex Medical Systems); *CRPS*, complex regional pain syndrome; *EA*, iliotibial band extra-articular procedure; *EMS*, electrical muscle stimulation; *ITB*, iliotibial band; *MCL*, medial collateral ligament; *ROM*, range of motion; *UBC*, upper body cycle.

assessment of symptoms and examination of knee motion, muscle strength, and ligament stability. The sum of the evaluation, not just one parameter, should determine return to function. In patients following this protocol, return to full activity is not usually expected to occur until the ninth to twelfth month postoperatively. It should also be noted that return to full activity does not guarantee return to preinjury activity levels. Consideration of use of a derotation or functional brace includes patients who have undergone ACL revision or multiligament reconstruction or who demonstrate an increase in AP displacement postoperatively of 3 mm or more compared with the contralateral limb. In addition, patients who are apprehensive about returning to strenuous activities or who experience a subjective sensation of instability are candidates for functional bracing.

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12

Neuromuscular Training After Anterior Cruciate Ligament Reconstruction

Kevin E. Wilk, Todd R. Hooks

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INTRODUCTION

Rehabilitation after anterior cruciate ligament (ACL) injury and surgery has evolved in the past 2 decades from programs that recommended 6 to 8 weeks of immobilization, restricted range of motion (ROM) and strengthening exercises, and a delay in return to sports activities for 9 to 12 months postoperatively. Current therapeutic programs implement immediate knee motion,[53,54] weight bearing, and functional exercises, as well as proprioception and neuromuscular control drills[43,66] aimed at improving the patient's overall outcome, thereby promoting an earlier restoration of functional dynamic stability and return to sports activities.

Although there have been numerous advances in surgery and rehabilitation after ACL injury and surgery, the rate of return to preinjury levels of activity is alarmingly low. Arden and associates[2] reported in a meta-analysis of 5770 patients that 63% returned to preinjury sports levels and only 44% returned to competitive sports. The most common reason reported for not returning to preinjury sport levels was fear of reinjury. These investigators found that 19% of all patients had a fear of reinjury and 13% stated they had structural integrity issues with the knee. This concept of fear of reinjury is referred to as *kinesophobia*, as described by Chmielewski and colleagues.[16] Lentz and coworkers[41] recently reported that 45% of the patients with ACL reconstructions did not return to preinjury sport levels. Of those patients not returning to sports, 45% reported kinesophobia and 68% had a feeling of knee instability. We believe a rehabilitation program that has a significant focus on proprioception and neuromuscular control exercises and drills will assist in preventing the development of kinesophobia and will ensure that patients develop confidence in their knee and improved function.

Fitzgerald and associates[24] reported improved outcomes in ACL-deficient patients who participated in a rehabilitation program that emphasized proprioception and perturbation training. Shelbourne and Nitz[61] first reported improved clinical outcomes in patients who participated in earlier functional activities after ACL reconstruction. The results of these studies increased the emphasis on neuromuscular training in postoperative programs. In this chapter, proprioception and neuromuscular control are defined, the implications after ACL surgery are discussed, and techniques commonly used to restore functional dynamic stability to allow a return to a prior level of function are described.

TERMINOLOGY

Proprioception, *kinesthesia*, and *neuromuscular control* are terms that are often used interchangeably to describe exercises and techniques implemented in treatment; however, these terms have distinctive definitions. *Proprioception* is the awareness of joint position, whereas *kinesthesia* is the cognizance of joint movement.[43] *Neuromuscular control* has been defined as the efferent response to an afferent input,[65] thus providing the functional component to movement and athletic activities that is referred to as dynamic stability.

Mechanoreceptors (pacinian corpuscles, Ruffini endings, muscle spindle, and Golgi tendon organs [GTO]) located in muscles, capsules, and ligaments provide sensory input into the central nervous system (CNS). These mechanoreceptors act together to give sensory awareness of joint position, movement, acceleration, and strain via afferent pathways to the CNS. The CNS provides an efferent response to the surrounding joint musculature to elicit the desired response.

Several proposed mechanisms have been described for the joint mechanoreceptors' influence for joint stability. Extrinsic muscle stiffness is mediated through two mechanisms: (1) force feedback, which is provided by the GTO,[34] and (2) length feedback, which is stimulated by the muscle spindle pathway that facilitates motor activity.[47,48]

Additionally, the joint mechanoreceptors contribute to joint stability through two possible mechanisms. The direct ligamentous-muscular protective reflex, a reflex between the ACL and hamstring muscles, causes reflex inhibition of the quadriceps and facilitation of the hamstrings when stimulated that is aimed at minimizing strain on the ACL. Another proposed mechanism for added joint stability is the receptors' indirect contribution to dynamic joint stability through what is termed *presetting*.[36] The receptors contribute to preparatory adjustments of muscle stiffness and dynamic stability that are essential in preparation for deceleration and cutting activities.

EFFECTS OF INJURY ON PROPRIOCEPTION

Normal recruitment and timing patterns of the surrounding musculature are impeded after an injury because of changes that occur within the joint. Two theories are proposed for this mechanism, including an alteration occurring in the ratio of muscle spindle-to-GTO activity that causes an interference of the proprioceptive pathway. Joint effusion has also been credited with a diminished ability of the musculature to contract, thereby decreasing proprioception. A significantly decreased activation of the vastus medialis and lateralis muscles during a single-leg drop landing has been demonstrated with a 30-mL knee joint effusion.[56]

After injury, the interactions within the neuromuscular system are disturbed as deafferentation of peripheral sensory receptors occurs, resulting in diminished proprioception and kinesthesia, abnormal patterns of muscle activity,[19] and reduced joint dynamic stability.[6,7,42] Changes in proprioception have been reported to occur within 24 hours following injury[43] and may persist for as long as 6 years.[22] Additionally, Hooks and coworkers[33] reported that within 24 to 48 hours after ACL injury, the contralateral extremity had diminished proprioceptive sense. Therefore the rehabilitation program should consist of bilateral motor and proprioceptive training to minimize proprioceptive loss after injury.

A significant decrease in muscle activation timing and recruitment order of the quadriceps, hamstrings, and gastrocnemius in response to anterior tibial translation in the ACL-deficient knee compared with the intact-ACL knee has been reported.[71] The delay in muscle recruitment may lead to decreased knee joint stability owing to the stabilization effect of the musculature. A reflexive activation of the hamstring musculature has been reported with the application of 100 N of anterior shear force on ACL-deficient knees.[7] Paterno and colleagues[57] reported a significant difference in force production 27 months after ACL reconstruction during a vertical jump in the involved knee compared with the contralateral knee.

Gait abnormalities are common after ACL injury because patients frequently demonstrate a "quadriceps avoidance gait pattern."[1,8] This altered pattern occurs because patients ambulate with a flexed knee gait as a result of increased hamstring activity and minimal or no quadriceps electromyography activity (EMG). This altered gait pattern can persist for several months because the patient will develop a protective neuromuscular adaptation if not addressed during rehabilitation.

The reported time frame varies regarding the length of time proprioceptive and neuromuscular control deficits persist after surgery. Harrison and coworkers[29] found no significant differences in postural sway (eyes open and closed) of the involved and uninvolved lower extremity during single-leg stance 10 to 18 months after surgery. However, other examiners have reported more extended periods of deficits after ACL injury. Fremerey and coauthors[27] measured joint position sense preoperatively and serially after surgery, and noted that restoration of joint position sense was virtually restored at near-end range of flexion and extension 6 months postoperatively. However, proprioception was impaired at the mid range of knee motion 6 months after surgery and persisted up to 3.5 years for some patients. Long-term deficits in proprioceptive awareness may influence the athlete's functional ability and/or likelihood of reinjury because dynamic stability is critical in the mid range position where the majority of activities occur.

Long-term follow-up studies after ACL injury have reported a 10-times greater incidence rate of knee osteoarthritis (OA), with a 40% to 90% occurrence 7 to 12 years after surgery.[25,44,59] Carey and colleagues[14] reported that although 80% of running backs and wide receivers returned to play in the National Football League, the performance was reduced by a third. Likewise, Busfield and associates[13] reported a 44% decrease in the performance of National Basketball Association players who returned to play after ACL reconstruction as measured with statistical and efficiency ratings. Barber-Westin and Noyes[5] conducted a systematic review with a minimum 2-year follow-up and reported reinjury rates of the ACL-reconstructed knee ranged from 0% to 24%, and injury to the contralateral knee ranged from 2% to 15%. Arden and coworkers[2] reported that 63% of athletes were able to return to preinjury levels and only 44% were able to return to competitive sports. The authors reported a fear of reinjury (19%) as the number one reason athletes did not return to sports participation, with 13% reporting structural/functional problems. As discussed previously, the fear of movement and/or reinjury (kinesophobia) is a common problem and appropriate interventions to improve self-efficacy should be implemented to improve knee function.[17,21,70]

CLINICAL IMPLICATIONS

The rehabilitation program after ACL injury should ensure the restoration of neuromuscular control beginning immediately after ACL reconstruction to prevent deafferentation of the joint. The therapist should safeguard against deleterious stresses that neuromuscular training may place on the healing structures, while ensuring a proper progression into advanced techniques. Therefore the clinician throughout the rehabilitation program monitors the progression of volume and advanced techniques.

MOTOR SKILL DEVELOPMENT STAGES

Three stages of motor skill development have been described: cognitive, associative, and autonomous.[15] The cognitive stage occurs when a new task or drill is introduced because increased movement errors occur, movement is stiff and/or rigid, and extended training is required as the individual learns the movement. This is followed by the associate stage where less time is spent processing the drill with improved movement; however, it is still not automatic. The final stage, autonomous, occurs as the movement becomes automatic, efficient, and more skilled. These stages of motor skill development are required in skilled sporting activities such as swinging a golf club or hitting a baseball. Additionally, a refining stage occurs as the individual refines the task/drill to an increased level of perfection.

When learning a new motor skill, patients will progress through four stages: mobility, stability, controlled mobility, and skill.[64] *Mobility* refers to the individual having both adequate ROM to assume a posture or position and motor recruitment to initiate the movement. *Stability* is the capability to produce a cocontraction to provide tonic holding. Controlled mobility occurs as movement is added to a stable posture. *Skill*, the highest level of motor control, refers to function and the

ability to perform tasks in an unstable environment such as football or soccer.

NEUROMUSCULAR TRAINING PROGRAM

Neuromuscular training, like any other form of treatment, should be adapted and prescribed based on the patient's neuromuscular status, desired goals, and current phase of healing and rehabilitation (acute, subacute, advanced, and return to activity). Although the neuromuscular techniques incorporated into the training program are numerous, the clinician should ensure an appropriate progression is implemented, including the required skill level and use of both isolated and combined movements. Additionally, the clinician should ensure an adequate level of difficulty is imparted into the training because studies have shown a 50% to 60% failure rate of a task is required for an individual to learn a new skill.[23,50] Therefore the clinician should carefully monitor these drills to ensure adequate training without preventing undue stresses and strains on healing tissues.

The clinician can impart various exercises depending on the current phase of treatment that are patient specific. These exercises are categorized into joint repositioning, balance training, perturbation training, plyometric drills, and technique training. Throughout the training, feedback is given to the patient using verbal instructions, technique guidance, and visual feedback such as a mirror or a force platform. These techniques and cueing may aid in modification and mastering a movement drill.

Lephart and colleagues[42,43] described joint repositioning drills in which the clinician passively positions the affected joint to a predetermined joint angle and then passively returns the knee to the starting position. The clinician then instructs the patient to actively reposition the prescribed knee joint angle. This drill can be performed as either a test or as a rehabilitation-training technique.

Balance-training exercises are used to incorporate postural control into the training program aimed at reducing postural sway. The patient performs exercises on various training surfaces based on level of difficulty. In the acute phase, a force platform can be used to determine weight acceptance and distribution with exercise (Fig. 12-1). Balance training can be initiated on flat ground incorporating upper and/or lower extremity movements (Fig. 12-2). Unstable surfaces such as foam, air mattresses, and wobble boards (Fig. 12-3) are included in the training program to promote further challenge. Furthermore, balance-training devices (Fig. 12-4) can be included to further challenge the neuromuscular system and provide the patient with visual feedback.

Perturbation training is performed by the clinician applying an external force to create a postural disturbance that initiates a reactive motor response. Wilk and coworkers[66] emphasized the importance of perturbation training in the female ACL patient and highlighted these drills as a critical component necessary for athletes to master to ensure a successful return to sports. Fitzgerald and associates[24] examined the efficacy of perturbation drills in the rehabilitation of ACL-deficient knees and reported increased satisfactory outcomes and decreased frequency of giving-way episodes. Chmielewski and coworkers[16,18] noted a restoration of knee joint kinematics and an increase in quadriceps-hamstring muscle coactivation after perturbation training in patients with ACL-deficient knees. Wilk and colleagues[66,67,69] and Snyder-Mackler and coworkers[62] highly recommended the incorporation of perturbation training in ACL rehabilitation.

Plyometric training drills can be performed to facilitate dynamic stabilization and neuromuscular control of the knee joint. These drills are used to train the lower extremity to produce and dissipate forces to avoid injury by using the muscle's stretch-shortening capabilities to produce maximal concentric contraction that is immediately followed by a rapid eccentric loading of the muscle tissues.[68,69] Hewett and associates[32] examined the effects of a 6-week plyometric training program on the strength and landing mechanics in female athletes. They reported a 22% decrease in peak ground reaction forces and a 50% decrease in frontal plane movement of the knee during landing. Significant increases in hamstring isokinetic strength, hamstring-to-quadriceps ratio, and vertical jump height were also noted. Furthermore, Hewett and coworkers[31] prospectively analyzed the effects of this plyometric training program in the prevention of ACL injuries and noted a statistically significant decrease in the knee ligament injury rate compared with a control group.

Wilk and associates[69] referred to plyometric training as "reactive neuromuscular training" that is initiated in the advanced phases of



FIG 12-1 Balance training performed while standing on a force gauge to give the patient feedback regarding the weight distribution.



FIG 12-2 Incorporating upper and lower extremity movements into single-limb stance for greater postural disturbance.



FIG 12-3 Mini-squats performed on a wobble board.



FIG 12-4 Stabilization training on the Biodex Stability System.



FIG 12-5 The patient begins jumping off one box, landing on the floor with both knees slightly flexed **(A)**, and then jumps to the second box, again landing with both knees slightly flexed **(B)**.

rehabilitation to increase performance. Plyometric training is implemented to increase performance and reduce the incidence of injury; therefore the patient should focus on proper technique and body mechanics throughout the exercise. These exercises are progressed from double-leg drills to single-leg drills, and from level-ground jumps to box jumps (Fig. 12-5).

The final stage of training is technique training and involves sports-specific and performance training. The patient performs drills such as running and cutting, deceleration training, and landing from a jump. The inclusion of technique training has been reported to reduce ACL injury.[49] Mandelbaum and coworkers[45] reported a reduction in ACL injuries in soccer players with an ACL prevention program that focused on proper technique. The Sportsmetrics program (see Chapter 14) emphasizes proper landing technique from plyometric jumps by instructing the patient to repeat an exercise if it is not performed appropriately after the technique has been corrected.[32,52]

TABLE 12-1 Rehabilitation After Anterior Cruciate Ligament Injury

Goals	Brace	Weight Bearing	Exercises	Electrical Muscle Stimulation	Neuromuscular, Proprioception Training	Cryotherapy	Patient Education
Diminish inflammation, swelling, pain	Elastic wrap or knee sleeve to reduce swelling	As tolerated, with or without crutches	Ankle pumps, passive knee extension to 0 degrees	To quadriceps during voluntary quadriceps exercises (4-6 h/day)	Eliminate quadriceps-avoidance gait	Apply ice 20 min/hr	Review postoperative rehabilitation program
Restore normal knee ROM, especially extension			Passive knee flexion to tolerance		Retro-stepping drills	Elevate leg with knee in full extension	Review instructional video (optional); select appropriate surgery date
Restore voluntary muscle activation			Straight leg raises (flexion, abduction, adduction).		Joint repositioning	Knee must be above heart	
Provide patient education to prepare for surgery			Quadriceps setting CKC: minisquats, lunges, step-ups		Passive/active reposition at 90, 60, and 30 degrees CKC: squat/lunge repositioning on screen		

CKC, Closed kinetic chain; *ROM*, range of motion.

POSTOPERATIVE REHABILITATION PROGRAM

The rehabilitation program after ACL reconstruction has undergone an evolution since the middle of the 1990s. Previously, crutches were recommended for 8 to 12 weeks with the knee immobilized for 6 to 8 weeks.[11,12,58,63] The avoidance of early isolated quadriceps activity was recommended to protect the reconstructed knee.[11,12,30,37,38,73,74] However, many complications were reported in the literature such as arthrofibrosis, quadriceps weakness, and extensor mechanism dysfunction as a result of a conservative program.[28,35,37,58,60] Shelbourne and Nitz[61] first reported improved clinical outcomes in patients who followed an accelerated program compared with patients who followed a conservative approach. Current programs emphasize immediate motion, full passive knee extension, immediate weight bearing, immediate muscular training, closed-chain exercises, and functional exercises to improve the patient's overall outcome. This rehabilitation program following ACL reconstruction using a bone-patellar tendon-bone autograft is outlined in Table 12-1.

Phase I: Acute Phase

Immediately following surgery, basic proprioceptive training is initiated based on adequate normalization of pain, swelling, and quadriceps recruitment. Passive ROM can be performed in the early acute phases of rehabilitation and is beneficial to stimulate joint mechanoreceptors. This exercise can be progressed to passive/active reproduction sense techniques to further improve proprioceptive sense (Fig. 12-6).

Weight-bearing exercises can be safely initiated in the early stages of rehabilitation. Weight shifts are performed in the medial-lateral and diagonal directions, as well as minisquats (0-40 degrees of knee flexion). These exercises can be performed on a force platform, which



FIG 12-6 Passive/active joint reproduction. The patient's lower extremity is placed at a prescribed range of motion by the clinician. The clinician then returns the lower extremity to the resting position and asks the patient to actively reposition the lower extremity in the clinician-placed position originally set.

measures the amount of weight distribution between the involved and noninvolved extremities. An elastic bandage worn postoperatively has been shown to improve joint position sense and proprioception and can be worn to provide sensory input.[9,10,39]

In addition, one of the primary goals during the first 5 to 7 days postoperative is to establish weight-bearing dynamic stability. This is accomplished using an exercise in which the patient stands with the knee at 30 to 45 degrees of flexion and attempts to maintain stability. The progression of this drill is first, static stability, then static stability with ball catches, and then stability with arm movements.

The patient may be progressed with minisquats onto an unstable surface such as a tilt board or foam. The patient squats to approximately 30 degrees and holds the position for 2 to 3 seconds while stabilizing the tilt board. Wilk and colleagues[67] reported that, during the squat exercise, the greatest amount of quadriceps and hamstring cocontraction occurred at approximately 30 degrees of knee flexion. Baratta and coworkers[3] reported an increased risk of ligamentous injury in knees with quadriceps-to-hamstring strength imbalances. Markolf and associates[46] demonstrated that contraction of the surrounding musculature can decrease the varus and valgus laxity in the knee joint threefold.

Gait activities such as stepping over cones are initiated during the second week after surgery. These drills can be performed either laterally (Fig. 12-7) or forward and backward (Fig. 12-8) to facilitate gait training, enhance dynamic stability, and to train the hip to control and dissipate forces at the knee. The patient is instructed to raise the thigh to the level of the hip and step over a series of cones to facilitate a heel/toe gait. These cone drills may be performed at various speeds to improve lower extremity stabilization and control momentum.



FIG 12-7 Lateral cone walking to facilitate hip stabilization. In addition, the patient can perform the exercise three times each way: (1) at normal speed, (2) at a faster speed, and (3) at a slower speed to emphasize knee and hip flexion.

Lateral lunges are initiated without resistance on a stable surface. The patient is instructed to land with a slight flexed knee (30 degrees) to improve dynamic stability through cocontraction of the hamstrings and quadriceps (Fig. 12-9). Gait activities can be performed with an elastic band around the patient's thighs to improve hip muscular strength (Fig. 12-10).



FIG 12-8 Forward and backward cone walking. The patient is instructed to facilitate a heel/toe gait with the exercise. The patient can also perform the three variations as performed with lateral cone walking.



FIG 12-9 Lateral lunge performed in a straight plane with the resistance of a SportCord as the patient lands unilaterally and pauses in single-leg stance to promote balance and stability.



FIG 12-10 Ambulation performed with a TheraBand (The Hygenic Corporation) around the hips to create a greater contraction of the hip musculature and emphasize stability of the hip muscles.



FIG 12-11 SportCord lateral lunges performed in the diagonal plane landing onto a foam pad.

Phase II: Dynamic Stability Drills

Phase II allows a progression in the degree of difficulty and complexity of the previous activities and a transition to more combined movement patterns. Ensure that the patient has mastered specific techniques and movements of the previous phase.

Lateral lunges are progressed in a functional manner, beginning with straight-plane lateral lunges, progressing to multiple-plane/diagonal lunges, lateral lunges with rotation, and finally, lateral lunges onto a foam surface (Fig. 12-11). As the patient progresses through the exercises, a ball toss can be added to further challenge the preparatory stabilization of the lower extremity with lessened conscious awareness.

Front step-downs and lateral step-ups are included into the treatment program. These exercises can be progressed to include ankle strategies by having the patient stand on half-circle foam and/or while catching a ball (Fig. 12-12). Chmielewski and associates[20] compared several weight-bearing activities in ACL-deficient and ACL-reconstructed knees and reported a strong correlation between functional outcome scores and patient satisfaction and the ability to perform the front step-down exercise. Squats on an unstable surface such as a BOSU ball (Fig. 12-13) can be performed during this phase to provide neuromuscular cocontraction of the quadriceps and hamstrings. Local muscular endurance exercises can be gradually implemented. Local muscular endurance is important because proprioception has been shown to significantly decrease as much as 75% once a joint is fatigued.[40,55,72] Wojtys and coworkers[72] reported that, after fatigue, a significantly slower response time occurred in the quadriceps, hamstrings, and gastrocnemius.

Single-leg balance exercises are progressed by incorporating movement of the upper extremity and uninvolved lower extremity aimed at altering the patient's center of gravity. The patient stands on a stable surface, progressing to foam, (Fig. 12-14) with the knee slightly flexed and performs flexion, extension, abduction, adduction, and diagonal movements of the upper extremity while holding a weighted ball (Fig. 12-15). Alternately, the patient can perform movements of the uninvolved lower extremity while performing single-leg stance. These drills can be progressed to incorporate combined upper and lower extremity movements during single-limb stance (Fig. 12-16), and are intended



FIG 12-12 Front step-down exercise performed while standing on half-circle foam and catching a ball.



FIG 12-13 Squatting exercise performed on a BOSU ball.

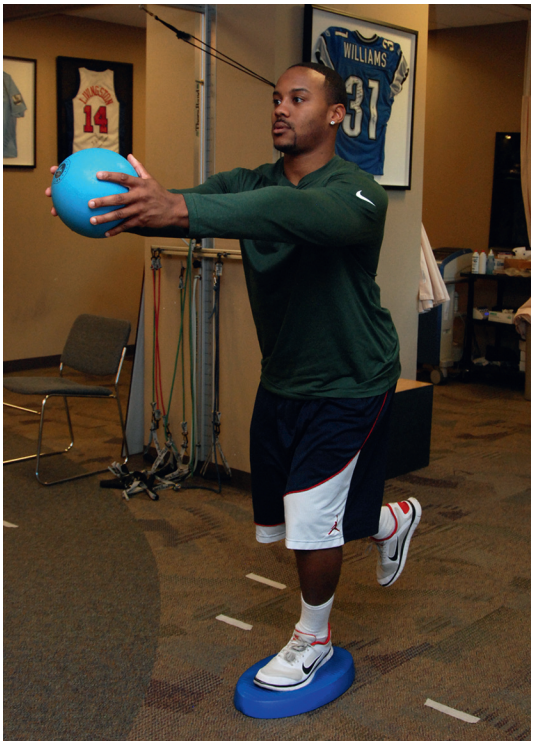


FIG 12-14 Single-limb stance on a foam pad while performing upper extremity movements with a weighted ball.

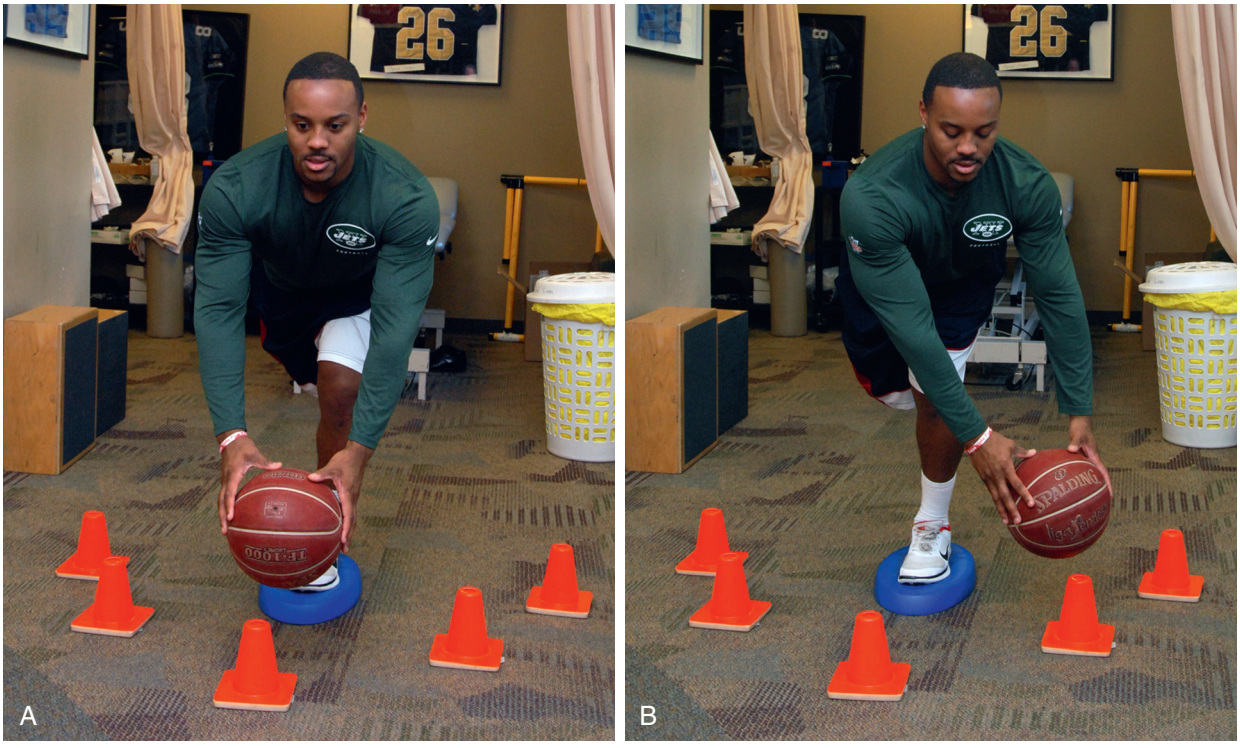


FIG 12-15 Single-limb stance on a foam pad with the knee flexed while performing diagonal movements of the upper extremity with a weighted ball.



FIG 12-16 PlyoBack (Exertools) ball toss while standing on a tilt board.



FIG 12-18 Single-limb stance on a foam pad while performing upper and lower extremity movements with a weighted ball as the clinician creates perturbations to the upper extremity.



FIG 12-17 Minisquats performed on a tilt board as the clinician taps the board to create a perturbation.



FIG 12-19 Perturbation training as the patient performs single-limb stance on a tilt board with ball toss.

to create alterations in the patient's center of gravity to increase the demands of the dynamic stabilizers.

Phase III: Neuromuscular Control Drills

The third phase of the program combines knee stabilizations with sports-specific drills by performing random designed movements in combined functional movement planes. Perturbation training is initiated on a tilt board and is progressed from a bilateral squat (Fig. 12-17) to single-leg holds at 30 degrees knee flexion, to single-leg squats, to single-leg stance at 30 degrees knee flexion with a ball toss using a 1- to 2-kg medicine ball (Fig. 12-18). The patient is instructed to stabilize the tilt board in a reaction to the sudden momentum forces produced by catching the weighted ball. Additionally, the clinician may provide manual perturbations by tapping the tilt board with his or her foot to impart a sudden postural disturbance, thus requiring the patient to stabilize the tilt board by using dynamic muscular contractions (Fig. 12-19). Furthermore, perturbations may be simultaneously performed as the clinician taps the patient at their hips or trunk to facilitate both proximal and distal perturbation forces. Neuromuscular training can be performed as the patient



FIG 12-20 Lunges performed on a tremor board.

performs lunges onto stability devices such as the tremor device (Fig. 12-20). Plyometrics is instituted during this phase and begins by having the patient perform plyometrics on the leg press with bilateral lower extremities. The patient is instructed to perform corner drills with plyometric leg press exercise to incorporate coordination and proprioception training (Fig. 12-21). Jump training has been shown[31] to reduce ACL injury rates in athletes and should be incorporated into the rehabilitation program after ACL injury or surgery. A word of caution is stressed in that, after ACL injury, the clinician should delay plyometric jump training until bone bruises resolve and the knee returns to the normal state. This is done to ensure the prevention of further deterioration of existing articular cartilage lesions or the early development of knee joint OA.

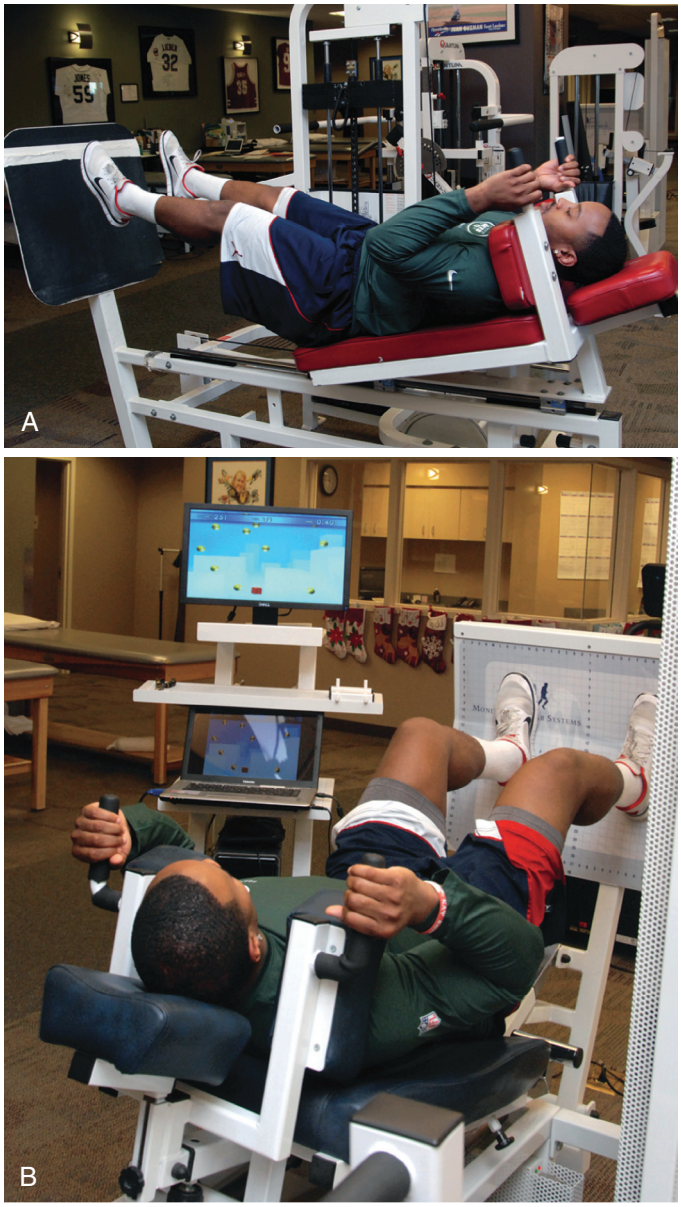


FIG 12-21 Plyometrics performed using bilateral lower extremities on the leg press.

Phase IV: Functional Activities and Skill Training

The final stage in the rehabilitation program is the functional skill and return to activity phase. During this phase, all four types of neuromuscular-training drills are incorporated: perturbations, plyometrics, technique, and progression of sports-specific drills. Plyometric activities are progressed from the leg press to flat ground (Fig. 12-22), to jumping over a hurdle, and then to box jumps. Box jumps begin using one box, then progress to two boxes, and finally, to four boxes.

A running program is initiated with backward running to facilitate knee flexion and muscle coactivation. Backward running also produces higher EMG activity of the quadriceps and hamstrings than that of running forward.[26] The patient progresses to lateral movements, including side shuffles and cariocas, before beginning forward running. The patient advances to running and deceleration drills, and finally to running and cutting once forward running is performed with a normal pattern.

Following the successful completion of the running program, the patient may begin a sports-specific training program. The patient should be carefully monitored throughout these activities, with the clinician ensuring protection of motor skill development and promote proper technique. Additionally single-leg hop functional tests may be implemented to determine limb symmetry.[4,51]

CONCLUSION

Significant deficits of the static and dynamic stabilizers exist at the knee after ACL injury because of changes in the muscular activation pattern of the muscles around the knee joint. The rehabilitation program after ACL surgery must restore normal knee motion, joint stability, and muscular strength while protecting the regeneration of the ACL graft. In addition, the therapy program must incorporate neuromuscular training to facilitate a full functional return to activities without compromise. The neuromuscular system is a vital



FIG 12-22 Scissor plyometric jumps performed on level ground.

component to the rehabilitation program of a patient with an ACL injury to the knee.

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Video Content

Video 7-5
Video 12-1

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13

Risk Factors for Anterior Cruciate Ligament Injuries in the Female Athlete

Sue D. Barber-Westin, Frank R. Noyes

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INTRODUCTION

It is well recognized that female athletes and military recruits have a higher incidence of noncontact anterior cruciate ligament (ACL) injuries than males participating in the same activity. A study done at our institution and published in 1994[144] was the first to recognize this gender disparity in female soccer players, who had nearly six times the rate of serious knee ligament injuries of male players ($P < .01$) during indoor games. In 2007, Prodromos and colleagues[212] conducted a meta-analysis of 33 articles and reported that the average ACL injury rate for females was significantly greater than that for males in basketball, soccer, and handball ($P < .0001$ for all comparisons). Several studies that compiled data from the National Collegiate Athletic Association (NCAA) were in agreement with these findings.[3,10,110] For instance, Hootman and colleagues[110] analyzed 16 years of NCAA data and reported that female basketball and soccer players had a threefold higher ACL injury incidence compared with male players. Recently, Beynnon and associates[25] compiled first-time noncontact ACL injury data from 8 colleges and 18 high schools and found that female collegiate athletes had the highest risk among the groups studied. The incidence rates were generally higher for females than for males (relative risk, 2.10) and for collegiate athletes compared with high school athletes (relative risk, 2.38).

In regard to ACL injuries that occur in the U.S. military, Gwinn and associates[89] reported that female midshipmen at the U.S. Naval Academy from 1991 to 1997 had a fourfold increase compared with their male counterparts in intercollegiate-level soccer, basketball, and rugby collectively ($P = .006$). In addition, women had nearly 11 times the incidence of ACL ruptures as men during obstacle course running ($P = .004$). Mountcastle and coworkers[171] reported female/male incidence ratios for noncontact ACL injuries of 4.95 for gymnastics, 3.72 for the obstacle course test, 3.01 for basketball, 1.71 for handball, and 1.27 for soccer at the U.S. Military Academy at West Point over a 10-year period.

A few investigators have noted that, although ACL ruptures represent a serious injury that results in months of lost playing time, the overall incidence in female athletes compared with other injuries, such as ankle sprains, is low.[3,110] Hootman and associates[110] concluded, "using the standard of <.05 as rare, the actual probability of ACL injury would be considered a rare event." We recently systematically reviewed eight studies of the effect of ACL injury prevention programs[179] found noteworthy differences in the ACL injury rates in female adolescent athletes, ranging from .03 to .08 per 1000 athlete-exposures to 0.21 to 0.49 per 1000 athlete-exposures. Three neuromuscular retraining intervention programs significantly reduced the noncontact ACL injury incidence rates: the Sportsmetrics, Prevent Injury and Enhance Performance, and Knee Injury Prevention programs. The number of athletes who needed to train to prevent one ACL injury in these three programs ranged from 70 to 98, and the

relative risk reduction ranged from 75% to 100%. Although the number of athletes needed to treat appeared somewhat high, in our experience many individuals participate in sports year-round with very little time off. They achieve within a few years a high number of exposures (in both practice and games) that place them at risk for ACL injury. This is especially true for athletes who begin competition at a very young age. For these athletes, by the time they are in high school, they will already have been exposed to well over 1000 hours of participation. These high rates of cumulative exposures validate ACL neuromuscular intervention programs.

Despite the many investigations that have been conducted on potential risk factors for noncontact ACL ruptures, definitive conclusions cannot be reached for either males or females regarding which factors may predispose an athlete to this serious injury. Investigators have attempted to develop risk-screening models using knee valgus motion, range of motion, body mass, tibial length, and quadriceps/hamstring ratio[100]; however, others have refuted their findings.[83] In one investigation, researchers found that the Landing Error Scoring System failed to predict ACL injuries in a cohort of 5047 high school and collegiate athletes.[248] This system rates body mechanics and technique of a vertical drop-jump on a 17-point scale, with a higher score indicating poor landing technique, and it has been shown in other studies to correlate with several measures of ACL loading and injury risk.[186,191]

The reasons for the increased incidence of this injury in female athletes over that in male athletes cannot be scientifically defined at present.[240] In many studies published to date, investigators examined a small sample size of each gender (and therefore the studies had insufficient power to avoid a type II statistical error[86]), focused on one or just a few of the possible risk factors, or examined neuromuscular characteristics in a controlled laboratory environment instead of more realistic playing conditions. Controlled laboratory experiments have variations that may influence results, such as performing a task with or without shoes or with arm movements controlled or uncontrolled. The major potential risk factors that have been proposed for this injury are shown in Table 13-1. This chapter reviews investigations related to these risk factors and emphasizes findings that may have a role in the gender disparity in noncontact ACL injury rates. We note that Elliot and associates[71] proposed other potential risk factors that should be explored in future studies. These include lifestyle habits and psychosocial influences on female athletes, such as fatigue from chronic sleep deprivation, poor nutrition and eating disorders, substance use and abuse, overtraining, stress, and depression.

TABLE 13-1 Hypothesized Risk Factors for ACL Injury in Female Athletes

Category	Risk Factor	Comment
Genetics	Family history, genotypic variants in collagen genes	Gender effect not determined to date; association may exist regardless of gender
Extrinsic	Footwear, climate conditions, playing surface, prophylactic knee braces	Gender effect not determined to date; majority of studies conducted in males
Anatomic	Intercondylar notch geometry, ACL size, tibial plateau geometry, foot pronation, pelvic tilt, quadriceps femoris angle, body mass index, generalized joint laxity, anterior knee laxity	No proven gender effect or results too diverse for conclusions
Hormonal	Phase of menstrual cycle, effect of hormonal cycling on ligament biomechanical properties, muscle strength, neuromuscular indices	No strong association proven, owing to difficulty in accurately identifying phase when ACL injuries occurred
Neuromuscular/ biomechanical	Muscle strength, knee joint stiffness Movement patterns during landing, cutting, agility tasks resulting in altered knee and hip joint angles and moments, muscle activation	Many gender differences exist (see Table 13-2)

ACL, Anterior cruciate ligament.

GENETICS

Regardless of gender, a question has been raised for many years about a potential genetic predisposition for ACL rupture. At the time of this writing, five studies had examined family history of ACL injuries. Webster and associates[275] noted a significant association among both ACL semitendinosus-gracilis graft rupture and contralateral ACL tears and a family history (first-degree relative) of ACL injury. In their cohort of 561 knees that had undergone ACL reconstruction, 26 procedures failed. Of these patients, 8% had a family history and 4% did not (odds ratio, 2.4; 95% confidence interval [CI], 1.1-5.3; $P = .04$). Forty-one patients tore their contralateral ACL; of these, 13% had a family history and 7% did not (odds ratio, 2.2; CI, 1.2-4.4; $P = .02$).

Bourke and associates[30] assessed the survival rate of 755 ACL reconstructions followed for a minimum of 15 years postoperatively. A positive family history of ACL rupture doubled the odds of tearing either the ACL graft or the contralateral ACL ($P = .003$). This occurred regardless of gender or graft type (patellar tendon or hamstring tendon autograft).

CRITICAL POINTS Genetics

- Possible evidence exists for familial predisposition for ACL injury.
- Potential exists for genotypic variants in collagen genes as an inherent risk factor for ACL injury.
- Variants may alter mechanical properties of ligaments and may be associated with increased genu recurvatum, anterior knee laxity, and general joint laxity.
- Important need for continued study in this area.

Flynn and associates[76] conducted a questionnaire-based study of 171 patients who sustained either contact or noncontact ACL ruptures to determine whether a familial predisposition existed for their injuries. The patients were matched with 171 uninjured control subjects according to age, gender, and primary sport. Patients who had sustained ACL ruptures were twice as likely as the control subjects to have a first-, second-, or third-degree relative who also had an ACL tear. Posthumus and associates[210] noted a significant difference in the self-reported family history of ligament injuries among 38 females who sustained ACL injuries and 84 controls (incidence rates of 50% and 21.5%, respectively; $P = .01$). In their investigation, there was no

significant difference in this factor between males with ACL injuries and controls. Harner and coworkers,[92] in a small series of 31 patients with noncontact bilateral ACL ruptures, found the patients had a significant increase in the incidence rate of immediate family members who had sustained an ACL injury compared with a control group (35% and 4%, respectively; $P < .01$).

More recently, investigators have examined the potential of genotypic variants in collagen genes as an inherent risk factor for knee ligament injuries.[18,54,75,128,153,182,209,210,213,214] The genes *COL1A1*, *COL5A1*, and *COL12A1* encode for the major α-chains that make up collagen types I, V, and XII, respectively.[208] Studies have identified sequence variants within these genes that are believed to be associated with ACL injuries in Caucasian South African patients,[209,210] Swedish patients,[128] and Polish/Eastern European patients.[75] The variants have been hypothesized to alter the structure and behavior (mechanical properties) of ligaments and other musculoskeletal soft tissues.[18,53,135] In addition, they may be associated with increased genu recurvatum, anterior knee laxity, and general joint laxity.[18] Posthumus and associates[208] recommended that further work be conducted in this area before genetic testing for ACL injury risk is initiated.

EXTRINSIC: FOOTWEAR, PLAYING SURFACE, CLIMATE CONDITIONS

Extrinsic risk factors for ACL injuries include footwear, playing surface, and climate conditions. The effect of footwear is assessed by calculating shoe-surface interaction, which is defined by the force of the friction between the athlete's shoe and the surface it comes into contact with during movement (quantified by the coefficient of friction [COF]).[66] Changing the COF of the shoe-surface interaction causes athletes to change their movement techniques, essentially their biomechanics, to accommodate for the change in COF. The type of shoe, playing surface, and climate conditions all affect the COF of the shoe-surface interaction. To date, all major studies on shoe characteristics and weather conditions and their association with ACL injuries have been conducted only in male athletes.

There are many different types of playing surfaces, including natural grasses, artificial turfs (first, second, third, and fourth generation), wood floors, and artificial rubberized floors. In general, artificial turfs have higher COF than natural grasses, and artificial rubberized floors have a higher COF than wooden floors.[66] Investigators have reported no differences in ACL injury rates in female soccer players who played on third- and fourth-generation artificial turfs compared with those who played on natural grass.[79,80,251,256] However, researchers in two studies[185,200] reported significantly higher ACL injury rates in female athletes who played floorball or handball on artificial rubberized floors compared with those who played on wooden floors. Dowling and Andriacchi hypothesized that it is "highly likely that the COF of the rubberized floor is high and may be the cause of the observed increase in ACL injury among female athletes on this surface."[66]

One other extrinsic risk factor is the use of a prophylactic knee brace to prevent ACL injuries. However, only a few investigations have been published on this topic, all of which involved male football players,[5,202,246] and no conclusions are possible regarding a potential benefit of the use of these braces for reducing the ACL injury rate in female athletes. It is important to note that no investigation to date has taken into account other risk factors (such as hormonal or neuromuscular factors) along with extrinsic factors that could confound possible conclusions.

CRITICAL POINTS Extrinsic: Footwear, Playing Surface, Climate Conditions

- To date, all studies on shoe characteristics and weather conditions and their association with ACL injuries have been conducted only in male athletes.
- Playing surface: higher ACL injury rates on artificial rubberized floors than wooden floors in female athletes.
- No study available on potential effect prophylactic knee brace in female athletes.
- No investigation has taken into account other risk factors (such as hormonal or neuromuscular) along with extrinsic factors that could confound possible conclusions.

ANATOMIC

Many authors have proposed that inherent anatomic differences between women and men are responsible or partially responsible for the disparity in noncontact ACL injury rates. Proposed anatomic risk factors include quadriceps femoris angle (Q-angle), foot pronation, intercondylar notch size, ACL size, tibial slope and surface geometry, anterior and generalized joint laxity, and body mass index (BMI).[40,41,45,64,164] However, no investigation has demonstrated that any anatomic factor alone is responsible for the increased risk of noncontact ACL injuries in female athletes. The major problem is that no study to date has entered anatomic indices along with hormonal and neuromuscular factors into an appropriate statistical model to determine the effects of all of these potentially important risk factors on ACL injury rates.

Geometry of the Intercondylar Notch and Anterior Cruciate Ligament

A correlation exists between the width and volume of the intercondylar notch and the cross-sectional area and volume of the ACL.[45,57,64,254] An association between a narrow intercondylar notch or a stenotic notch and an increased incidence of ACL ruptures has been reported or suggested by many authors.[72,111,138,149,233,245,252,253,257,269,289] In a meta-analysis of this topic published in 2013, Zeng and associates[289] found statistically significant differences in the intercondylar notch width index (pooled data from 16 studies, 0.02; CI, –0.04 to –0.01; $P < .001$) and

CRITICAL POINTS Anatomic

- No investigation has demonstrated that any anatomic factor alone is responsible for the increased risk of noncontact ACL injuries in female athletes.
- Association exists between a narrow intercondylar or stenotic notch and an increased incidence of ACL rupture, regardless of gender.
- Female ACL has smaller cross-sectional area, mass, volume, and material properties.
- Association may exist between ACL noncontact injuries and increased posterior slope of the lateral proximal aspect of the tibia, regardless of gender.
- Excessive foot pronation, anterior pelvic tilt may be risk factors for ACL injuries, regardless of gender.
- Women have greater inherent joint laxity, but no evidence exists that this factor increases their risk of ACL injury.
- No evidence that body mass index or quadriceps femoris angle are risk factors for ACL tears.

notch width (–2.15; CI, –3.09 to –1.21; $P < .001$) among subjects with ACL injuries and control groups. These results were found regardless of measurement methods. A few investigations[99,147,226,259] have refuted these findings. This is most likely because of variations among studies with regard to techniques used to determine notch size (plain non-weight-bearing and weight-bearing radiographs, magnetic resonance imaging [MRI], computed tomography [CT], and photographic techniques), notch indices studied (lateral condylar width, total condylar width, notch width, notch width at two-thirds notch height, notch width index, and notch angle), and the statistical methods used to determine results. When measured on radiographs, the notch width index does not necessarily correlate with the notch volume (overall notch size), a finding that has led some authors[8,269] to caution against using radiographs to predict risk of ACL rupture. Newer MRI techniques are preferred over plain radiographs for measuring interchondral notch and ACL size and geometric indices.[49,64,72,245]

The association between notch area or shape and ACL injury appears to be unrelated to gender.[7,49,65,72,120,138,233,245,253,267,289] A general speculation has been raised[9,45,64,87,172] that a small notch will contain a small ACL that is vulnerable to rupture owing to decreased strength properties. In addition, a narrow or stenotic notch may increase the risk of ACL impingement and subsequent rupture.[7,64,81,172] Hoteya and coworkers[111] measured the notch width index near the femoral ACL attachment on coronal MRI scans in 25 patients with bilateral ACL injuries, 30 patients with unilateral ACL injuries, and 20 healthy subjects. The notch was significantly narrower in the subjects with bilateral ACL injuries compared with those with unilateral injuries and controls. The authors concluded that the risk for ACL injuries is "very high" when the notch width is less than 0.25 (odds ratio, 22.667 for risk of bilateral ACL tears). A gender comparison was not conducted. Other authors have proposed different values for notch width that may be associated with increased risk of ACL injury regardless of gender, including 0.18,[267] 0.19,[138] and 0.24.[65]

Many investigators have reported that a gender difference exists in the cross-sectional area, mass, and volume of the ACL in uninjured subjects on the basis of MRI[9,45,57,64,254,282] evidence and cadaveric specimens.[40,41,145,172] Dienst and colleagues[64] reported significant differences between women and men in mean ACL cross-sectional area (45.4 ± 10 mm^2 and 68.4 ± 20 mm^2, respectively; $P = .003$), mean notch area (537 mm^2 and 634 mm^2, respectively; $P = .008$), and mean ACL notch area index (0.33 and 0.45, respectively; $P = .02$) measured using MRI. A significant correlation was found between ACL cross-sectional area and notch areas in three planes. Staeubli and associates[254] reported a significant difference between men and women in the absolute width of the ACL at the cruciate intersection on MRI (6.1 ± 1.1 mm and 5.2 ± 1.0 mm, respectively; $P < .01$). The intercondylar notch widths were also significantly greater in males, as were height, weight, and bicondylar femoral width.

Chandrashekar and colleagues[40,41] studied the length, area, mass, volume, and material properties of the ACL in 20 cadaveric knees (10 male, 10 female, aged 17-50 years). The male specimens had significantly greater values than the females for ACL length (29.82 ± 2.51 mm and 26.85 ± 2.82 mm, respectively; $P = .01$), mid substance area (83.54 ± 24.89 mm^2 and 58.29 ± 15.32 mm^2, respectively; $P = .007$), mass (2.04 ± 0.26 g and 1.58 ± 0.42 g, respectively; $P = .009$), and volume (2967 ± 886 mm^3 and 1954 ± 516 mm^3, respectively; $P = .003$). The female specimens had significantly lower mechanical properties than the male specimens, including 30% load to failure, 22.49% modulus of elasticity, 14.3% stress at failure, 9.43% strain energy density at failure, and 8.3% strain at failure. The authors concluded that the smaller ligament size and mechanical properties in women may contribute to their increased rate of noncontact ACL rupture. It is important to recognize that the mechanical properties reported, including load at failure (1818 ± 699 for male and 1266 ± 527 for female; $P < .05$), may underestimate the expected higher values in young athletes. Lipps and coworkers[145] in a recent cadaveric study, simulated strain of the distal third of the anteromedial region of the ACL incurred during a pivot landing in height- and weight-matched specimens. These investigators concluded that this region of the female ACL will develop greater strain than the male ACL upon landing, owing to its smaller cross-sectional area and lateral tibial slope.

Tibial Plateau Geometry

A potential association between the surface geometry of the tibial plateau (e.g., convexity in its lateral aspect) and clinical instability in ACL-deficient knees was speculated years ago by a few investigators.[60,132,155] Studies conducted more recently have measured a multitude of anatomic indices, including the relative length, width, concavity, and depth of the tibial surface, using radiography, CT, and MRI. Several investigations have indicated that an association may exist between ACL noncontact injuries and increased posterior slope of the lateral proximal aspect of the tibia,[23,26,32,94,95,127,154,160,245,258,264] although a few have refuted these findings.[114,165] In healthy subjects, gender differences have been found in the slopes of both the medial and lateral proximal aspects of the tibia.[94,114] However, many studies have failed to identify gender differences in the posterior tibial slope in ACL-injured knees.[32,95,127,258,264,268] One recent study in which researchers examined the radial geometry of the articular surfaces of the lateral compartment of the knee[272] indicated that ACL-injured male patients and all female subjects (ACL-injured and control) had a common lateral tibiofemoral geometry of a relatively short and steeply convex tibial articular surface and increased convexity of the femoral surface. In another investigation, Beynnon and coworkers[23] found a 21.7% increased risk of noncontact ACL injury with each degree of increase of the lateral tibial plateau slope in women, but not in men. Other investigators[105,260,268] also found that the increased posterior tibial slope was a risk factor only in women.

Recent work in this area involves the in vivo assessment of the effect of variations in knee joint anatomy on knee joint forces and moments during dynamic activities such as landing from a jump. McLean and associates[159] examined six anatomic indices in 20 female athletes during single-leg land-and-cut tasks. Of interest among several findings was that increases in lateral tibial slope were associated with increased peak anterior knee joint reaction force on landing. The observed force magnitudes ranged between 100 N and 130 N, well below loads required for ACL rupture. Even so, the authors speculated that increases in tibial slope may impact other joint mechanics that contribute to ACL injury. Shultz and Schmitz[239] conducted a similar study of 23 female subjects who performed double-legged drop-jumps. An association was noted between increased lateral tibial slope and increased hip internal rotation upon landing, as well as decreased mediolateral tibial slope and increased knee internal rotation on landing. Tibial plateau geometry was not a predictor of hip adduction, hip external rotation, knee varus, or knee internal rotation joint moments. To date, no investigators have examined the influence of knee joint anatomic indices on dynamic activities in male athletes, and therefore a gender comparison is not currently available.

Foot Pronation, Pelvic Tilt

Excessive foot pronation (hyperpronation)[6,16,98,148,283] and anterior pelvic tilt[98,148,266] have been suggested as potential risk factors for ACL injuries. However, even if these factors do increase risk, gender does not appear to play a role. Authors have speculated that hyperpronation

leads to increased internal tibial rotation,[16,55,263] and an anterior pelvic tilt may be associated with increased hip internal rotation, both of which could place the ACL at risk for injury.[98]

Foot pronation is measured by the navicular drop test.[34] In four investigations, researchers reported significantly higher navicular drop values in patients who sustained ACL ruptures than in matched control subjects: a mean of 6 mm in one study,[16] 2 to 2.5 mm in two studies,[6,283] and 1.6 mm in another.[98] Woodford-Rogers and associates[283] reported that navicular drop, calcaneal alignment, and anterior tibial translation (when combined) were predictors of classification of athletes into the ACL-injured and ACL non-injured groups, because 87.5% of the female athletes and 70.5% of the male athletes in their investigation were correctly classified. Hertel and coworkers[98] reported that increased navicular drop and anterior pelvic tilt were predictors of ACL injury history, regardless of gender. These investigators measured navicular drop, Q-angle, leg length, hip internal and external rotation, and pelvic tilt in 20 patients with a history of ACL injuries and 20 control subjects. Patients with a greater than 8-mm navicular drop were 20 times more likely to have torn their ACL than were subjects with less than 6.3 cm ($P = .01$).

In a study composed of only female athletes, a combination of postural "faults" was found to have a greater predictive value for ACL injury than a single problem (such as excessive pronation).[148] The combination of excessive knee hyperextension, navicular drop, and subtalar joint pronation significantly identified the patients compared with 20 control subjects ($P = .0001$).

It is important to note that other studies failed to find an association between foot hyperpronation and ACL injury risk. Jenkins and coworkers[122] did not find an association between subtalar joint neutral position and navicular drop and ACL injury in a group of 16 athletes with ACL injuries. Smith and colleagues[250] were also unable to find an association between excessive pronation and noncontact ACL injuries. These authors cautioned that static measurements of pronation may not be representative of dynamic conditions and that future research should include not only dynamic analyses, but other anatomic risk factors as well.

Joint Laxity

Some authors have reported that women appear to have greater inherent joint laxity and/or anterior tibial translation than men.[22,216,217,225,237,265,267] Huston and Wojtys[119] reported that females had significantly greater anterior tibial translation than males (6.5 and 5.8 mm, respectively; $P < .05$), as did Rozzi and associates[219] (6.05 ± 1.46 and 4.80 ± 1.53 mm, respectively; $P = .02$). Seckin and colleagues[230] reported a significantly greater prevalence of generalized joint hypermobility in female high school students compared with male students (16.2% and 7.2%, respectively; $P < .0001$). Remvig and coworkers[216] found considerable evidence in the literature of an increased prevalence of hypermobility among women. A few studies have examined gender differences in tibial rotation and varus-valgus angles, with mixed results.[113,197,238]

Even though women may have inherently greater joint laxity than men, there is no strong evidence that this factor plays a role in their increased risk of noncontact ACL injury.[267,270] Uhorchak and associates[267] reported that, regardless of gender, generalized joint laxity was a significant risk factor of ACL injury, because subjects who had at least five regions classified as lax according to the Beighton score were 2.8 times more likely to sustain an ACL rupture. Ramesh and colleagues[215] reported a prevalence of generalized joint laxity (>6 Beighton score) in 169 ACL-deficient knees (137 men and 32 women) compared with a control group of 65 subjects (42.6% and 21.5%, respectively; $P < .01$). Knee hyperextension was present in 78.7% of the ACL-deficient knees compared with 37% of the control knees ($P < .001$), but a gender comparison was not performed. Two studies in which researchers assessed only female athletes found an association between increased knee hyperextension and ACL injury.[148,173]

Body Mass Index, Q-Angle

There is no evidence to support that an excessive BMI alone is a risk factor for noncontact ACL injuries. Ostenberg and Roos[189] found that BMI was not a risk factor for knee injuries in female soccer players, as did Knapik and coworkers[130] in military training–related injuries in female recruits. When combined with a narrow femoral notch and generalized joint laxity, a BMI greater than 1 standard deviation above the mean did contribute to a high prediction of noncontact ACL injuries in Uhorchak and coworkers' series.[267] Although the Q-angle has been commonly cited as a potential independent risk factor for ACL injuries, there is no clinical evidence supporting this belief.[98,117,148]

HORMONAL

The presence of female sex hormones (namely, estrogen, progesterone, and relaxin) and their fluctuations during the menstrual cycle have been proposed by several investigators to affect muscle and neuromuscular indices, as well as the material and mechanical properties of the female ACL.* Some researchers have hypothesized that hormonal influences may increase the risk of ACL injury in female athletes.[1,24,146,279,285] However, several problems have been identified with the methods of published studies that preclude drawing definitive conclusions.[208,249,271] These include difficulty in accurately identifying the phase of the cycle at the time of injury and inconsistent classifications of the various phases of the cycle.[208,249]

Two basic methods have historically been used to identify the phase of the cycle at the time of ACL injury. These include the analysis of a single biologic sample on the day of or a few days after an ACL injury and/or the collection of retrospective self-reported menstrual history questionnaires. These methods do not accurately verify current cycle length for several reasons.[249,271] There is no validated outcome measure that uses a biological sample (serum, urine, or saliva) concentration alone or in combination with cycle history that accurately predicts cycle phase at the time of an ACL injury.[249] Substantial variability exists in menstrual cycle length and hormone profiles among and within women, as summarized by Vescovi.[271] Vescovi recommended against assuming a 28-day cycle exists in all women and that consistent cycle lengths exist within women. There are wide variations in the lengths of the follicular and luteal phases (9-23 days and 8-17 days, respectively), as well as the length of the total cycle (22-36 days). This is especially true in physically active women. Vescovi[271] also remarked that female athletes who appear to be eumenorrheic, with regularly occurring menses, may not necessarily have normal sex steroid hormone profiles. This fact negates the assumption that normal ovarian endocrine function is closely associated with regularly occurring menses.

Several studies have shown no influence of the phase of the menstrual cycle on passive knee anterior tibial translation.[17,38,97,104,204] These findings bring into question the role of sex hormone concentrations on knee joint laxity. Hormonal cycling that occurs throughout the menstrual cycle did not appear to affect loading on the knee (hip and/or knee moments or knee flexion angles) during high-risk tasks in one investigation[48]; however, another study[241] found that intersubject

*References 22, 59, 70, 102, 146, 198, 199, 204, 235, 237, 241, 285

Table 13-2 Hypothesized Neuromuscular and Biomechanical Risk Factors for Noncontact ACL Injury in the Female Athlete

Category	Risk Factor	Hypothesized Gender Difference
Muscle strength, activation, recruitment patterns	Lower extremity muscle strength and activity Hip muscle strength Lower extremity muscle recruitment patterns Fatigue Core stability	Compared with males, females have: • Weaker quadriceps and hamstring muscle peak torques • Slower times to reach lower extremity muscle peak torques • Higher quadriceps activity and reduced hamstring activity during athletic maneuvers • Weaker hip muscles • Poor core stability • Different muscle activation patterns during preplanned and unplanned athletic tasks • Faster time to fatigue • Different muscle recruitment patterns in response to a passive anterior tibial translation force
Knee stiffness		Compared with males, females have: • Decreased inherent passive and active knee joint stiffness
Movement patterns	Knee and hip flexion Tibial rotation Knee abduction Hip internal rotation, abduction Knee abduction and/or adduction moments	During high-risk activities, compared with males, females have: • Smaller knee and hip flexion angles • Less internal tibial rotation • Larger knee abduction angles • Smaller hip abduction angles • Greater hip adduction and knee abduction and/or adduction moments • Smaller hip extensor and flexor and knee flexor moments

ACL, Anterior cruciate ligament.

CRITICAL POINTS Hormonal

- Researchers have hypothesized that hormonal influences may increase the risk of ACL injury in female athletes.
- Problems identified with methods of published studies preclude definitive conclusions.
- Analysis of single biological sample after an ACL injury and/or the collection of retrospective self-reported menstrual history questionnaires are not accurate in predicting cycle phase.
- No influence exists of the phase of the menstrual cycle on passive knee anterior tibial translation.
- Use of oral contraceptives has not been found to protect against ACL injury.

CRITICAL POINTS Neuromuscular/Biomechanics

- Differences between female and male athletes in muscle strength and stiffness, movement patterns, and body positions that occur during various athletic activities have been demonstrated in the laboratory and during videotape analysis of game injuries.
- Women tend to perform athletic maneuvers (landing from a jump, cutting) with less knee and hip flexion, greater quadriceps activity, reduced hamstring activity, higher knee extensor moments, increased knee valgus angles, and increased hip adduction and knee abduction/adduction moments compared with men.
- Women have less lower extremity strength and knee stiffness than men.
- Fatigue appears to affect landing mechanics regardless of gender.

variability in multiplanar knee laxity (anterior, genu recurvatum, varus-valgus, and internal-external rotation) changes during the cycle did affect kinematic patterns on a drop-jump. The use of oral contraceptives has not been found to protect against ACL injury.[4,220] More research is required in this area to determine whether a link exists between menstrual cycle phase, hormone concentrations, and risk of ACL injury.

NEUROMUSCULAR/BIOMECHANICS

Muscular Protection of the Knee: Lower Extremity, Hip, Core

Several neuromuscular and biomechanical factors have been hypothesized by various investigators to play a major role in the disparity between genders in noncontact ACL injury rates (Table 13-2). Differences between female and male athletes in muscle strength and stiffness, as well as movement patterns and body positions that occur during various athletic activities, have been demonstrated under controlled preplanned and reactive conditions in the laboratory. Videotape analyses of noncontact ACL injuries demonstrate certain lower extremity positions and characteristics in female athletes that lend support to the theory that movement pattern differences during athletics may likely play a role in this problem.[29,131,184] Women tend to perform athletic maneuvers with less knee and hip flexion, greater quadriceps activity, reduced hamstring activity, higher knee extensor moments, and increased knee valgus angles and moments compared with men. Several studies have found that men have greater strength[9,12,31,101,108,119,142,170,203,232] and knee stiffness[84,85,278,280] than women. The sagittal plane shear stiffness of the knee represents the resistance exerted by soft tissues (passive and active) in response to an anterior tibial translation force.[175] It is technically defined as the ratio of change in force in a muscle to its change in length.[162] A higher degree of muscle stiffness prevents muscle lengthening in response to an anterior tibial translation, thereby theoretically decreasing the likelihood of ACL injury.[27] Blackburn and colleagues[27] reported that individuals with greater hamstring stiffness displayed smaller frontal plane knee moments, smaller anterior tibial shear forces, and greater knee flexion upon landing from a drop-jump compared with athletes with lower hamstring stiffness. In this investigation, hamstring stiffness was quantified using a damped oscillatory technique and normalized to body mass. The high-stiffness group (25.81 ± 4.61 N-m $\times$ kg^{-1}) was

composed of 5 men and 7 women, and the low-stiffness group (14.52 ± 1.51 N-m × kg^{-1}) contained 7 men and 5 women.

It is important to briefly review the role of the muscles in the lower extremity, hip, and core in protecting athletes from noncontact ACL injuries. The major lower extremity muscles are the quadriceps, hamstring, and gastrocnemius-soleus. Many investigators have described the association between high quadriceps forces and noncontact ACL injuries.[52,61,88,273] High quadriceps forces produce anterior shear force during the last 30 degrees of knee extension. Grood and associates[88] reported that, during the knee extension exercise, the quadriceps force required to extend the knee remained at a constant value of 177 N between 50 and 15 degrees, but then rose rapidly to reach 350 N at 0 degrees (Fig. 13-1). The addition of resistance doubled the quadriceps force required to extend the knee, resulting in large forces on the ACL and patellofemoral joint.

DeMorat and colleagues[61] reported that a high quadriceps load (4500 N) simulated in cadaveric knees at 20 degrees of flexion produced significant anterior tibial translation (mean, 19.5 mm). The authors concluded that the quadriceps can serve as a major intrinsic force in noncontact ACL injuries. Wall and associates[273] showed in cadaveric knees that, although an axial compressive force (such as that incurred when landing from a jump) to the knee can injure the ACL, the addition of a quadriceps force significantly lowers the axial compressive force threshold required to disrupt the ligament.

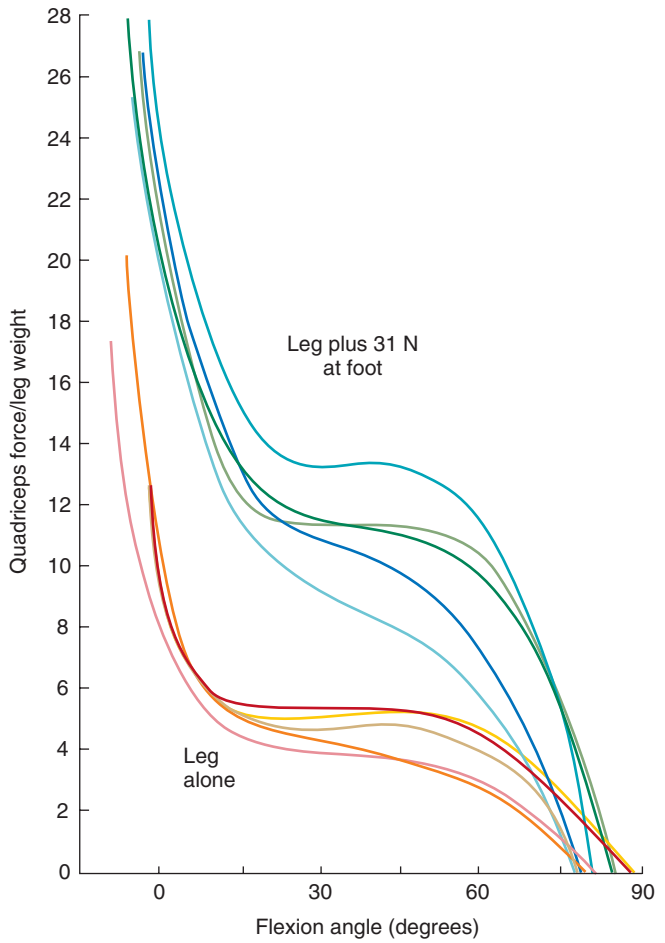


FIG 13-1 The ratio of quadriceps force to leg weight is shown for five specimens as a function of flexion angle. The *lower group of curves* demonstrates the force measured when extending the leg against its own weight. The *upper group of curves* shows the forces measured when 31 N was placed at the foot.

Colby and coworkers[52] measured hamstring and quadriceps muscle activation and knee flexion angles during sidestep cutting, cross-cutting, stopping, and landing in nine male and six female collegiate athletes. A high-level quadriceps muscle activation occurred just before foot-strike and peaked in mideccentric motion. Hamstring muscle activation was submaximal at and after foot-strike. Colby and coworkers concluded that the combination of the high level of quadriceps activity, low level of hamstring activity, and low angle of knee flexion during eccentric contractions in these maneuvers could produce significant anterior translation of the tibia.

The hamstring musculature is important in stabilizing the knee joint because it functions as a joint compressor and restrains anterior tibial translation.[151,169] The biomechanical function of the sartorius, gracilis, and semitendinosus muscles was assessed many years ago when investigators found these muscles had a marked functional dependence on the angle of knee flexion and degrees of external tibial rotation.[181] For instance, the flexion force of the hamstrings was greatest at 90 degrees of knee flexion (Fig. 13-2). As the knee was extended, the tendon insertion angle became more acute relative to the tibia, resulting in a decrease in the mechanical advantage of the muscle and a subsequent decrease in the flexion moment about the knee joint. At 0 degrees of extension, the flexion force was reduced to 49% of that measured at 90 degrees of flexion. The rotation force of the hamstrings was also reported to be greatest at 90 degrees of knee flexion (Fig. 13-3). The rotation force of the hamstrings (under the same muscle load) increased with increasing external tibial rotation at the four knee flexion positions shown in Figure 13-4. The rotation force produced at 15 degrees of external tibial rotation was approximately double that measured at 0 degrees of external tibial rotation. The conclusion reached was that the hamstrings actively oppose extension by stabilizing the knee posteriorly and preventing knee hyperextension and anterior subluxation of the tibia. In addition, these muscles actively oppose external tibial rotation.

The major antigravity hip muscles are the gluteus maximus (GMAX, hip extensor) and the gluteus medius (GMED, hip abductor). The GMAX has a large cross-sectional area and long muscle fibers that allow it to produce a large amount of force at high velocities. It also has the ability to act as a hip abductor and external rotator at small degrees of hip flexion. The GMED works to stabilize the pelvis and limit hip adduction during single-leg stance. Both of these muscles contribute significantly to total power generation and absorption during jumping and landing. Insufficient use of GMED (owing to either inherent muscle weakness or poor landing strategies) may predispose an athlete to land in greater hip adduction or internal rotation during athletic activities, which may in turn lead to increased knee abduction angles and moments that place the ACL at risk for injury.[106,121,140] However, data from studies that have examined the relationship between hip muscle strength and knee joint biomechanics are not in agreement.[109,168,201,242,261] Powers[211] suggested that factors other than hip strength, such as impaired motor control, may be associated with movement patterns that may increase the risk of ACL injury. Walsh and associates[274] reported that a high level of both quadriceps and GMAX activation, along with low levels of hamstring and gastrocnemius activation, led to smaller knee flexion angles upon landing from a drop-jump. Homan and coworkers[109] found that individuals with poor hip abductor and external rotator muscle strength activated their GMED and GMAX muscles at higher levels than subjects with high hip strength during a drop-jump task. There were no differences in frontal plane hip or knee kinematics between subjects with high and low hip strength. They hypothesized that weaker athletes use greater

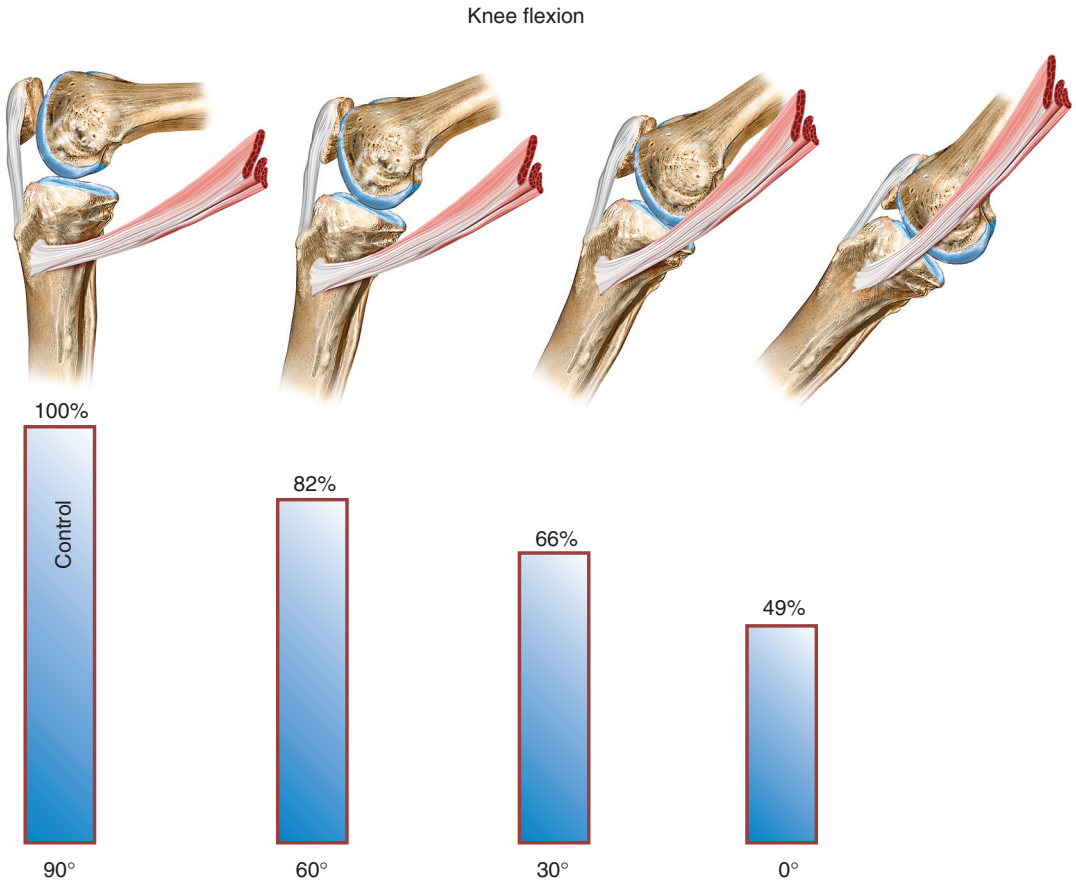


FIG 13-2 Pes anserine flexion forces. Knee extension yields a decrease in insertion course angles with respect to the tibia. The resulting loss in mechanical advantage is indicated by reduced flexion forces with extension ($P < .05$).

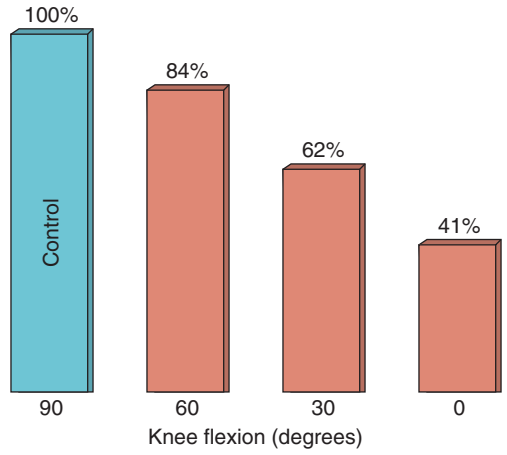


FIG 13-3 Pes anserine rotation forces. Reduction in mechanical advantage with knee extension is accompanied by corresponding decreases in rotation forces ($P < .05$).

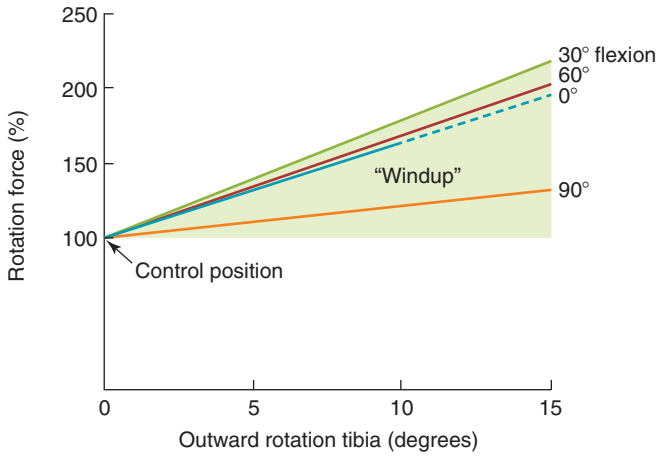


FIG 13-4 Rotation windup forces. The rotation forces under the same muscle loading increase significantly with external tibial rotation at each knee flexion position tested ($P < .05$).

neural drive to the gluteal muscles to achieve the same landing position as stronger individuals.

The "core" of the body includes all of the muscles of the trunk and pelvis required to stabilize the spine and pelvis during activities. *Core stability* may be defined as the "ability of the core, or the muscles of the abdomen and lower back, to maintain or resume a relative position (or trajectory) of the trunk after a perturbation."[47] The core provides a stable base for enhanced lower extremity control, leading to the belief that poor core strength or trunk position (e.g., excessive anterior pelvic tilt) may place the ACL at risk for injury.[133,134,286] However, further research is required to understand the relationship between core strength and stability and ACL injury.

TABLE 13-3 Significant Gender Differences in Isokinetic Quadriceps and Hamstring Strength

Study	Subjects	Testing Protocol	Male (Mean ± SD)	Female (Mean ± SD)	*P* Value
Holm et al[108] (2008)	31 female, 28 male athletes, age 12 yr	Hamstring PT 240 degrees/sec (N-m)	56 ± 11	52 ± 13	>.05
Claiborne et al[51] (2006)	15 female, 15 male healthy adults	Quadriceps PT ECC 60 degrees/sec (N-m)	196	160	<.05 for all comparisons
		Quadriceps PT CONC 60 degrees/sec (N-m)	176	116	
		Hamstring PT ECC 60 degrees/sec (N-m)	117	86	
		Hamstring PT CONC 60 degrees/sec (N-m)	122	81	
Bowerman et al[31] (2006)	27 female, 27 male collegiate athletes	Quadriceps PT 60 degrees/sec (N-m)	253 ± 65	167 ± 28	<.0001
		Hamstring PT 60 degrees/sec (N-m)	132 ± 40	87 ± 14	<.0001
Barber-Westin et al[12] (2006)	206 female, 16 male athletes, age 14 yr	Quadriceps PT 300 degrees/sec (N-m)	92 ± 24	71 ± 15	.001 for all comparisons
		Hamstring PT 300 degrees/sec (N-m)	65 ± 15	49 ± 13	
	175 female, 37 male athletes, age 15 yr	Quadriceps PT 300 degrees/sec (N-m)	116 ± 34	77 ± 15	
		Hamstring PT 300 degrees/sec (N-m)	81 ± 23	54 ± 12	
	209 female, 56 male athletes, age 16-17 yr	Quadriceps PT 300 degrees/sec (N-m)	128 ± 35	85 ± 19	
		Hamstring PT 300 degrees/sec (N-m)	90 ± 19	59 ± 13	
Noyes et al[180] (2005)	27 female, 27 male athletes, age 14-17 yr	Hamstring IR 180 degrees/sec (N-m/BW)	30 ± 9	25 ± 7	.05
		Hamstring IR 120 degrees/sec (ms)	234 ± 84	323 ± 168	.02
Salci et al[223] (2004)	8 female, 8 male collegiate athletes	Quadriceps PT 60 degrees/sec (% mass)	302 ± 91	195 ± 23	<.05
		Hamstring PT 60 degrees/sec (% mass)	128 ± 27	95 ± 21	<.05
Pincivero et al[203] (2003)	20 female, 19 male recreational athletes, age 20-28 yr	Quadriceps PT 180 degrees/sec (N-m)	172 ± 27	87 ± 13	<.001
		Hamstring PT 180 degrees/sec (N-m)	100 ± 14	53 ± 9	<.001
Wojtys et al[278] (2002)	13 female, 10 male sedentary subjects to elite athletes	Quadriceps PT 60 degrees/sec (ft-lb/lb BW)	89 ± 10	69 ± 14	.001
		Hamstring PT 60 degrees/sec (ft-lb/lb BW)	45 ± 7	37 ± 8	.02
Lephart et al[142] (2002)	15 female, 15 male collegiate athletes	Quadriceps PT 60 degrees/sec (N-m)	271 ± 59	222 ± 31	.01
		Hamstring PT 60 degrees/sec (N-m)	131 ± 22	11 ± 23	.04
Anderson et al[9] (2001)	50 female, 50 male high school athletes	Quadriceps PT 60 degrees/sec (% BW)	85	79	<.01
		Quadriceps PT 240 degrees/sec (% BW)	53	42	<.0001
		Hamstring PT 60 degrees/sec (% BW)	51	44	<.0001
		Hamstring PT 240 degrees/sec (% BW)	32	28	.02
Huston & Wojtys[119] (1996)	40 female, 60 male collegiate athletes; 20 female, 20 male nonathletes	Quadriceps PT 60 degrees/sec (% BW)	82	77	<.05 for all comparisons
		Hamstring PT 60 degrees/sec (% BW)	48	41	
		Quadriceps PT 60 degrees/sec (ms)	408	420	
		Quadriceps PT 240 degrees/sec (ms)	153	158	
		Hamstring PT 60 degrees/sec (ms)	328	430	
		Hamstring PT 240 degrees/sec (ms)	150	169	

BW, Body weight; *CONC,* concentric; *ECC,* eccentric; *PT,* peak torque; *SD,* standard deviation.

Gender Differences in Lower Extremity Muscle Strength and Stiffness

Marked differences among adolescent and adult male and female athletes in quadriceps and hamstring isokinetic peak torques (Table 13-3), hamstring/quadriceps ratios (Table 13-4), time to reach peak torque,[119,178] and internal-external tibial rotation[178] have been documented in numerous investigations. Huston and Wojtys[119] reported several years ago that collegiate female athletes had significantly weaker quadriceps and hamstring strength and endurance, as well as slower time-to-peak torque values for knee flexors, than male athletes. They also reported gender differences in muscle recruitment order in response to an anterior tibial translation force. The female athletes tended to recruit the quadriceps first, followed by the hamstrings and gastrocnemius. The male athletes tended to recruit the hamstrings first, followed by the quadriceps and gastrocnemius.

One of the largest studies conducted to date, on 853 females and 177 males aged 9 to 17 years, demonstrated that significant gender differences in lower extremity strength become evident at age 14 years (Fig. 13-5).[12] This investigation revealed that females appear to reach peak hamstring strength at age 11 years, with no significant difference found in this factor between girls 11 years of age and those up to 17 years (Fig. 13-6). No difference in isokinetic muscle strength values between boys and girls younger than 14 years has been reported by many laboratories.[62,63,107,231]

Several investigators have reported gender differences in knee stiffness (Table 13-5). Wojtys and colleagues[278] measured passive and active anterior shear stiffness of the knee joint with a testing apparatus that recorded anterior tibial translation and muscle activity with surface electromyography (EMG). Although there was no significant difference between genders in passive shear stiffness, men produced significantly higher active stiffness values during a maximum cocontraction.

TABLE 13-4 Significant Gender Differences in Isokinetic Hamstring/Quadriceps Ratio

Study	Subjects	Testing Protocol	Male (mean ± SD)	Female (mean ± SD)	*P* Value
Holm & Vollestad[108] (2008)	165 female, 144 male athletes	8 yr, 240 degrees/sec	65 ± 14	54 ± 12	<.01
		9 yr, 60 degrees/sec	61 ± 12	55 ± 11	<.05
		10 yr, 60 degrees/sec	61 ± 12	53 ± 09	<.01
		11 yr, 60 degrees/sec	68 ± 11	51 ± 09	<.05
		12 yr, 60 degrees/sec	58 ± 08	53 ± 10	<.05
		12 yr, 240 degrees/sec	64 ± 12	55 ± 13	<.05
Anderson et al[9] (2001)	50 female, 50 male high school athletes	60 degrees/sec (% BW)	62	57	<.01
Moul[170] (1998)	25 female, 23 male collegiate athletes	180 degrees/sec, right leg, eccentric: eccentric	89	46	.01
		180 degrees/sec, left leg, eccentric: eccentric	93	52	.01
Hewett et al[101] (1996)	11 female, 9 male high school athletes	Dominant leg 60 degrees/sec	62 ± 8	55 ± 9	<.05
		Nondominant leg 60 degrees/sec	67 ± 7	47 ± 8	<.05

BW, Body weight; *SD,* standard deviation.

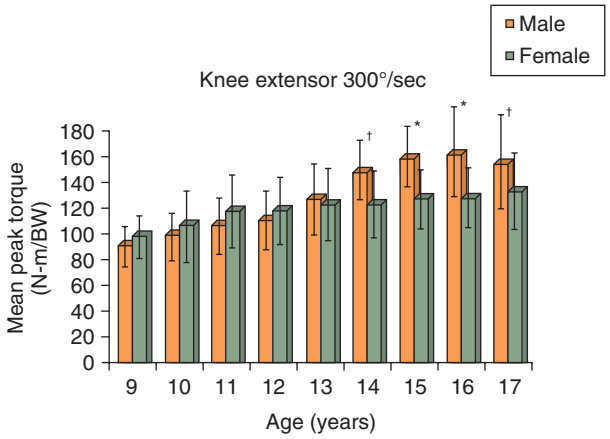


FIG 13-5 No significant difference was found in the mean extensor peak torque ratio values between females and males in the 9- to 13-year-old age groups. However, from the ages of 14 to 17 years, males had significantly greater mean extensor peak torque ratio values than females. *$P < .0001$; †$P = .001$. *BW,* Body weight.

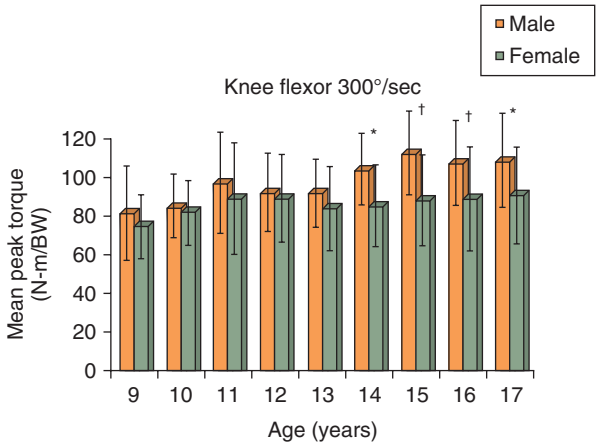


FIG 13-6 No significant difference was found in the mean flexor peak torque ratio values between females and males in the 9- to 13-year-old age groups. However, from the ages of 14 to 17 years, males had significantly greater mean flexor peak torque ratio values than females. *$P < .001$; †$P = .0001$. *BW,* Body weight.

In a separate investigation, Wojtys and coworkers[280] reported that female athletes involved in pivoting sports had significantly smaller increases in torsional stiffness of the knee under internal rotation loading conditions than male athletes. The athletes were matched for age, height, weight, BMI, shoe size, and activity level. A significant reduction in active muscle stiffness in females compared with males during isometric knee flexion and extension and hopping tasks was reported by Granata and associates.[84,85] The gender difference was amplified at higher loads, leading the investigators to conclude that this finding had implications for potential injury during functional loading tasks.

Data published to date on hip strength are conflicting in regard to gender differences. Studies have assessed hip strength either isometrically with dynamometers under non-weight-bearing conditions or with surface EMG under passive or active conditions. Leetun and associates[141] measured hip abduction and external rotation isometric strength, abdominal muscle function, and back extensor and quadratus lumborum endurance in 79 female and 60 male collegiate athletes. The male athletes had greater hip isometric abduction and external rotation strength, as well as lateral core strength, than the female athletes (Table 13-6). However, Brophy and coworkers[35] measured isometric hip abduction and found no gender-based differences between 54 male and 44 female soccer players when the values were adjusted for limb length, weight, and height. The women had significantly weaker hip abductors in their nondominant hip, which was not present in the male players. In the majority of studies in which hip and core strength have been measured, the measurements were done during activities such as a single-leg squat and a single-leg land from a jump, described next.

Gender Differences in Strength, Lower Extremity Function and Alignment During Single-Leg Tasks

Several investigators have reported gender differences in muscle strength and frontal lower extremity alignment during a single-leg

TABLE 13-5 Significant Gender Differences in Knee Stiffness

Study	Subjects	Testing Protocol	Male (mean ± SD)	Female (mean ± SD)	*P* Value
Lyle et al[150] (2014)	14 female, 14 male high school soccer players	Single-leg drop landing (N-m/kg)	304.8 ± 54.9	395.7 ± 101.6	.008
Blackburn et al[28] (2004)	15 female, 15 male recreational athletes, age 18-28 yr	Active isometric contraction, 30 degrees flexion (N-m/rad)	223.7 ± 40.2	160.7 ± 23.2	<.05
Wojtys et al[280] (2003)	26 female, 26 male college athletes, nonpivoting and pivoting sports	Increase active rotational joint stiffness (% increase):			<.001
		30 degrees flexion, pivoting sport			
		60 degrees flexion, pivoting sport	258 ± 40	171 ± 18	≤.02
		30 degrees flexion, all athletes	218 ± 22	178 ± 9	.01
		60 degrees flexion, all athletes	231 ± 21	185 ± 12	≤.02
Wojtys et al[278] (2002)	13 female, 10 male sedentary to elite athletes, age 19-31 yr	Sagittal shear stiffness (N/mm)	70.9	40.7	.005
		Increase stiffness compared with passive state (%)	379	212	.003
Granata et al[84] (2002)	11 female, 12 male recreational athletes, age 21-31 yr	Two-legged vertical hopping frequency (kN/m): 2.5 Hz	31 ± 8	24 ± 5	<.01
		3.0 Hz	43 ± 8	35 ± 7	<.01
		Subjects' own rate	26 ± 9	19 ± 8	<.01
Granata et al[85] (2002)	11 female, 12 male recreational athletes, age 21-33 yr	Quadriceps, no perturbation (N-m/rad)	97.6 ± 31.1	72.2 ± 30.3	<.05
		Quadriceps, 6 kg perturbation (N-m/rad)	262.2 ± 78.3	170.1 ± 29.0	<.05
		Quadriceps, 20% MVE perturbation (N-m/rad)	326.9 ± 105.9	182.5 ± 43.2	<.05
		Hamstrings, no perturbation (N-m/rad)	73.3 ± 25.1	53.6 ± 16.2	<.05
		Hamstrings, 6 kg perturbation (N-m/rad)	196.8 ± 36.9	130.5 ± 22.2	<.05
		Hamstrings, 20% MVE perturbation (N-m/rad)	159.1 ± 51.0	94.0 ± 22.0	<.05

MVE, Maximal voluntary exertion; *SD,* standard deviation.

TABLE 13-6 Significant Gender Differences in Hip and Core Strength

Study	Subjects	Testing Protocol	Results
Baldon et al[11] (2011)	16 female, 16 male recreational athletes	Single-leg squat to 75 degrees of knee flexion 3-dimensional motion analysis, 2 planes Isokinetic eccentric hip abductors (side lying), eccentric hip lateral rotators (sitting)	Males had greater hip abductor, lateral rotator strength (normalized to mass; $P < .001$) Females had greater knee abduction, hip adduction, femur adduction excursions ($P < .01$)
Willson et al[277] (2006)	22 female, 24 male collegiate athletes	Single-leg squat Isometric trunk flexion and extension, lateral trunk flexion, hip abduction, hip external rotation, knee flexion, knee extension, handheld dynamometer	Males had greater strength trunk flexion, lateral trunk flexion, hip abduction, hip external rotation, knee flexion, knee extension ($P < .05$) Females moved toward greater valgus position ($P = .056$)
Claiborne et al[51] (2006)	15 female, 15 male healthy adults	Single-leg squat to 60 degrees knee flexion 3-dimensional motion analysis frontal plane Isokinetic hip abduction, adduction, flexion, extension, internal rotation, external rotation and knee flexion, extension strength 60 degrees/sec (normalized mass)	Males had greater strength concentric hip adduction and flexion, eccentric hip extension, concentric knee flexion and extension ($P < .05$)
Leetun et al[141] (2004)	79 female, 60 male collegiate athletes	Hip abductors: isometric (side lying, % BW) Hip external rotators: isometric (sitting, % BW) Lateral core (quadratus lumborum): side bridge(s)	Abductors: male, 32%; female, 29%; $P = .04$ External rotators: male, 21%; females, 18%; $P < .001$ Lateral core: male, 84.3 sec; female, 58.9 sec; $P < .001$
Zeller et al[288] (2003)	9 female, 9 male collegiate athletes	5 single-leg squats to maximum flexion possible Surface EMG	Females had greater mean muscle activation for rectus femoris ($P < .05$) Females had larger excursions in hip flexion, external rotation, adduction; knee varus/valgus; ankle dorsiflexion, and pronation ($P < .05$)

BW, Body weight; *EMG,* electromyography.



FIG 13-7 Single-leg squat showing poor hip and knee control. (From Barber-Westin SD, Noyes FR: Testing for neuromuscular problems and athletic performance. In: Noyes FR, Barber-Westin SD, editors: *ACL Injuries in the Female Athlete: Causes, Impacts, and Conditioning Programs*. Heidelberg: Springer-Verlag; 2012:235-272.)

squat (Fig. 13-7).[11,51,277,288] Zeller and associates[288] reported that female athletes had significantly greater angles of ankle dorsiflexion, ankle pronation, hip adduction, and hip flexion, as well as greater quadriceps femoris activation, than males (Table 13-6). The women began the movement in a greater amount of valgus alignment and remained in this position throughout the squat. Clairborne and coworkers[51] found that men had greater hip and lower extremity strength than women; however, there were no gender differences noted for frontal plane kinematic values, including peak knee valgus angle. Hip abduction, hip internal rotation, knee flexion, and knee extension strength were predictors of frontal plane knee motion. These authors speculated that the single-leg squat may not produce the magnitude of external moments required to produce a significant difference in frontal plane knee motion. Willson and colleagues[277] reported that, at the deepest angle of the squat, women assumed a greater valgus position than men. Hip external rotation strength was associated with frontal plane position angle. Baldon and associates[11] found that women had greater contralateral pelvic depression, femur adduction, and knee abduction than men. A relationship was found in female subjects between eccentric hip abduction strength and femoral adduction and knee abduction movements. These authors concluded that weakness of this muscle group may play a greater role in altering overall lower limb alignment in women than in men.

Muscle activation patterns and lower extremity alignment have been studied extensively in single-leg landings from a drop-jump* and from a forward hop.[93,112,121,192,193] Significant gender differences have been noted for various phases of these maneuvers, including preland-ing, landing, and postlanding (Table 13-7), although the conclusions drawn in the studies vary because of differences in study methods. Shimokochi and associates[234] found few differences between 10 male and 10 female recreational athletes in lower extremity alignment upon landing. However, the authors noted that individuals who landed in an "upright" position had increased vertical ground reaction forces (GRF), peak knee extensor moments, and quadriceps muscle activation compared with those who landed in a forward-leaning position. Generally, authors have found muscular weaknesses and/or imbalances in women compared with men during single-leg tasks. Female athletes appear to have higher levels of quadriceps activity upon landing, tend to land in an overall valgus position, land with greater vertical GRF, and have reduced hip and knee flexion angles compared with male athletes. The authors of a systematic review[39] of 27 studies that measured gender differences in landing found that 45% of females landed from a single-leg task with increased knee abduction angles compared with males.

Gender Differences in Strength, Lower Extremity Function, and Alignment During Two-Legged Landings

Many investigators have reported gender differences in two-legged landings similar to those just described for single-leg landings (Table 13-8). A study conducted at our laboratory[101] many years ago was one of the first to demonstrate gender differences in muscle strength and movement patterns upon two-legged landings from a volleyball block jump. The hypothesis was advanced that male athletes most likely use different mechanisms from those used by female athletes to compensate for high landing forces and moments at the knee.

Researchers in several studies have assessed gender differences in two-legged landing from a drop-jump (Fig. 13-8). Huston and associates[118] believed that GRF were likely to be greater in women per unit body weight than in men because women landed from a drop-jump with a straighter knee. Decker and colleagues[58] found that females landed in a more erect posture upon initial impact compared with males. More recently, Joseph and coworkers[124] concluded on the basis of their investigation that female and male athletes use a "completely different kinematic landing/jumping strategy" because females landed and collapsed into a valgus alignment more rapidly than males. Sigward and colleagues[243] found gender differences across prepubertal, pubertal, postpubertal, and young adult athletes. The female athletes had significantly higher knee adductor moments and used their knee extensors to a greater extent than the hip extensors (knee/hip extensor moment ratio) during the deceleration phase of landing. Stearns and associates[255] agreed and also found that women displayed lower knee and hip flexion angles and increased knee adduction angles and knee abductor moments during this phase. The authors of a systematic review[39] of 27 studies that measured gender differences in landing found that 72% of females landed in a double-leg task with increased knee abduction angles compared with males.

In contrast, some studies have not found gender differences during two-legged tasks or have refuted earlier findings in regard to the relationship between quadriceps muscle activation and lower limb alignment landing position.[37,56,73,96,187,190,222] For instance, Shultz and associates[236] found no association in female subjects between high levels of quadriceps activation on landing and lower hip and knee flexion angles or greater peak knee extensor moments. Afifi and Hinrichs[2] reported several differences in mechanics when a two-legged drop jump was compared with a countermovement jump for both genders and cautioned that "stepping off a box onto the ground may not be the best way to study landings if the purpose is to generalize to real-world landings from a jump." More realistic athletic tasks have

*References 67, 129, 150, 163, 174, 188, 195, 221, 228, 234, 276, 287.

TABLE 13-7 Significant Gender Differences on Single-Leg Landing

Study	Subjects	Testing Protocol	Muscle Activation, Ground Reaction Forces	Knee, Hip Flexion Angles	Knee, Hip Moments
Lyle et al[150] (2014)	14 female, 14 male high school soccer players	Single-leg drop land, 30-cm height, dominant side	Time to peak vertical GRF occurred significantly earlier in females	No differences between genders	NA
Orishimo et al[188] (2014)	40 women, 40 men, ballet dancers and team sport athletes	Single-leg drop land 30-cm height Surface EMG	No gender or sport differences	Female athletes greater peak knee valgus angle than all others ($P = .007$)	Female dancers lower peak hip adduction moment than all others ($P = .003$)
Howard et al[112] (2011)	30 female, 15 male recreational athletes	Single-leg land from forward hop Isometric hip abduction, ER dynamometer	NA	Females increased hip adduction ($P < .001$), knee abduction ($P < .05$), knee ER ($P < .01$) excursions	NA
Weinhandl et al[276] (2010)	17 female, 16 male recreational athletes	Single-leg drop land according to subjects' highest jump height	NA	Females smaller hip and knee range of motion sagittal plane ($P < .05$)	None
Kiriyama et al[129] (2009)	81 female, 88 male high school students	Single-leg drop land 20-cm height Isometric IR/ER dynamometer	Females weaker IR, ER strength and ER/IR ratio ($P < .001$)	Landing, females greater IR ($P < .01$)	NA
Palmieri-Smith et al[193] (2008)	11 female, 10 male recreational athletes	Single-leg land from forward hop Surface EMG	Females lower cocontraction medial side (vastus medialis/ medial hamstrings) ($P = .008$) Females had greater activation vastus lateralis than vastus medialis and lateral hamstrings than medial hamstrings; no difference in men	NA	NA
Pappas et al[195] (2007)	16 female, 16 male recreational athletes	Single-leg drop land, 40-cm height Surface EMG	Females landed with greater vertical GRF (1 BW) ($P < .001$)	Landing, females increased knee valgus (4.5 degrees, $P < .001$)	NA
Jacobs et al[121] (2007)	15 female, 15 male healthy adults	Single-leg land from forward hop Surface EMG Isometric hip abductor (side lying) strength and endurance	Females weaker hip abductors ($P < .01$)	Landing, females greater valgus ($P < .05$)	NA
Hart et al[93] (2007)	8 female, 8 male collegiate athletes	Single-leg land from forward jump Surface EMG	Females weaker mean gluteus medius activity ($P < .01$)	NA	NA
Nagano et al[174] (2007)	19 female, 18 male collegiate athletes	Single-leg drop land, 30-cm height Surface EMG	Females greater % MVC rectus femoris and hamstring/quadriceps ratio preland only ($P < .001$)	Landing, females greater internal tibial rotation ($P < .05$)	NA
Schmitz et al[228] (2007)	14 female, 14 male recreational college athletes	Single-leg drop land, 30-cm height	Females landed with greater peak normalized vertical GRF ($P = .004$)	Landing, females less hip and knee total flexion displacements and less time to reach peak flexion ($P < .05$)	NA

TABLE 13-7 Significant Gender Differences on Single-Leg Landing—cont'd

Study	Subjects	Testing Protocol	Muscle Activation, Ground Reaction Forces	Knee, Hip Flexion Angles	Knee, Hip Moments
Russell et al[221] (2006)	16 female, 16 male healthy subjects	Single-leg drop land, 60-cm height Surface EMG	None	Initial contact, females landed in valgus, men in varus ($P < .01$)	NA
Zazulak et al[287] (2005)	13 female, 9 male collegiate athletes	Single-leg drop land 30.5, 45.8-cm height Surface EMG	Females lower gluteus maximum peak and mean muscle activation postcontact ($P = .01$) Females greater rectus femoris peak precontact ($P = .03$)	NA	NA

BW, Body weight; *EMG,* Electromyography; *ER,* external rotation; *GRF,* ground reaction force; *IR,* internal rotation; *MVC,* maximal voluntary contraction; *NA,* not assessed or not available.

TABLE 13-8 Significant Gender Differences on Two-Legged Landings

Study	Subjects	Testing Protocol	Muscle Activation/Timing, Ground Reaction Forces	Knee, Hip Flexion Angles	Knee, Hip Moments
Butler et al[36] (2013)	14 female, 14 male recreational soccer players, age 18-30 yr	Two landings: forward stop-jump, countermovement vertical	Both genders showed differences in peak vertical GRF between two landings. Males had greater increases from first to second landing ($P < .01$).	Males had 19% decrease in peak hip flexion compared with females ($P < .05$).	Males had 20% increase in peak knee extension moment compared with females ($P < .01$).
Stearns et al[255] (2013)	20 female, 20 male recreational athletes	Drop-jump 36 cm, isometric strength testing	Females had higher knee/hip extensor ratio ($P < .001$).	Females had lower peak knee and hip flexion angles and higher peak knee abduction angles ($P < .001$).	Females had higher knee adductor moments ($P < .001$), lower knee and hip extensor moments ($P < .001$), and higher knee/hip extensor moment ratios ($P < .001$).
Norcross et al[176,177] (2013)	41 female, 41 male physically active subjects	Drop-jump 30 cm	Females had greater peak posterior GRF and greater peak anterior tibial shear force ($P < .05$). Females were 3.6 times more likely than males to use landing strategy with greater frontal plane initial impact phase energy absorption.	Females had greater knee valgus angles ($P < .05$).	Females had greater peak knee extension moments and greater peak knee varus moments ($P < .05$).
Sigward et al[243] (2012)	60 female, 59 male athletes, age 9-22 yr	Drop-jump 36 cm	Females had greater knee/hip energy absorption ratio ($P < .001$).	NA	Females had greater knee adductor moments ($P < .005$) and knee/hip extensor moment ratios ($P = .001$).
Joseph et al[124] (2011)	10 female, 10 male collegiate athletes	Drop-jump 31 cm	Frontal plane motion of hip, knee, ankle in females occurred earlier in stance phase than in males. Females had increased angular velocity knee valgus excursion.	Females decelerated with hip adduction, knee valgus, and ankle eversion before maximum knee flexion.	

Continued

TABLE 13-8 Significant Gender Differences on Two-Legged Landings—cont'd

Study	Subjects	Testing Protocol	Muscle Activation/Timing, Ground Reaction Forces	Knee, Hip Flexion Angles	Knee, Hip Moments
Hughes et al[116] (2010)	6 female, 6 male collegiate athletes	Volleyball block jumps (unopposed and opposed)	None	Females had greater valgus position on initial contact and maximum position on opposed jumps ($P < .05$). Females had greater knee flexion on opposed jumps ($P < .05$).	NA
Beutler et al[21] (2009)	1046 female, 1707 male cadets	Drop-jump 30 cm, LESS score, isometric strength testing with handheld dynamometer and normalized body mass	Females had weaker quadriceps, hamstrings, hip IR and ER, gluteus maximum and minimum ($P < .001$). Females had lower LESS scores ($P < .001$).	Females more likely to land with less hip and knee flexion at initial contact, more knee valgus, and less flexion displacement over entire landing phase ($P < .001$).	NA
Shultz et al[236] (2009)	39 female, 39 male adults	Drop-jump 45 cm, surface EMG, isometric strength dynamometer	Females had weaker quadriceps and hamstring peak torque ($P < .001$).	Females had smaller knee and hip flexion excursion angles ($P < .05$).	NA
Hughes et al[115] (2008)	6 female, 6 male collegiate athletes	Volleyball block jump	NA	Females had greater maximum knee valgus angle and greater valgus ROM ($P < .01$)	NA
Pappas et al[196] (2007)	16 female, 16 male recreational athletes	Drop-jump 40 cm, surface EMG	Females landed with increased vertical GRF ($P < .001$).	Females had increased knee valgus on landing ($P < .001$)	None
Kernozek et al[126] (2005)	15 female, 15 male recreational athletes	Drop-jump 60 cm	Females had greater peak vertical and posterior GRF ($P < .05$).	Females had greater peak ankle dorsiflexion, foot pronation, and knee valgus angles on landing ($P < .05$) as well as greater ankle dorsiflexion, foot pronation ROM, and varus-valgus ROM frontal plane ($P < .05$).	Females had lower peak knee varus moments on landing ($P < .05$).
Salci et al[223] (2004)	8 female, 8 male collegiate athletes	Spike and block landings 40 cm, 60 cm	Females had greater normalized vertical GRF ($P < .05$) and weaker quadriceps and hamstring peak torques normalized to BW.	Females had lower knee and hip flexion angles ($P < .05$).	
Decker et al[58] (2003)	9 female, 12 male recreational athletes	Drop-jump 60 cm	Females had greater energy absorption from knee and ankle compared with hip ($P < .05$). Males had equal amounts of energy absorption from all joints. Females had 34% less negative hip work, 30% more negative knee work, 52% more negative ankle work than males ($P < .05$).	Females had greater knee extension and ankle plantar flexion angles at initial ground contact ($P < .05$)	NA
Ford et al[77] (2003)	47 female, 34 male high school athletes	Drop-jump 31 cm	NA	Females had greater valgus limb alignment on landing ($P < .01$).	NA

BW, Body weight; *EMG,* electromyography; *ER,* external rotation; *GRF,* ground reaction forces; *IR,* internal rotation; *LESS,* Landing Error Scoring System; *MVC,* maximal voluntary contraction; *NA,* not available; *ROM,* range of motion.

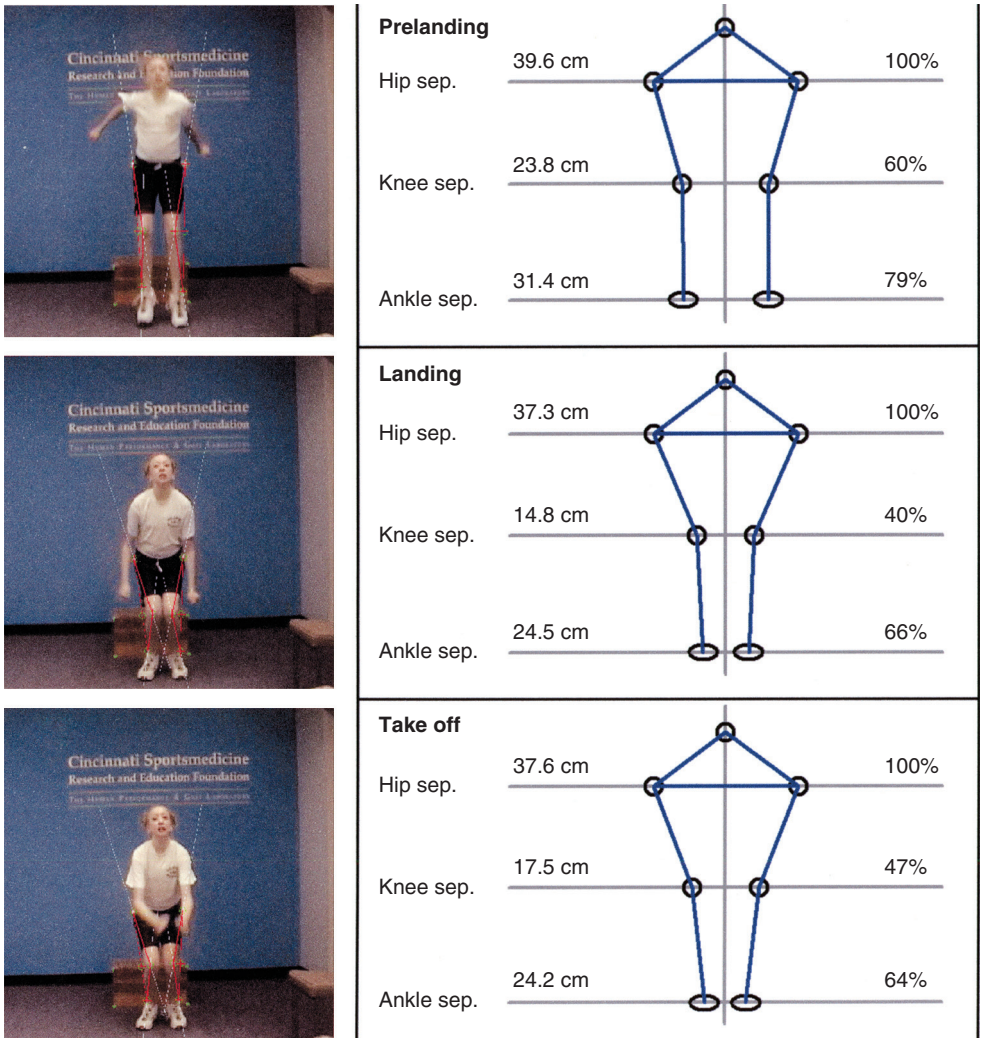


FIG 13-8 The three phases of the two-legged drop-jump test as conducted at our laboratory. The distance between the hips, knees, and ankles is calculated in centimeters with normalized knee and ankle separation *(sep.)* distances (according to the hip separation distance). Shown are the results of a 14-year-old female.

been studied, such as running, cutting, and agility maneuvers, discussed next.

Gender Differences in Strength, Lower Extremity Function, and Alignment During Running, Cutting, Stop-Jump Tasks

Gender differences during straight running have been found in regard to activation of the peroneus longus, tibialis anterior, hamstring, gastrocnemius, GMED, GMAX, and vastus lateralis muscles.[13,50,68,137,152] Comparisons of hip and knee joint angles and moments have also revealed differences between female and male athletes (Table 13-9). The relationship of these gender differences during straight running in regard to ACL injury risk remains unclear.

Many different types of cutting maneuvers have been studied with respect to gender differences in 3-dimensional kinematics and kinetics in male and female athletes (Table 13-10). These include preplanned side cuts,[19,69,91,152,157,158,161,183,207,244] preplanned box-jump cut maneuvers,[183] randomly cued or unanticipated 45-degree cuts,[14,15,78,183,205,206] unanticipated cross-cuts,[136] and unanticipated side cuts.[137] The majority of studies reported gender differences in muscle activation patterns, hip and knee flexion angles, and moments about the hip and knee. For instance, Beaulieu and colleagues[14,15] reported that female athletes had increased hip external rotation, knee abduction angles, and ankle pronation compared with male athletes on a randomly cued 45-degree cut. In addition, female subjects performed the task with greater lateral gastrocnemius activity than males and contracted their vastus lateralis more than their vastus medialis muscles. The authors concluded this muscular imbalance may be the reason the females struck the ground with a more abducted knee position compared with the males. Chaudhari and coworkers[46] observed a correlation between frontal plane lower limb alignment and knee moments, because subjects who assumed a valgus lower limb position during a 90-degree lateral run-to-cut maneuver had significantly higher knee abduction moments than those who had a neutral or varus lower limb position ($P < .01$). Of the 21 subjects tested, 67% of females assumed a lower limb valgus alignment, compared with 22% of males.

In a gender comparison of knee kinetics in three stop-jump tasks (Fig. 13-9), investigators found that women had significantly greater proximal anterior shear forces, extension moments, and valgus

TABLE 13-9 Significant Gender Differences During Running

Study	Subjects	Testing Protocol	Muscle Activation/ Timing	Knee, Hip Flexion Angles	Knee, Hip Moments
Chumanov et al[50] (2008)	17 female, 17 male recreational athletes	Straight run 1.2, 1.5, 1.8 m/s with surface inclinations of 0%, 10%, 15% grade Surface EMG	Females had greater gluteus maximus activity ($P < .001$) for all conditions.	Females had greater peak hip internal rotation ($P < .05$), adduction ($P < .001$), and lateral pelvic tilt excursion ($P < .001$) during stance for all conditions.	NA
Landry et al[136] (2007)	21 female, 21 male elite adolescent athletes	Straight run 0.5 s before planting and cutting Surface EMG	Females had lower lateral hamstring activity, higher quadriceps activity ($P < .01$), and greater lateral gastrocnemius activity ($P < .002$) than males. Females had greater lateral gastrocnemius activity than medial gastrocnemius activity ($P = .02$).	Females landed with greater hip adduction angles ($P = .01$).	Females landed with greater hip external rotation moments ($P < .05$) and knee extension moments ($P = .01$).
Ferber et al[74] (2003)	20 female, 20 male recreational athletes	Straight run	NA	Females had higher hip adduction ($P < .05$), knee abduction ($P < .05$), and hip internal rotation ($P = .01$) angles.	NA
Malinzak et al[152] (2001)	9 female, 11 male recreational athletes	Straight run Surface EMG	Females had greater quadriceps activation and lower hamstring activation during stance phase ($P < .001$).	Females had smaller knee flexion angles and greater knee valgus angles during stance phase ($P < .001$).	NA

EMG, Electromyography; *NA,* not available.

TABLE 13-10 Significant Gender Differences During Cutting

Study	Subjects	Testing Protocol	Muscle Activation/ Timing	Knee, Hip Flexion Angles	Knee, Hip Moments
Miranda et al[166] (2013)	5 female, 5 male recreational athletes	Jump 45-degree sidestep cut	Females had larger peak vertical GRF ($P < .001$) and reached peak force earlier than males ($P = .02$).	Females had smaller knee flexion angle total excursion ($P = .002$).	NA
Bencke et al[19] (2011)	12 female, 12 male team handball players	Side-cut on subjects' preferred leg Surface EMG	Females had lower hamstring preactivity (50 ms before toe-down; $P < .01$) and lower hamstring/ quadriceps preactivity ratio ($P < .01$).	NA	NA
Ebben et al[69] (2010)	12 female, 12 male collegiate athletes	Side-cut, 8-mm approach run, 45 degrees Surface EMG	Females had lower hamstring activity postcontact phase ($P < .05$) and longer quadriceps activity ($P < .05$).	NA	NA

TABLE 13-10 Significant Gender Differences During Cutting—cont'd

Study	Subjects	Testing Protocol	Muscle Activation/ Timing	Knee, Hip Flexion Angles	Knee, Hip Moments
Beaulieu et al[15] (2009)	15 female, 15 male collegiate athletes	Randomly cued 45-degree cut Surface EMG	Females had greater lateral gastrocnemius activity than males and greater vastus lateralis activity than vastus medialis.	Females had increased hip external rotation ($P = .01$), knee abduction angles ($P = .05$), and ankle pronation ($P < .05$).	NA
Hanson et al[91] (2008)	20 female, 20 male collegiate athletes	Side-cut 60 degrees onto nondominant leg Surface EMG	Females had greater vastus lateralis activation before contact and stance phase ($P = .001$) and greater gluteus medius activation stance phase ($P = .01$).	NA	NA
Beaulieu et al[14] (2008)	15 female, 15 male collegiate athletes	Randomly cued 45-degree cut Surface EMG	Males had higher quadriceps activation at initial contact ($P = .01$) and at stance phase of cutting cycle ($P < .05$). Females had lower frequency lateral hamstring at initial contact ($P < .05$).	Females had greater knee valgus angles at initial contact ($P = .04$) and peak knee valgus angles ($P = .01$).	NA
Landry et al[136] (2007)	21 female, 21 male elite adolescent athletes	Unanticipated crosscut (cut to the right), 35- to 60-degree angle Surface EMG	Females had greater lateral gastrocnemius activity ($P < .001$), rectus femoris activity ($P < .001$), and reduced hamstring activity ($P = .05$).	Females had reduced hip flexion angles ($P = .01$) and increased ankle eversion angles ($P = .002$).	Females had reduced hip flexion moments ($P = .003$) and increased knee extension moments ($P < .05$) and knee adduction moments ($P < .05$) throughout stance.
Landry et al[137] (2007)	21 female, 21 male elite adolescent athletes	Unanticipated side-cut (cut to the right), 35- to 60-degree angle Surface EMG	Females had greater gastrocnemius ($P < .01$) and rectus femoris activity ($P = .05$).	Females had reduced hip flexion ($P = .01$) and greater hip external rotation ($P < .05$).	Females had smaller hip flexion moments ($P < .05$).
Pollard et al[207] (2007)	15 female, 15 male collegiate athletes	Side-cut from right onto left leg, 45 degrees	NA	Females had greater hip IR ($P = .01$) and decreased hip flexion ($P = .05$) during early deceleration.	Females had greater hip adductor moments ($P < .05$) and decreased hip extensor moments ($P = .04$).
Sigward & Powers[244] (2006)	15 female, 15 male collegiate athletes	Side-cut from right onto left leg, 45 degrees Surface EMG	Females had greater quadriceps activity ($P = .02$).	None	Females had smaller peak knee flexor moments ($P = .05$) and greater knee adductor moments ($P < .01$) during early deceleration.
McLean et al[157] (2005)	10 female, 10 male collegiate athletes	Side-cut, 35-55 degrees	NA	Females had larger hip IR and knee valgus angles ($P < .05$).	Females had larger peak knee valgus moments ($P < .05$).

Continued

TABLE 13-10 Significant Gender Differences During Cutting—cont'd

Study	Subjects	Testing Protocol	Muscle Activation/ Timing	Knee, Hip Flexion Angles	Knee, Hip Moments
McLean et al[158] (2004)	8 female, 8 male subjects	Side-cut from right onto left leg, 30-40 degrees, with and without simulated defensive opponent	None	Females had larger peak knee valgus and rearfoot pronation angles and smaller peak hip flexion, hip abduction, hip IR, and knee flexion and IR angles ($P < .01$).	NA
Pollard et al[205] (2004)	12 female, 12 male collegiate athletes	Randomly cued 45-degree cut	NA	Females had less peak hip abduction ($P = .03$) during first 40 degrees of knee flexion of stance phase.	None
Malinzak et al[152] (2001)	9 female, 11 male recreational athletes	Side-cut (8-m approach run, dominant to nondominant leg) 45 degrees Cross-cut (8-m approach run, dominant leg only) 45 degrees Surface EMG	Females had greater quadriceps activation and lower hamstring activation during stance phase ($P < .001$).	Females had smaller knee flexion angles and greater knee valgus angles during stance phase ($P < .001$).	NA

EMG, Electromyography; *IR,* internal rotation; *NA,* not available.

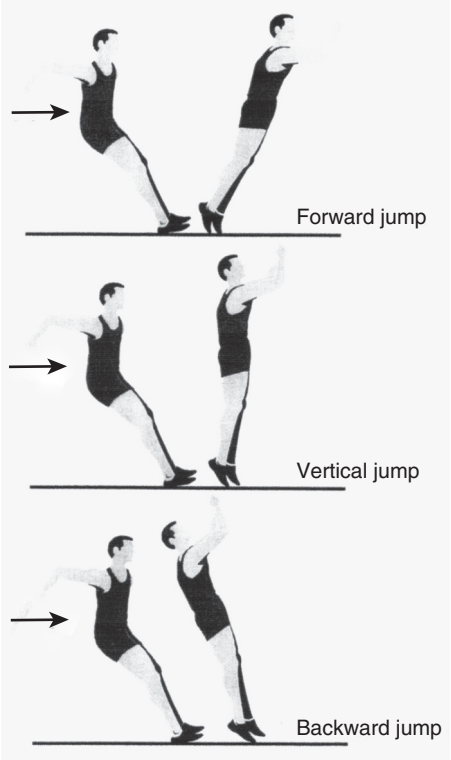


FIG 13-9 Three stop-jump tasks.

moments upon landing compared with men (Fig. 13-10).[44] Chappell and colleagues[44] believed that the observed increased proximal shear force was because of a high quadriceps muscle force, a low hamstring muscle force, a straight knee upon landing, or a combination of all of these factors. Chappell and associates[43] also assessed the effect of fatigue on knee kinetics in stop-jump tasks. Female subjects had significantly greater peak proximal tibial anterior shear forces than males, greater knee extension moments at peak proximal tibial anterior shear force, and smaller knee flexion angles ($P = .001$, all comparisons) in both unfatigued and fatigued states. The mean valgus moment at the peak proximal tibial anterior shear force of female subjects increased 96% from the unfatigued to fatigued condition. Male subjects decreased their mean valgus moments by 43% between test conditions. Chappell and colleagues concluded that fatigue increased the risk of ACL injury more in females than in males. In a third investigation by Chappell and colleagues,[42] female recreational athletes displayed less knee and hip flexion, less hip external rotation, and increased hip abduction than male athletes upon preparation for landing. The authors hypothesized that the athletes "preprogrammed" these lower extremity motions during the flight phase of the last step of the approach run in this task.

Yu and coworkers[284] studied lower extremity kinematics during a stop-jump task in soccer players aged 11 to 16 years. Female players older than 12 years of age had decreased knee and hip flexion angles than the male athletes on landing. Female players increased the amount of knee valgus motion as their age increased. However, male players older than 12 years of age demonstrated a varus knee angle at initial contact. The authors acknowledged the small sample size as a limitation of the study.

Sell and associates[232] conducted an investigation involving high school basketball players in which both planned and reactive stop-jump tasks were performed vertically, horizontally to the left, and

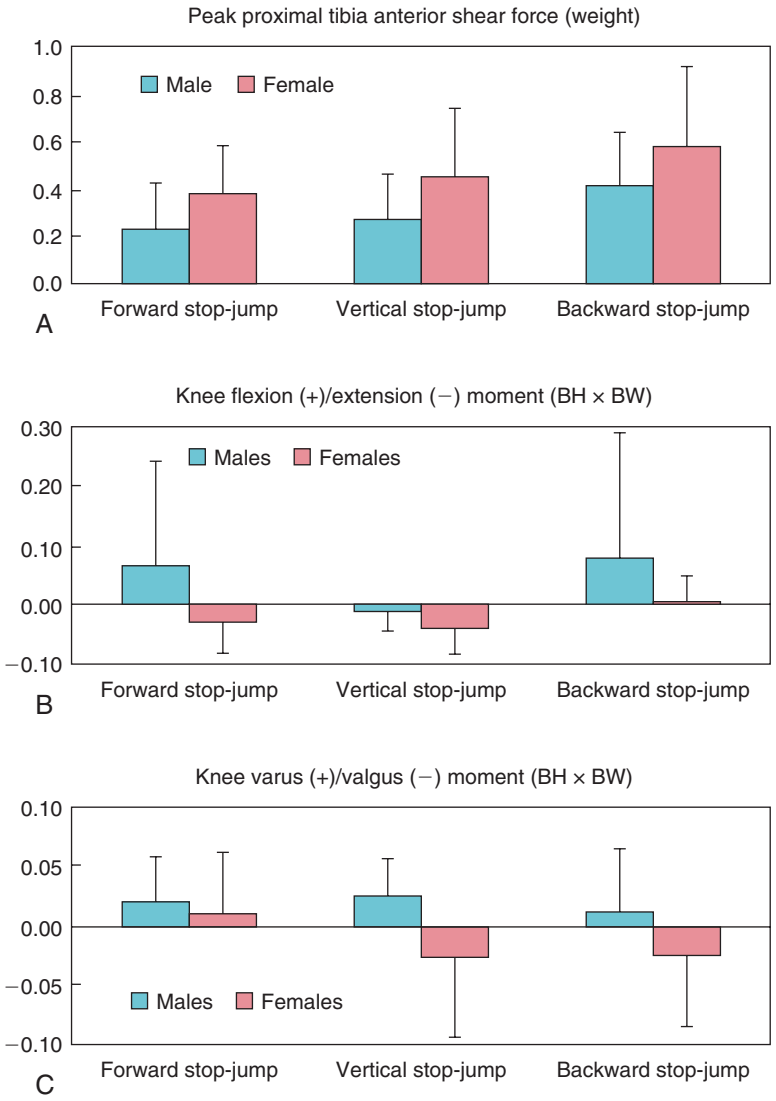


FIG 13-10 Comparisons of peak proximal tibia anterior shear force **(A),** knee flexion-extension moment **(B),** and knee varus-valgus moment **(C)** during the landing phase of three stop-jump tasks. The results are normalized by body weight (BW) (peak shear force) or by body height × body weight (BH × BW) (knee flexion-extension moment and varus-valgus moment). (Modified from Chappell JD, Yu B, Kirkendall DR, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med.* 2002;30: 261-267.)

horizontally to the right. During the reactive tasks, females had lower maximum knee flexion angles than males ($P = .001$), greater maximum knee valgus angles ($P < .05$), greater anterior shear force at peak posterior GRF ($P < .05$), and greater knee flexion moment at peak posterior GRF ($P < .05$). During the horizontal jump to the left, females had significantly lower maximum knee flexion angles than males ($P = .007$), lower knee flexion at posterior GRF ($P = .006$), and greater knee valgus at posterior GRF ($P < .05$). The authors hypothesized that these differences could place greater strain on the female ACL.

FATIGUE

Many ACL injuries occur in the later stages of competition, and several investigators have examined the effects of fatigue on factors such as motor control performance,[123,281] neuromuscular control,[281] knee joint laxity,[218,281] and proprioception.[103,139,167,247] Some investigators found gender differences following fatigue protocols in muscle activation patterns, joint angles, and joint moments (Table 13-11). However, several other studies have failed to identify gender differences in terms of changes in muscle strength or body mechanics.[20,33,43,143,262] Overall, it appears that most fatigue protocols affect landing biomechanics regardless of gender.[20,33,43,143] In a systematic review of fatigue investigations, Santamaria and Webster[224] recommended development of a standardized fatigue protocol, confirmation that fatigue has been reached in all subjects, use of unanticipated single-leg landing tasks, and assessment of all joints of the limb and core before and after fatigue.

CONCLUSION

To determine which risk factors for noncontact ACL ruptures are significant and which may play a more negligible role, future investigations must include greater sample sizes, include analyses of factors in all of the major categories (anatomic, environmental, hormonal, and neuromuscular), and follow athletes for at least one entire athletic

TABLE 13-11 Significant Gender Differences Following Fatigue Protocols

Study	Subjects	Testing Protocol	Muscle Activation/ Timing	Knee, Hip Flexion Angles	Knee, Hip Moments
Liederbach et al[143] (2014)	40 female, 40 male, ballet dancers and team sport athletes	Single-leg drop-jump 30 cm; sets of stepping and jumping protocol until 10% decrease in maximum vertical jump height	Female ballet dancers took significantly longer to reach fatigue ($P = .02$) than athletes did.	All subjects had decreased hip external rotation angle ($P < .01$) and increased knee flexion angle ($P < .001$).	All subjects increased peak knee valgus moments ($P < .05$), decreased peak hip adduction moments ($P < .05$), and increased hip internal rotation moments ($P = .001$).
Thomas et al[262] (2010)	12 female, 13 male, collegiate recreational athletes	Single-leg forward hop, dominant side; reps of five alternating quadriceps-hamstring maximum voluntary concentric contractions until torque dropped <50% of baseline	Quadriceps and hamstring decreased torque production 15%. No effect of gender. Women had larger peak vertical GRF ($P < .05$).	All subjects had increased hip internal rotation at initial contact. Females landed with greater hip flexion; males had greater hip abduction. All subjects increased knee extension and external rotation. Females landed with greater hip and knee flexion.	All subjects had increased knee extension moments and decreased knee flexion and external rotation moments. Females landed with less hip abduction.
Brazen et al[33] (2010)	12 female, 12 male collegiate athletes	Single-leg drop landings 0.36 m; course consisting of 4 ladder drills, side-to-side bounds, minitrampoline jumps, minihurdle hops, and vertical jumps	Anterior-posterior and vertical time to stabilization increased in all subjects, demonstrating reduced postural stability. All subjects landed with greater peak vertical GRF ($P = .002$).	All subjects increased knee flexion and ankle plantar flexion angles ($P = .01$). No change in knee valgus angles.	NA
Gehring et al[82] (2009)	13 female, 13 male recreational athletes	Two-leg drop-jump 52 cm; reps in leg press at 50% of their 1-rep maximum until unable to achieve this load	Females landed with increased knee flexion velocities ($P < .01$) and had delayed activation lateral hamstring and vastus lateralis ($P < .05$) preparatory phase.	Females landed with greater knee abduction angles ($P < .01$).	NA
Benjaminse et al[20] (2008)	15 female, 15 male physically active, age 18-30 yr	Single-leg stop-jump; treadmill run maximum effort to exhaustion	No gender difference in time to fatigue.	All subjects had decreased maximal knee valgus and knee flexion angles on initial contact.	NA
Kernozek et al[125] (2008)	14 female, 16 male recreational athletes	Single-leg drop-jump 50 cm; reps in parallel squat; Smith machine at 60% of their 1-rep maximum until unable 4 times	Females landed with greater anterior knee shear force than men did ($P = .01$).	Men landed with higher knee flexion angles than women ($P < .05$).	None
McLean et al[156] (2007)	10 female, 10 male collegiate athletes	Two-leg drop-jump 50 cm; series of continuous jump drills for 4 minutes	NA	Females landed with increased ankle plantar flexion initially, then peak stance knee abduction, knee internal rotation, and ankle supination angles ($P < .001$).	Females had increased knee abduction and internal rotation moments ($P < .01$). Females had smaller ankle dorsiflexion moments ($P = .001$).

TABLE 13-11 Significant Gender Differences Following Fatigue Protocols—cont'd

Study	Subjects	Testing Protocol	Muscle Activation/ Timing	Knee, Hip Flexion Angles	Knee, Hip Moments
Pappas et al[196] (2007)	16 female, 16 male recreational athletes	Two-leg drop-jump 40 cm; 100 consecutive jumps over obstacles and 50 maximal vertical jumps	Females landed with higher normalized vertical GRF ($P = .003$).	Females landed with greater knee valgus ($P = .001$).	NA
Chappell et al[43] (2005)	10 female, 10 male recreational athletes	3 stop-jump tasks; unlimited reps of 5 vertical jumps followed by 30-m sprint until exhaustion	Peak proximal anterior tibial shear force increased in all ($P < .01$). Women had greater shear force than men across fatigue states and tasks.	Knee flexion angle decreased in all subjects ($P = .03$). Women had smaller knee flexion angles across fatigue states and tasks.	Knee valgus moment increased in all subjects ($P = .03$). Knee valgus moment increased 96% in women. No effect of knee extension moment.

GRF, Ground reaction forces; *NA,* not available.

season for injury. Epidemiologically sound study methodology must be followed, including tracking injury exposures and conducting power analyses to avoid a type II statistical error. Athletes from multiple sports should be included to determine whether certain factors are sport specific in terms of injury risk. Future studies need to incorporate reactive tasks because there appear to be significant differences in movement and muscle activation patterns under these conditions versus those of controlled preplanned maneuvers. As technology improves, these studies may be able to move from the laboratory and measure neuromuscular indices under actual playing conditions.

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Video Content

Video 11-4

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14

Decreasing the Risk of Anterior Cruciate Ligament Injuries in Female Athletes

Sue D. Barber-Westin, Frank R. Noyes

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VIDEO CONTENT

Video 11-4 Sportsmetrics Neuromuscular Conditioning Programs to Prevent ACL Injuries in Female Athletes

SCIENTIFIC RATIONALE AND SUPPORTING INVESTIGATIONS FOR SPORTSMETRICS NEUROMUSCULAR RETRAINING PROGRAM

This chapter presents the scientific rationale, supporting data, and specific strategies for the implementation of Sportsmetrics, a neuromuscular knee ligament injury prevention training program. Since Sportsmetrics was first introduced to the medical community by the senior author (F.R.N.) and associates in 1996,[25] at least 50 other so-called *anterior cruciate ligament (ACL) injury prevention programs* have followed that are focused on female athletes.[5] Many investigations have been conducted to determine the effectiveness of these programs in reducing ACL injury rates,[16,24,31,33,38,43,54-56,63,68] improving knee kinematic and kinetic factors,* and enhancing athletic performance indicators.†

There exist differences in opinion among investigators regarding the frequency, intensity, duration, and components that should comprise an ACL intervention training program. One issue is whether a true reduction in the injury rate can be accomplished with *warmup programs* that are relatively short in session duration (10-20 minutes) but long in total training duration (for instance, one season). This is in contrast to *preseason programs* that last 6 to 8 weeks but require 60 to 120 minutes of training per session. A second issue is whether ACL intervention training should be modified according to the athlete's age and sport. A third issue is whether athletes may be identified as having a high risk of sustaining a noncontact ACL injury and thus whether they should undergo a different training program than those who are at a lower risk for this injury. There does not exist to date an accurate prediction model for ACL injury according to all of the potential risk factors discussed in Chapter 13.

We recently reviewed all published ACL neuromuscular retraining programs to determine those that significantly reduce the incidence of noncontact ACL injuries in female adolescent athletes (Table 14-1).[46] Only eight studies were found that assessed noncontact ACL injury rates in these athletes according to athlete exposures (AEs).[24,31,33,38,53,56,63,68] Three programs—Sportsmetrics, Prevent Injury and Enhance Performance,[38] and Knee Injury Prevention[33]—were found to be effective in reducing noncontact ACL injuries. Unfortunately, several programs[16,31,43,53-56,63,68] failed to have an effect on reducing the ACL injury rate. Issues related to poor compliance with training and too few ACL injuries to avoid a type II statistical error were commonly cited as the reasons for the outcomes of these investigations. In general, ACL intervention programs published to date have had methodologic problems that preclude definitive answers regarding which programs are effective and which are ineffective. These include lack of randomization and control, limited statistical power because of the small number of exposures and ACL injuries, failure to determine ACL injury incidence according to AEs, poor compliance with training, poor documentation of contact versus noncontact ACL injuries, and changes in study protocols over the course of the investigations.

The Sportsmetrics program is proven effective in inducing changes in neuromuscular indices in female athletes because studies have

*References 7-9, 14, 17, 21-23, 25, 28, 30, 34, 35, 40-42, 44, 47-50, 57, 61, 66, 69, 70, 73.

†References 4, 8, 9, 13, 21-23, 25, 26, 34, 35, 44, 47-50, 62, 64, 66, 67, 69, 70, 72, 73.

TABLE 14-1 Intervention Training Programs That Significantly Reduce Noncontact Anterior Cruciate Ligament Injury Rates in Female Adolescent Athletes

	TRAINED ATHLETES				CONTROL ATHLETES						
Program (year)	Athletes (n)	NC ACL (n)	AE (n)	NC ACL Injury Incidence Rate†	Athletes (n)	NC ACL (n)	AE (n)	NC ACL Injury Incidence Rate†	*P* Value	Relative Risk Reduction (95% CI)	Number Needed to Treat* (95% CI)
Sportsmetrics[24] (1999)	366	0	17,222	0	463	5	23,138	0.22	<.05	100 (NA)	93 (50-722)
Sportsmetrics[46] (1999, 2012)	700	1	36,724	0.03	1120	13	61,244	0.21	.03	88 (6-98)	98 (59-302)
PEP[38] (2005)	1885	6	67,860	0.09	3818	67	137,448	0.49	<.0001	82 (58-92)	70 (52-105)
KIPP[33] (2011)‡	485	2	20,345	0.10	370	6	12,467	0.48	.04	75 (-25-95)	83 (38-503)

*Positive value to benefit, negative value to harm.
†Calculated per 1000 athlete exposures.
‡Data provided by personal communication with senior author.
ACL, Anterior cruciate ligament; *AE,* athlete exposures; *CI,* confidence interval; *KIPP,* Knee Injury Prevention Program; *NA,* not applicable; *NC,* noncontact; *PEP,* Prevent Injury and Enhance Performance Program.

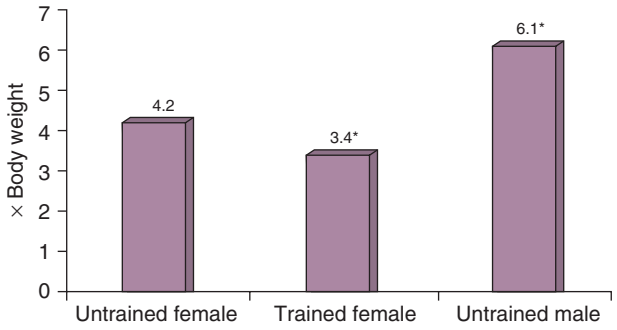


FIG 14-1 Decrease in peak landing forces with training in female subjects before and after training and relative to age- and weight-matched male athletes. *$P < .01$. (From Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996; 24:765-773.)

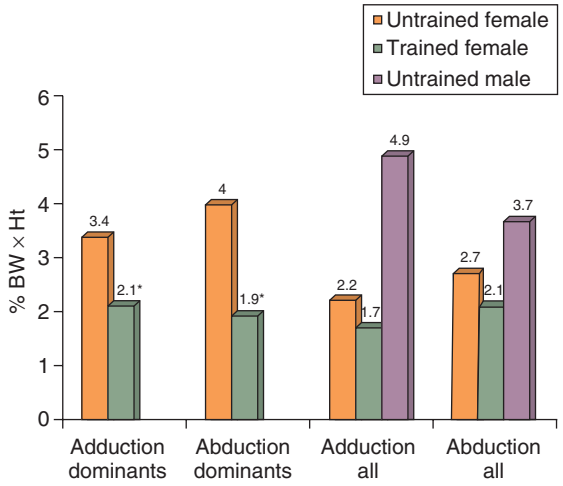


FIG 14-2 Peak knee adduction and abduction moment data at landing before and after training. The female subjects were grouped according to the dominant moment (adduction or abduction) and all the female subjects grouped together (all). *$P < .05$ compared with untrained females. *BW,* Body weight; *Ht,* height. (From Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24:765-773.)

shown improved overall lower limb alignment on a drop-jump test,[7,47-50] increased hamstring strength,[25,47,70] increased knee flexion angles on landing,[25,58] and reduced deleterious abduction and adduction moments and ground reaction forces.[25] Sportsmetrics significantly reduces the risk of noncontact ACL injuries in female athletes participating in basketball and soccer.[24,46] In addition, this program enhances athletic performance indicators in female soccer,[50] basketball,[49] volleyball,[48] and tennis[4] players.

A pilot laboratory study was conducted at our institution using 11 high school female volleyball players to determine the effect of Sportsmetrics training on landing mechanics and lower extremity strength.[25] The control group consisted of nine male subjects matched for height, weight, and age. Training was performed three times per week for 6 weeks. Before and after the training program, the athletes completed isokinetic muscle testing at 360 degrees/sec and force analysis testing to measure motions and ground reaction forces during volleyball jumping and landing maneuvers.

After 6 weeks of training, peak landing forces from a volleyball block jump decreased 22% ($P = .006$), or an average of 456 N (103 lb) (Fig. 14-1). Knee adduction and abduction moments decreased approximately 50% (Fig. 14-2). Decreased abduction or abduction moments may lessen the risk of liftoff of the medial or lateral femoral condyle, improve tibiofemoral contact stabilizing forces,[39] and reduce the risk of knee ligament injury. In addition, the female athletes demonstrated lower landing forces than male athletes and lesser adduction and abduction moments compared with pretraining values. Hamstring-to-quadriceps muscle peak torque ratios increased 26% on the nondominant side and 13% on the dominant side, correcting side-to-side imbalances.

A second study was conducted in 62 high school female athletes to determine whether Sportsmetrics training altered lower limb alignment on a drop-jump task and improved isokinetic lower limb muscle strength.[47] Before training, 80% of the female athletes had a valgus overall lower limb alignment on landing from a drop-jump. After training, 34% of the females demonstrated this alignment ($P < .0001$).

Significant increases were noted after training in knee flexion peak torque in both the dominant and nondominant limbs ($P < .0001$).

Sportsmetrics training has been shown to significantly reduce the incidence of noncontact ACL injuries in female adolescent athletes. Our research institution[24,46] followed 700 females who underwent Sportsmetrics training, as well as 1120 female controls and 434 male control athletes. All athletes were followed throughout their sports seasons for injury documentation. The total numbers of AEs were 36,724 for the trained group, 61,244 for the control female group, and 21,390 for the control male group. Noncontact ACL injuries were sustained in 1 trained female athlete, 13 control female athletes, and 1 control male athlete. The knee injury incidence per 1000 AEs was 0.03 in trained female athletes, 0.49 in control female athletes, and 0.09 in male athletes ($P = .03$).

We recently reviewed the effectiveness of Sportsmetrics training in 1000 female athletes 13 to 18 years of age who participated in a variety of sports activities. There were statistically significant improvements and large effect sizes (ESs) in overall lower leg alignment in the coronal plane on the drop-jump test ($P < .0001$; ES = 0.97). Before training, 79% had a valgus alignment appearance on landing. The program markedly improved the alignment in 75% of these athletes. There were significant improvements in the single-leg triple-crossover hop in the mean distance hopped (33 cm; $P < .0001$; ES = 0.47). In addition, 13% had abnormal limb symmetry on this test before training, whereas only 2% were rated as having abnormal symmetry after completing the program. There were significant improvements in the agility *t* test ($P < .0001$; ES = 0.64) and the multistage fitness test (MSFT) ($P < .0001$; ES = 0.57). Isokinetic hamstring strength significantly improved ($P < .0001$; ES = 0.57 dominant, ES = 0.61 nondominant), as did quadriceps strength ($P < .01$; ES = 0.27 dominant, ES = 0.35 nondominant). Significant improvements, but low ESs, were found in the vertical jump and sit-up tests.

We also compared the difference in noncontact ACL injury rates between a subset of 700 trained athletes with that of 700 untrained athletes matched for age, sport, and body mass index. The subgroup of 700 trained athletes had a significant reduction in the noncontact ACL injury incidence rate (according to AEs) compared with the control group. The trained group had 36,724 AEs and 1 ACL injury, whereas the control group had 61,244 AEs and 13 ACL injuries (incidence rates, 0.03 and 0.21 per 1000 AEs, respectively; $P = .03$).

The risk factors that have been hypothesized to increase the potential for an ACL injury are discussed in Chapter 13. The final position of the knee joint on landing, pivoting, and cutting is influenced by the center of gravity of the upper body and the trunk over the lower extremity. Equally important are the factors of trunk-hip adduction or abduction, foot-ankle pronation-supination, and foot separation distance. These effects additively produce either a varus or valgus moment about the knee joint that must be balanced by the lower limb musculature. If the athlete is off balance or contacts another player, a loss of trunk and lower limb control and position may occur and the knee joint may go into a hyperextended or valgus position. Although there are many potential mechanisms for ACL injury, it has been postulated that excessive valgus moments about the knee joint, with subsequent high anterior tibial shear forces, may be one of the most common to occur in females.[18,27,37] Excessive valgus loading may result in decreased tibiofemoral contact, or condylar liftoff,[39] and a reduction in the normal joint contact geometry that contributes to knee joint stability. This position, coupled with a highly activated quadriceps muscle that produces maximum anterior shear forces with the knee joint at low flexion angles (0-30 degrees)[10,20,52] and a relatively inactive hamstring musculature, could potentially lead to ACL rupture. The function of the hamstrings is dependent on the angle of knee flexion and degrees of external tibial rotation.[51] The mechanical advantage of these muscles increases as the knee is flexed because at 0 degrees of extension, the flexion force is only 49% of that generated at 90 degrees of flexion. Withrow et al.[71] speculated that it may be possible to limit ACL strain by accentuating hip flexion during the knee flexion phase of jump landings because this increases the tension in the active hamstring muscles.

The time within which an ACL rupture occurs has been estimated to range from 17 to 50 milliseconds after initial ground contact.[32] It is evident that there is not enough time for an athlete, upon sensing a knee injury about to occur, to alter the body's or lower extremity's position to prevent this injury. To have a significant impact on reducing the incidence rate of noncontact ACL tears, the goals of a training program are to teach athletes to control the upper body, trunk, and lower body position; lower the center of gravity by increasing hip and knee flexion during activities; and develop muscular strength and techniques to land with decreased ground reaction forces. Athletes should be taught to pre-position the body and lower extremity before initial ground contact to obtain the position of greatest knee joint stability and stiffness. This includes avoidance of sudden deceleration and cutting and pivoting with an extended knee that induces a large quadriceps contraction. The program should consist of a dynamic warmup, plyometric jump training, strengthening exercises, agility and aerobic conditioning, and risk awareness training.[19]

SPORTS INJURY TEST

We developed a sports injury test (SIT) to obtain a profile of each athlete before and after Sportsmetrics training. Before testing begins, a history is collected regarding prior injuries to the knees and ankles. The SIT is completed just before training begins and then again within 1 week after the program is completed. The SIT measures (1) knee and ankle position on landing and takeoff from a drop-jump during a video test, (2) lower limb symmetry[2,45] and a general assessment of lower limb control on single-leg hop tasks (Fig. 14-3), (3) hamstring flexibility, and (4) vertical jump height (countermovement and two-step approach). Athletes participating in sport-specific Sportsmetrics programs, discussed later in this chapter, also undergo additional agility, speed, and aerobic tests as required for their sport. These may include a *t* test, 37-meter sprint, 18-meter sprint, MSFT, sit-up test, and 1-mile run.[48-50] Tennis players perform a series of tests on the court, including a suicide sprint, service box and baseline speed and agility tests, and a medicine ball toss described elsewhere.[4]

SPORTSMETRICS ESSENTIAL COMPONENTS

There are four essential components of Sportsmetrics: dynamic warmup, plyometric jump training, strengthening, and flexibility. It is recommended that training be conducted either during the off-season or just before the start of the athlete's sport season. The training is conducted three times per week on alternating days for 6 weeks. As described later in this chapter, sport-specific speed and agility components may be added to the training program if desired by an athlete or team. A maintenance training program (Sportsmetrics Warm-up for Injury Prevention and Performance [WIPP]) may be performed upon completion of the formal Sportsmetrics program to continue to instill the skills and techniques learned during the athlete's sports season. Training may be accomplished either in classes led by an instructor who has completed certification training from our foundation or by following an instructional step-by-step DVD series. Athletes who do not train with a certified instructor are encouraged to perform training either in front of a mirror or with a partner so that mistakes in technique, form, and body alignment may be detected and



FIG 14-3 Single hop for distance video screening allows a qualitative assessment of an athlete's ability to control the upper and lower extremities upon landing, which may be rated as either good (**A**), fair (**B**), or complete failure, fall to ground (**C**).

corrected. A list of certified instructors and sites is available at www.sportsmetrics.org.

Dynamic Warmup

The dynamic warmup prepares the body using function-based activities that incorporate sport-specific motions. The goals are to raise core body temperature, increase heart rate, increase blood flow to the muscles, and improve flexibility, balance, and coordination. Upon completion of this warmup, the athlete will be physically prepared for training. All of these exercises should be performed across the width of a court or field or for approximately 20 to 30 seconds.

1. **Toe walk.** The athlete walks up on the toes with the legs straight. The heel of the foot should not touch the ground, and the hips should remain neutral throughout.
2. **Heel walk.** The athlete walks on the heels with the legs straight. The toes should not touch the ground; the knees should not lock; and the hips should remain neutral.
3. **Straight-leg march**. The athlete walks with both legs straight, alternating lifting up each leg as high as possible without compromising form. The knees are kept straight and posture is erect, and the body should not lean backward. The arms are swung in opposition.
4. **Leg cradle** (Fig. 14-4). The athlete walks forward, keeping the entire body straight and neutrally aligned. One leg is lifted in front of the body, bent at the knee. The knee is rotated outward and the foot inward. The foot is held with both hands while standing on one leg, and this position is held for 3 seconds. The foot is placed back down, and the exercise is repeated with the opposite leg.
5. **Dog and bush (hip rotator) walk** (Fig. 14-5). The athlete is instructed to pretend that there is an obstacle directly in front of her or him. The athlete faces forward and keeps the shoulders and hips square. One leg is extended at the hip, and the knee is kept softly bent. The leg is externally rotated out at the hip, and the knee is bent to approximately 90 degrees. The leg is rotated and brought up and over the obstacle and then placed back on the ground. The exercise is repeated with the opposite leg.
6. **High-knee skip.** The athlete begins to skip. One knee is driven up in the air as high as possible while the other leg is used to hop off the ground. As the athlete lands, the exercise is immediately repeated on the opposite side. The opposite arm of the high knee is swung up in the air to help gain height.
7. **High knees.** The athlete begins to jog forward. With each step, the knees are driven up as high as possible using short, choppy steps. The athlete remains facing forward, keeping the shoulders and hips square throughout the exercise.
8. **Glute kicks.** The athlete begins to jog forward. With each step, the athlete kicks the feet back as if trying to reach the glutes with the heel, using short, choppy steps. The athlete remains facing forward, keeping the shoulder and hips square throughout the exercise.
9. **Stride out.** The athlete begins jogging forward with an exaggerated running form. The knees are driven as high as possible and the feet are kicked back, as if trying to make a large complete circle



FIG 14-4 Leg cradle.

with the legs. The athlete should stay up on the balls of the feet throughout the exercise.

10. **All-out sprint.** The athlete sprints forward as fast as possible while maintaining proper technique and running form.

Plyometrics/Jump Training

Plyometrics help develop the muscle control and strength considered critical to reducing the risk of knee ligament injuries. These exercises are well known to increase muscular power, vertical jump height, acceleration speed, and running speed.[29,36,59,60,65] However, if done improperly, plyometrics would not be expected to have a beneficial effect in reducing the risk of a noncontact ACL injury. Therefore the philosophy of the plyometric and jump-training component in the Sportsmetrics program is to place a major emphasis on correct jumping and techniques throughout the 6 weeks of training. Specific drills and instruction are used to teach the athlete to pre-position the entire body safely when accelerating or decelerating on landing. The selection and progression of the exercises entail neuromuscular retraining and proceed from simple two-legged jumping drills (to instill correct form) to multidirectional single-foot hops and plyometrics with an emphasis on quick turnover (to add movements that mimic sport-specific motions). The jump training is divided into three 2-week phases. Each 2-week phase has a different training focus, and the exercises change correspondingly (Table 14-2).

The aim of phase 1, termed the *technique development phase,* is to teach the athlete proper form and technique for eight different jumps. Four basic techniques are stressed: correct posture and body alignment throughout the jump (spine erect, shoulders back, chest over knees); jumping straight up with no excessive side-to-side or forward-backward movement; soft landings, including toe-to-midfoot rocking and bent knees; and instant recoil preparation for the next jump. The athletes are taught these techniques through verbal queues from instructors, such as "On your toes," "Straight as an arrow," "Light as a feather," "Shock absorber," and "Recoil like a spring." Constant feedback is offered by instructors, and mirrors are used in the training sessions to provide direct visual feedback if possible. Throughout each session, exercises are increased by duration or repetition. If the athlete becomes fatigued and cannot perform the jumps with the proper technique, he or she is encouraged to stop and rest. Approximately 30 seconds of recovery time is allowed between each exercise.

In phase 2, called the *fundamentals phase,* emphasis continues to be on proper technique and quality jumping form. Five jumps from phase 1 are continued, but these are performed for longer periods of time. In addition, four new jumps of increased difficulty are incorporated.

In phase 3, the *performance phase,* the quantity and speed of the jumps are increased to develop a truly plyometric exercise routine. The athlete is encouraged to complete as many jumps as possible with proper form and to concentrate on the height achieved in each jump.

1. **Wall jump** (weeks 1-6). Also known as *ankle bounces,* these jumps are performed with the knees slightly bent and both arms raised over the head (Fig. 14-6, *A*). From this position, the athlete bounces up and down off his or her toes (Fig. 14-6, *B*). The knees should be soft and the hips, knees, and ankles in neutral alignment. This jump is performed first to prepare the athlete mentally and physically for plyometric training. This also provides the trainer with an opportunity to observe and begin positive feedback and instruction.

   Mistakes to correct include slouched posture, too much knee flexion, and eyes watching the feet with the head down. The athlete should be told to keep the eyes and head focused upward, bend the knees slightly, and maintain neutral alignment.

2. **Tuck jump** (weeks 1-6). The athlete begins in an upright neutral stance with the feet shoulder width apart (Fig. 14-7, *A*). The athlete jumps up, bending the knees together to bring the thighs up toward the chest as high as possible (Fig. 14-7, *B*).

   Mistakes to correct include lowering the chest to the knees rather than lifting the knees to the chest, bringing the knees together during takeoff or landing, double-bouncing between jumps, and producing a loud landing with a lack of muscle control. The athlete should be told to lift the knees up to the chest, control and keep the landing quiet, land on the balls of the feet,

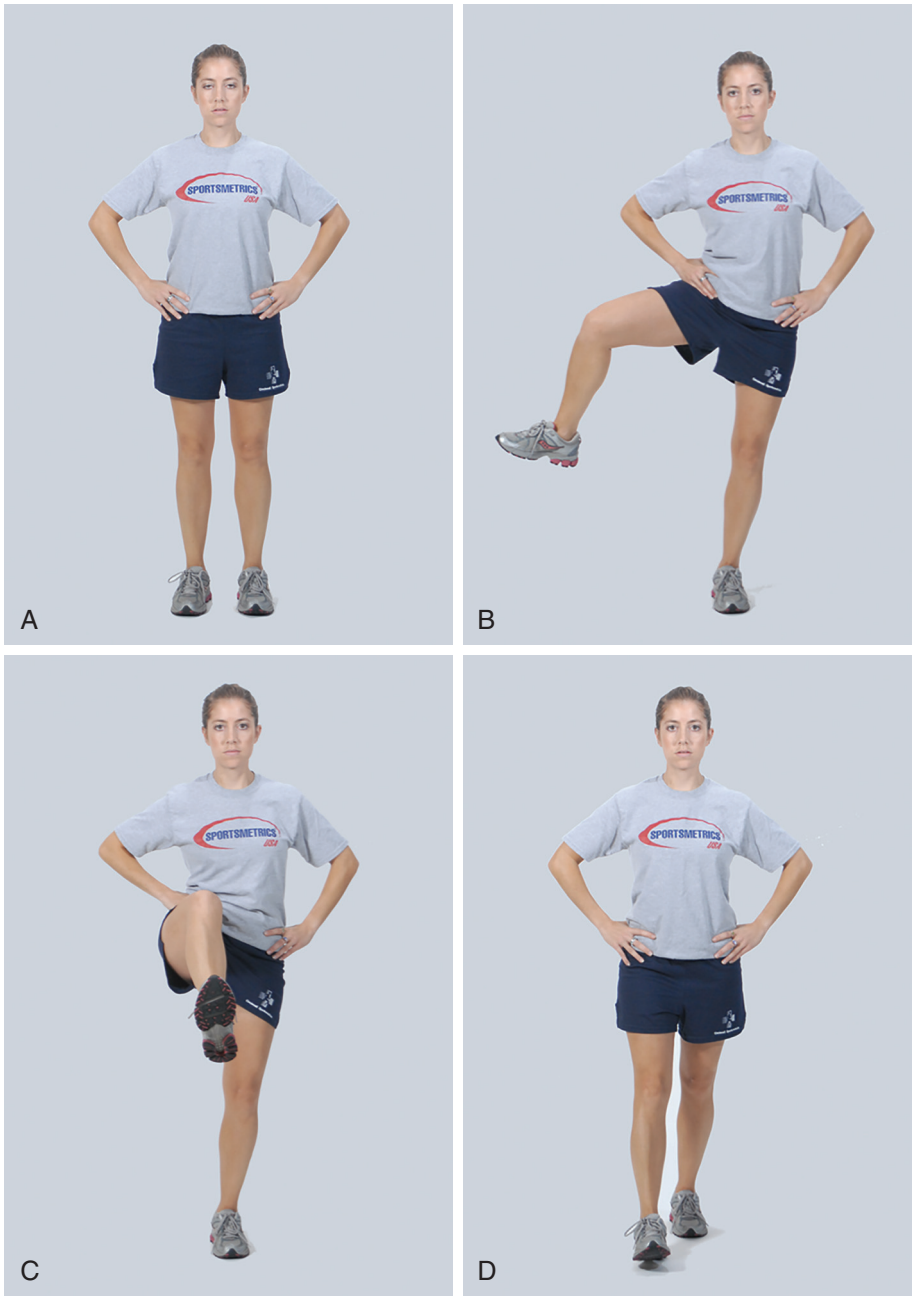


FIG 14-5 Dog and bush walk.

keep the knees bent when landing to go immediately into the next jump, keep the knees and ankles at shoulder and hip width at all times, keep the back straight and shoulders back, and keep the head and eyes up with each jump.

3. **Squat jump** (weeks 1-6). The athlete begins in a fully crouched position as deep as comfortable (Fig. 14-8, *A*). The knees and feet are directed forward and are in alignment with the hips. The upper body is upright with the chest open. The hands touch or reach toward the ground on the outside of the heels. The athlete jumps up, reaching as high as possible (see Fig. 14-8, *B*), and then returns to the crouched position with hands reaching back toward the heels (see Fig. 14-8, *C*).

   Mistakes to correct include landing with body and/or knees forward and/or off-balance, bringing the knees together during takeoff or landing, and producing a loud landing with a lack of muscle control. The athlete should be told to keep the hands reaching back toward the heels (not forward), keep the knees tracking under the hips on takeoff and landing, maintain the knees and ankles at shoulder and hip width at all times, keep the back straight and the shoulders back, and keep the head and eyes up with each jump.

4. **Barrier jump side to side** (weeks 1 and 2). A cone or barrier approximately 6 to 8 inches in height is used. The athlete stands in a modified squat position (Fig. 14-9, *A*). The athlete then jumps from one side of the barrier to the other side with the feet kept together (Fig. 14-9, *B*) and lands in the same amount of knee flexion as the starting position (Fig. 14-9, *C*).

   Mistakes to correct include landing or taking off with stiff, straight, or wobbly knees; jumping side to side quickly without bringing the entire body over the barrier; double-bouncing on landing

TABLE 14-2 Sportsmetrics Neuromuscular Training Program: Jump Training Component

Phase	Jumps	Duration		Emphasis, Goals
1: Technique Development		Week 1	Week 2	Proper form and technique for each jump
	Wall jump	20 seconds	25 seconds	Correct posture, body alignment throughout each jump
	Tuck jump	20 seconds	25 seconds	Jump straight up with no excessive side-to-side or forward-backward movement
	Squat jump	10 seconds	15 seconds	Soft landings that include toe-to-midfoot rocking and bent knees
	Barrier jump (side to side)	20 seconds	25 seconds	Deep knee flexion
	Barrier jump (forward and back)	20 seconds	25 seconds	Instant recoil preparation for the next jump, no double-bouncing
	180-degree jump	20 seconds	25 seconds	
	Broad jump (stick 5 seconds)	5 reps	10 reps	
	Bounding in place	20 seconds	25 seconds	
2: Fundamentals		Week 3	Week 4	Proper technique to build a base of strength, power, agility
	Wall jump	25 seconds	30 seconds	Focus on well-performed, quality jumps
	Tuck jump	25 seconds	30 seconds	Same jumps from phase 1 done for longer duration
	Jump, jump, jump, vertical jump	5 total	8 total	New, more difficult jumps introduced to build on skills mastered from phase 1
	Squat jump	15 seconds	20 seconds	
	Barrier hop side to side	25 seconds	30 seconds	
	Barrier hop forward and back	25 seconds	30 seconds	
	Scissors jump	25 seconds	30 seconds	
	Single-leg hop (stick)	5 reps	5 reps	
	Bounding for distance	1 run	2 runs	
3: Performance		Week 5	Week 6	Enhance basic skill and muscle control learned in first two phases
	Wall jump	20 seconds	20 seconds	Increase quantity, speed of jumps with well-performed, quality jumping technique
	Jump up, down, 180 degrees, vertical	5 total	10 total	
	Squat jump	25 seconds	25 seconds	
	Mattress jump side-side	30 seconds	30 seconds	
	Mattress jump forward-back	30 seconds	30 seconds	
	Hop, hop, hop, stick	5 reps	5 reps	
	Jump into bounding	3 runs	4 runs	



FIG 14-6 Wall jump.



FIG 14-7 Tuck jump.



FIG 14-8 Squat jump.

and takeoff; and not landing with the feet together. The athlete should be told to bend the knees up to clear the barrier, land quietly on the balls of the feet and rock back to the heels, control the landing to be able to immediately take off again, keep the back straight with the shoulders back, keep head and eyes up with each jump, keep the knees tracking under the hips and toes pointed forward on takeoff and landing, and keep the feet parallel to each other.

5. **Barrier jump forward-backward** (weeks 1 and 2). A cone or barrier approximately 6 to 8 inches in height is used. The athlete stands facing the barrier in a modified squat position (Fig. 14-10, *A*). The athlete jumps forward and backward with the feet kept together (Fig. 14-10, *B*) and lands in the same amount of knee flexion as the starting position (Fig. 14-10, *C*).
   Mistakes to correct include landing or taking off with stiff, straight, or wobbly knees; jumping forward and backward quickly

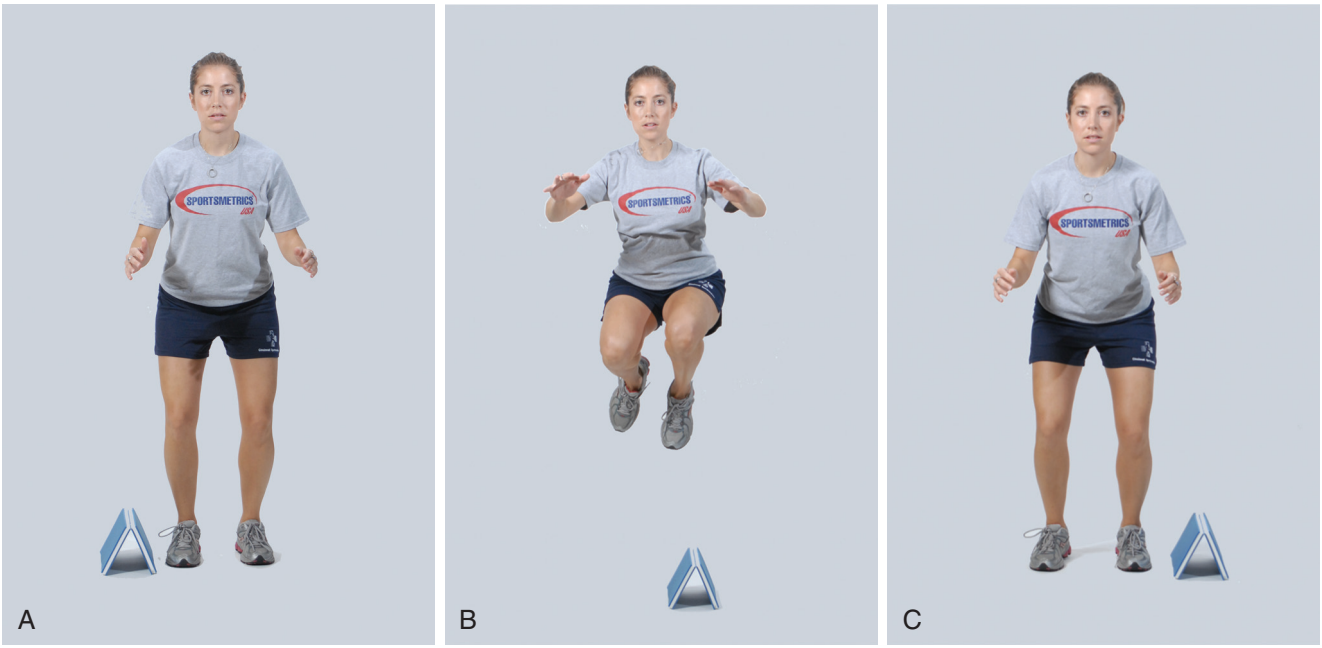


FIG 14-9 Barrier jump side to side.

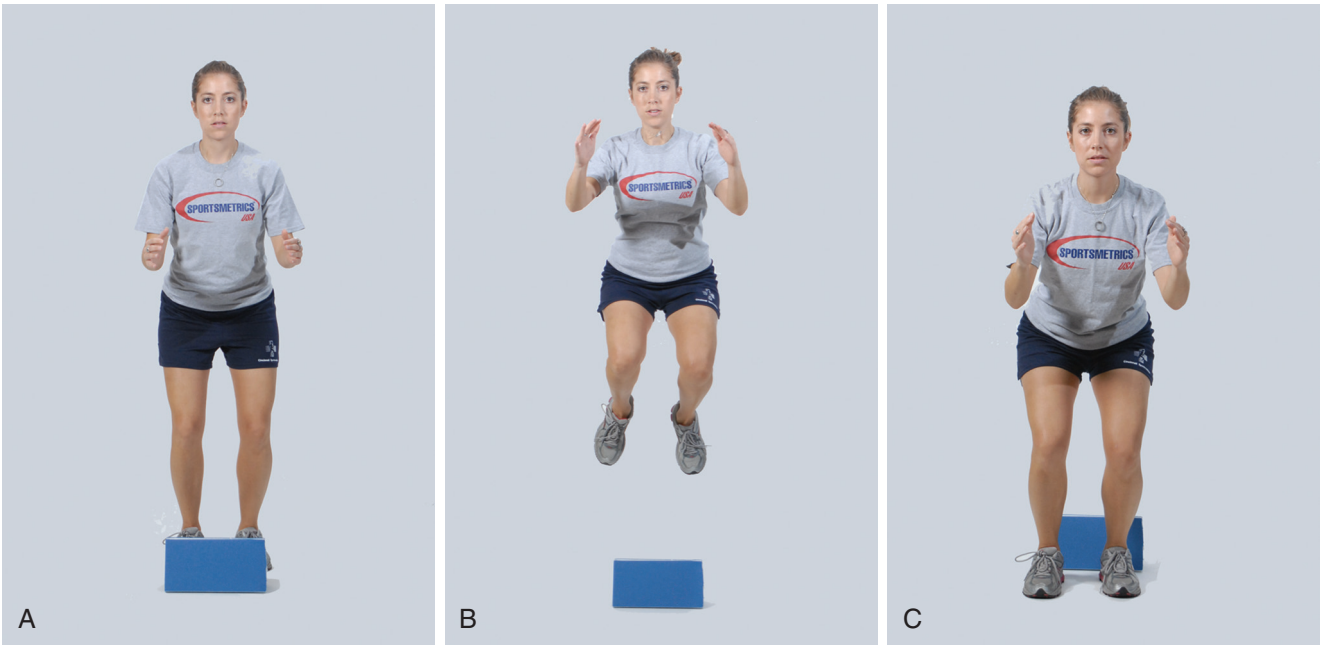


FIG 14-10 Barrier jump forward and backward.

without bringing the entire body over the barrier; double-bouncing on landing and takeoff; and separating the feet to clear the barrier. The athlete should be told to lift the knees up to the chest to clear the barrier, land quietly on the balls of the feet and rock back to the heels, control the landing to be able to immediately take off again, keep the back straight with the shoulders back, keep the head and eyes up with each jump, and keep the knees tracking under the hips and the toes pointed forward on takeoff and landing.

6. **180-degree jump** (weeks 1 and 2). The athlete begins from an upright neutral stance with the feet shoulder width apart (Fig. 14-11, *A*). The athlete jumps straight up into the air with both feet and makes a 180-degree turn in midair (Fig. 14-11, *B*) before landing (Fig. 14-11, *C*). The landing is held for 2 seconds, and then the direction is reversed and the jump repeated.

Mistakes to correct include overrotating or underrotating; not turning the body 180 degrees; not rotating the body as a unit; landing loud, straight, and stiff-legged, with staggered feet or one foot landing before the other; always jumping in the same direction (in a circle); rotating back and forth with minimal height during the jump; and separating the feet beyond the desired "feet, shoulder, and/or hip width" distance.

The athlete should be told to jump straight upward and rotate the body as a unit from the head to the toes; land with soft, slightly

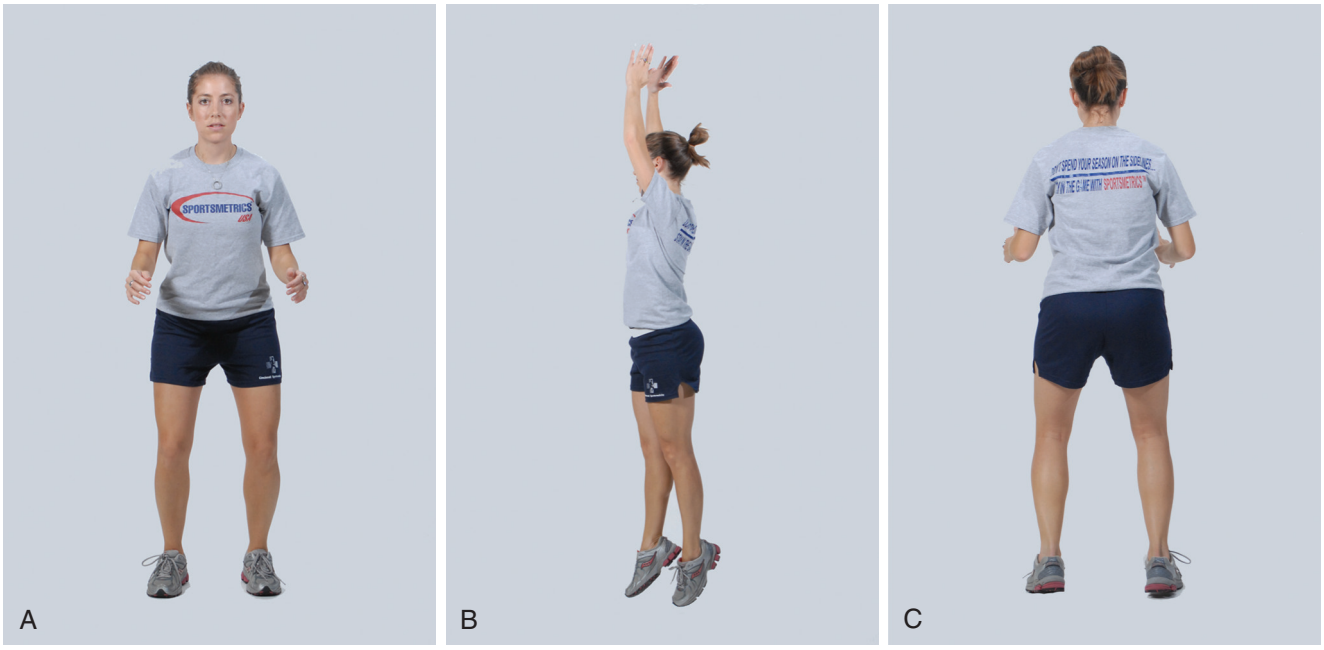


FIG 14-11 A 180-degree jump.

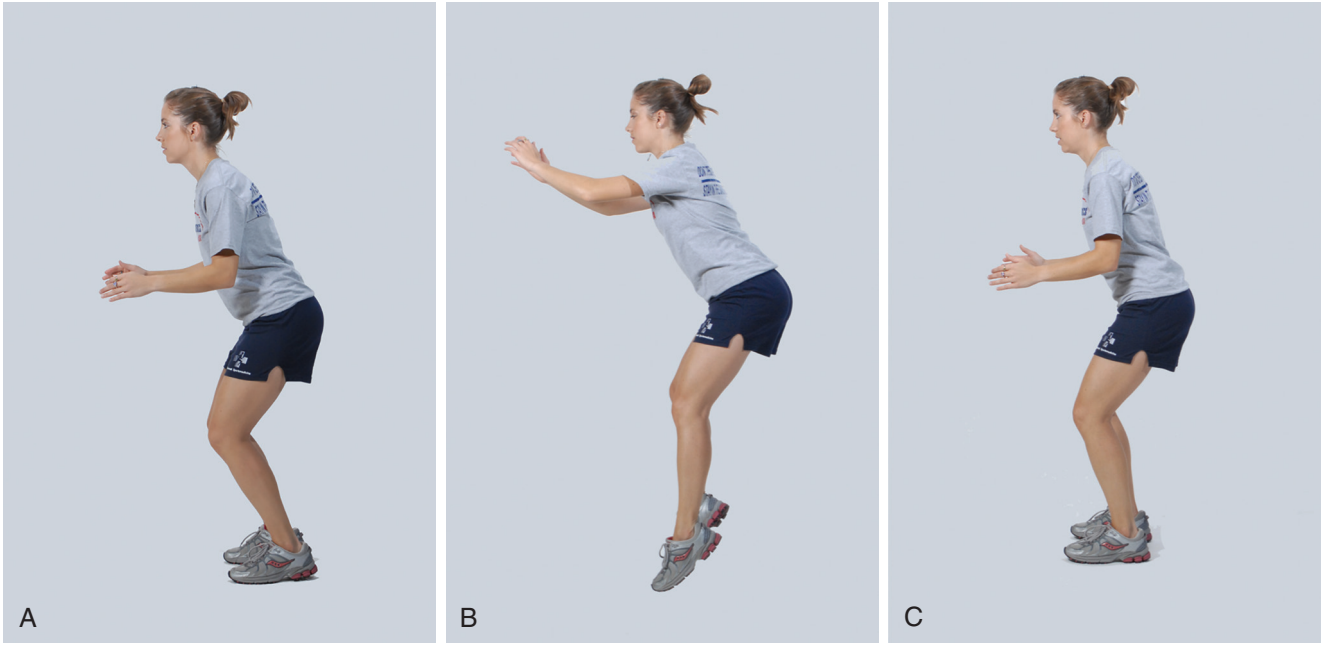


FIG 14-12 Broad jump.

flexed knees; always jump in opposing directions (one jump over the right shoulder, the next over the left); keep the knees tracking under the hips on takeoff and landing; maintain the knees and ankles at shoulder and/or hip width at all times; keep the back straight with the shoulders back; and keep the head and eyes up with each jump.

7. **Broad jump** (weeks 1 and 2). The athlete starts from an upright neutral stance (Fig. 14-12, *A*) and jumps forward as far as possible (see Fig. 14-12, *B*), taking off with both feet. The athlete lands on both feet, remains in a deep crouch position (see Fig. 14-12, *C*) for 5 seconds, and then repeats the jump.

   Mistakes to correct include not holding or sticking the landing, pointing the knees inward during landing and takeoff, and landing in a straight-legged or upright position. The athlete should be told to track the knees over the heels and under the hips on takeoff and landing, land with a soft toe-ball-heel rock with the knees flexed, and hold the landing for 5 seconds.

8. **Bounding in place** (weeks 1 and 2). The athlete begins this jump on a single leg, with the opposite leg bent behind. While the athlete stays in one place, the leg positions are alternated by driving the back leg forward and upward. The rhythm and height are progressively increased throughout the exercise (Fig. 14-13).

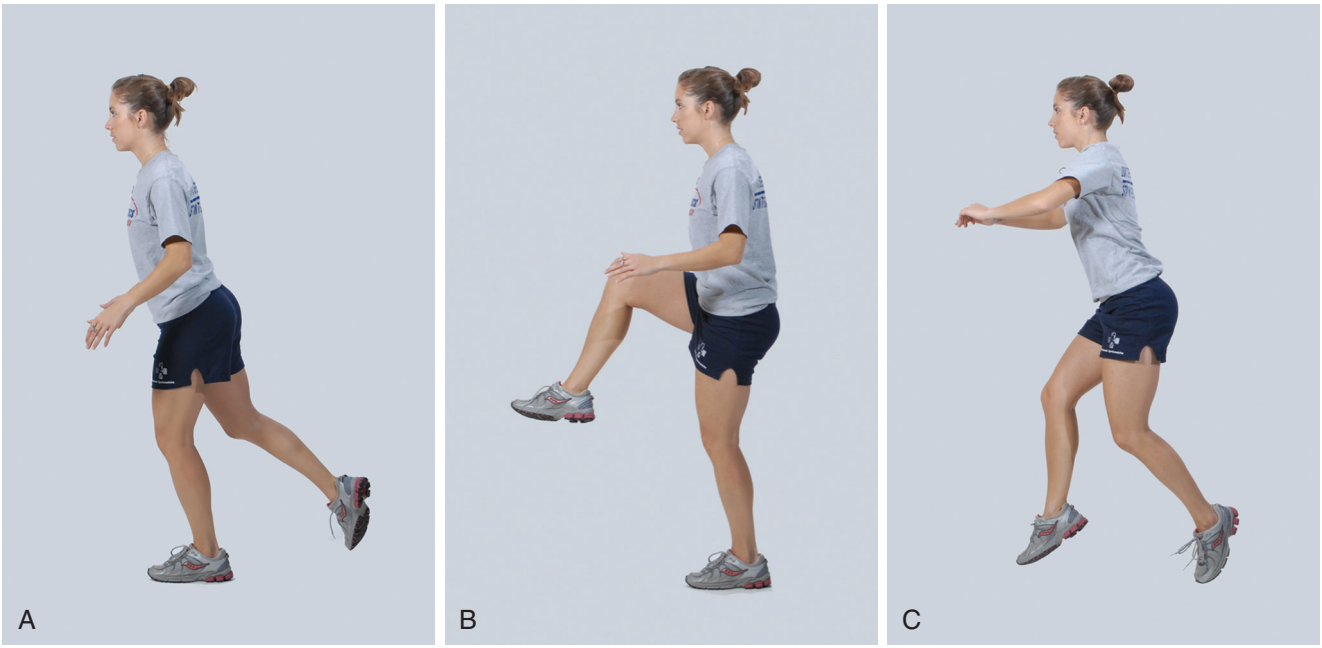


FIG 14-13 Bounding in place.

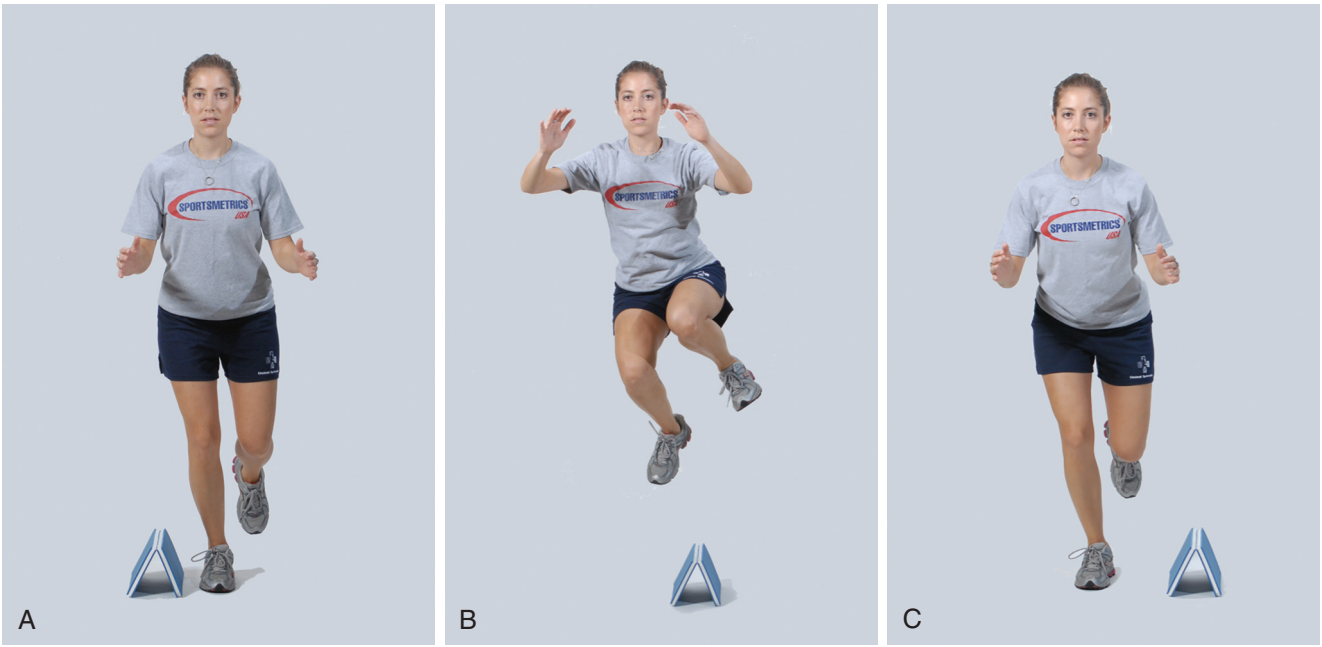


FIG 14-14 Barrier hop side to side.

Mistakes to correct are simply alternating the knees or jogging in place and landing loudly or with wobbly knees. The athlete should be told to use the arms as a countermovement to progress to increasing height and power, drive the knees upward, and land with soft knees and a toe-ball-heel rock landing pattern.

9. **Jump, jump, jump, vertical jump** (weeks 3 and 4). The athlete performs three broad jumps with each takeoff and landing in a deep crouch position. Then, the athlete finishes with a maximum vertical jump and returns to the deep crouch position and holds the position for 5 seconds.

   Mistakes to correct include pointing the knees inward during landing and takeoff and carrying the body forward rather than upward on the vertical jump. The athlete should be told to keep the knees over the heels and under the hips on takeoff and landing, land with the toe-ball-heel rock with the knees flexed, and go straight up on the vertical jump.

10. **Barrier hop side to side** (weeks 3 and 4). Using the same cone or barrier from phase 1, the athlete performs a single-leg hop rather than a double-leg jump side to side over the barrier (Fig. 14-14).

    Mistakes to correct are landing or taking off with stiff, straight, or wobbly knees; hopping side to side quickly without bringing the entire body over the barrier; and double-bouncing on landing. The athlete should be told to bend the knee to clear the barrier; land quietly on the ball of the foot and rock back to the heel; control the landing to be able to immediately take

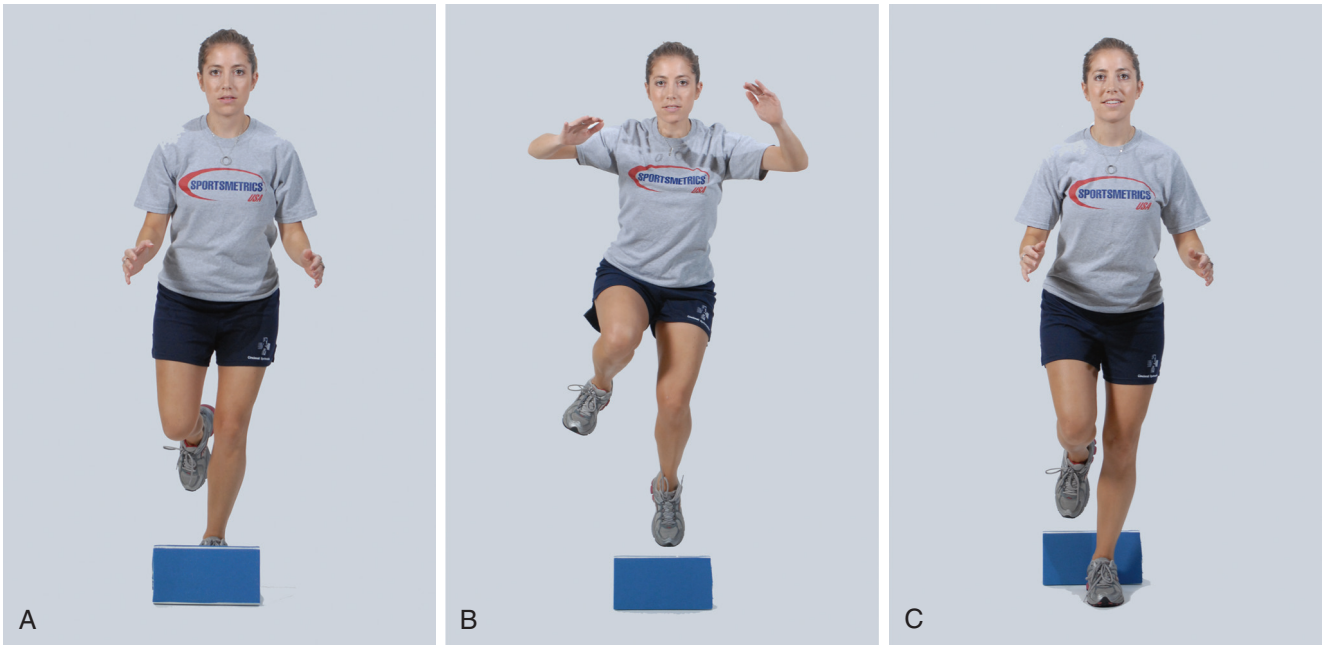


FIG 14-15 Barrier hop forward and backward.

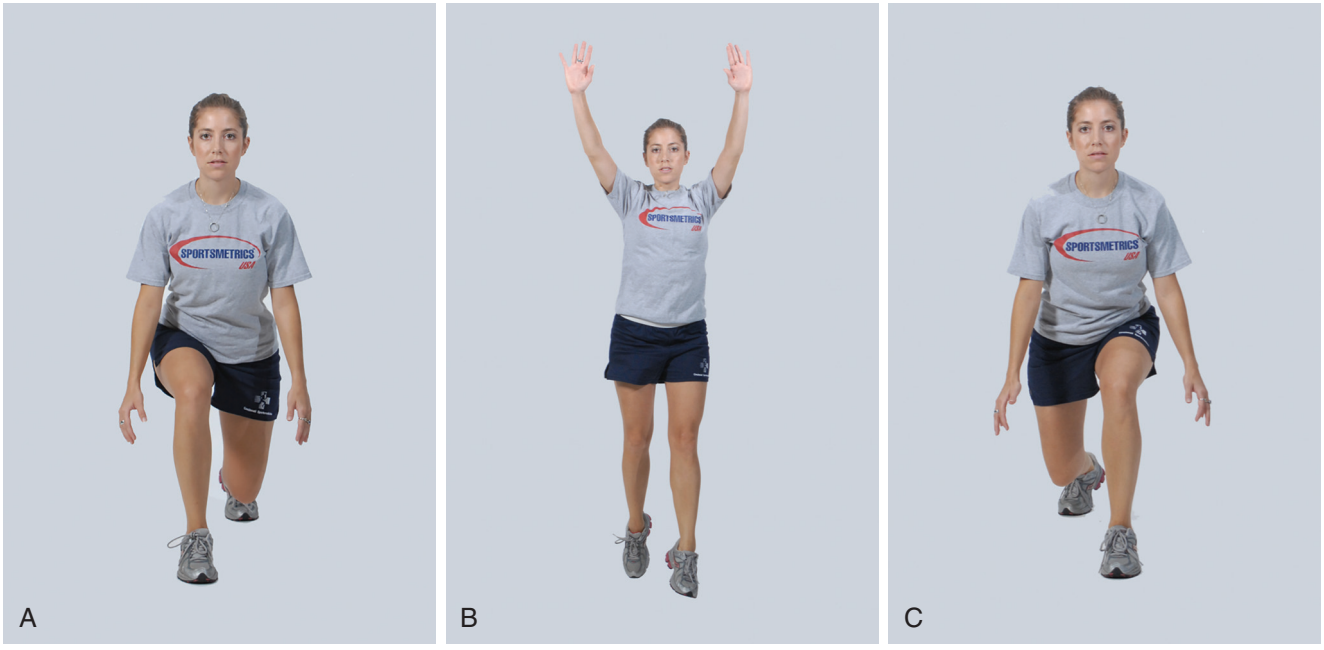


FIG 14-16 Scissors jump.

off again; keep the back straight, shoulders back, and head and eyes up with each hop; keep the knee tracking under the hips; and keep the toes pointed forward on takeoff and landing.

11. **Barrier hop forward and backward** (weeks 3 and 4). Using the same cone or barrier from phase 1, the athlete performs a single-leg hop rather than a double-leg jump forward and backward over the barrier (Fig. 14-15).

    Mistakes to correct are landing or taking off with stiff, straight, or wobbly knees; hopping forward and backward quickly without bringing the entire body over the barrier; and double-bouncing on landing. The athlete should be told to bend the knee to clear the barrier; land quietly on the ball of the foot and rock back to the heel; control the landing to be able to immediately take off again; keep the back straight, shoulders back, and head and eyes up with each hop; keep the knee tracking under the hips; and keep the toes pointed forward on takeoff and landing.

12. **Scissors jump** (weeks 3 and 4). The athlete begins in a long lunge position with the front knee bent directly over the ankle (Fig. 14-16, *A*). The athlete pushes off the front leg, jumps straight up in the air (see Fig. 14-16, *B*), lands with the opposite leg bent in front (see Fig. 14-16, *C*), and then alternates legs.

    Mistakes to correct are landing with wobbly knees or knees extended past the front ankle, jumping up to alternate legs with minimal height, not switching legs directly under the body, simply switching legs without power, landing loudly, landing with a straight or stiff leg, landing with staggered feet, or

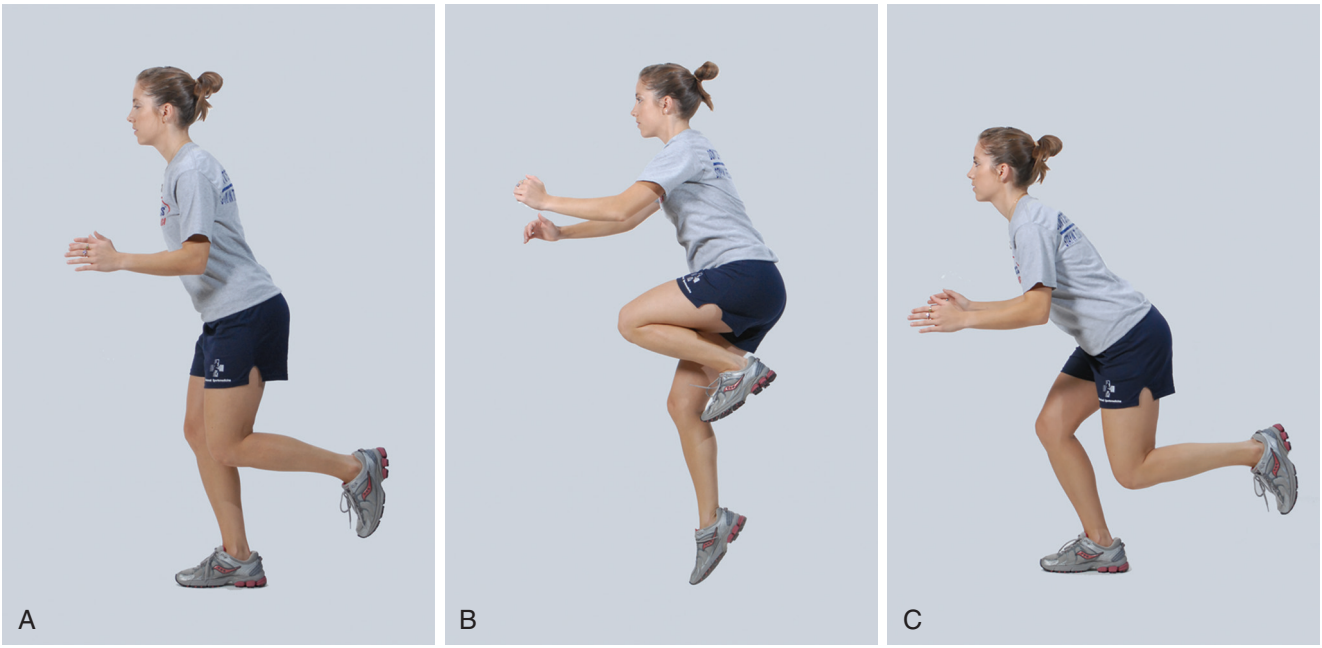


FIG 14-17 Single-leg hop.

landing with one foot before the other. The athlete should be told to push off with power from the front leg, obtain maximum height on the leg switch, land in control with the legs bent and the front knee directly over the ankle, keep the back straight, keep the shoulders back, keep the head and eyes up with each jump, and keep the toes pointed forward with each takeoff and landing.

13. **Single-leg hop** (weeks 3 and 4). This hop is performed just like the broad jump, except the athlete starts and lands on the same leg. The athlete lands in a deep crouched position, which is held for 5 seconds, and then repeats the hop on the opposite leg (Fig. 14-17).
    Mistakes to correct include landing with a wobbly knee, landing upright with the knee straight, and landing in deep knee flexion but standing up immediately. The athlete should be told to keep the knees over the heels and under the hips on takeoff and landing, land with the toe-ball-heel rock and the knees and ankles flexed, and hold the landing for 5 seconds (more important than distance).
14. **Bounding for distance** (weeks 3 and 4). The athlete begins bounding in place and progresses forward, increasing the distance with each step while keeping the knees high.
    Mistakes to correct include performing alternating knee lifts or a high knee jog, landing loudly or with wobbly knees, and keeping the knee low instead of lifting it up. The athlete should be told to use the arms as a countermovement to progress and increase height and power, and also to drive the knee upward and forward.
15. **Jump up, jump down, 180 degrees, vertical** (weeks 5 and 6). This is a double-foot jump onto a 6- to 8-inch box or stacked mat. The athlete lands in a deep crouched position and immediately performs a double-foot jump-down (a depth jump) off the box or mat. The athlete lands again in a deep crouched position and immediately performs a 180-degree jump. Upon landing, the athlete jumps right into a maximum vertical jump, landing once again in the deep crouched position, which is held for 5 seconds.
    Mistakes to correct are landing each jump in an upright straight- or stiff-legged stance or landing with one foot. The athlete should be told to land every jump in a deep crouch with the knees and ankles flexed and to have the feet land at the same time.
16. **Mattress jump side to side** (weeks 5 and 6). The cone or barrier is placed on a cushioned surface approximately 2 to 3 inches deep. The athlete performs a double-foot jump from side to side (Fig. 14-18).
    Mistakes to correct are landing with wobbly knees or knees pointed inward, double-bouncing on landing, landing with the feet staggered, or landing with one foot in front of the other. The athlete should be told to land and take off with both feet together, control the landing to be able to immediately take off back over the barrier, and keep the feet parallel to each other.
17. **Mattress jump forward and backward** (weeks 5 and 6). The cone or barrier is placed on a cushioned surface approximately 2 to 3 inches deep. The athlete performs a double-foot jump forward and backward (**Fig. 14-19**).
    Mistakes to correct include landing with wobbly knees or knees pointed inward, double-bouncing on landing, landing with the feet staggered, or landing with one foot in front of the other. The athlete should be told to land and take off with both feet together, control the landing to be able to immediately take off back over the barrier, and to keep the feet parallel to each other.
18. **Hop, hop, hop, stick** (weeks 5 and 6). The athlete performs three single-leg hops for distance, holding and sticking the final landing for 5 seconds.
    Mistakes to correct include landing with wobbly knees or knees pointed inward, landing upright with poor knee and ankle flexion, and landing in keep knee flexion but immediately standing up. The athlete should be told to keep the knees over the heels and under the hips on takeoff and landing, land with a toe-ball-heel rock and keep the knees flexed, and hold the landing for 5 seconds (more important than distance).

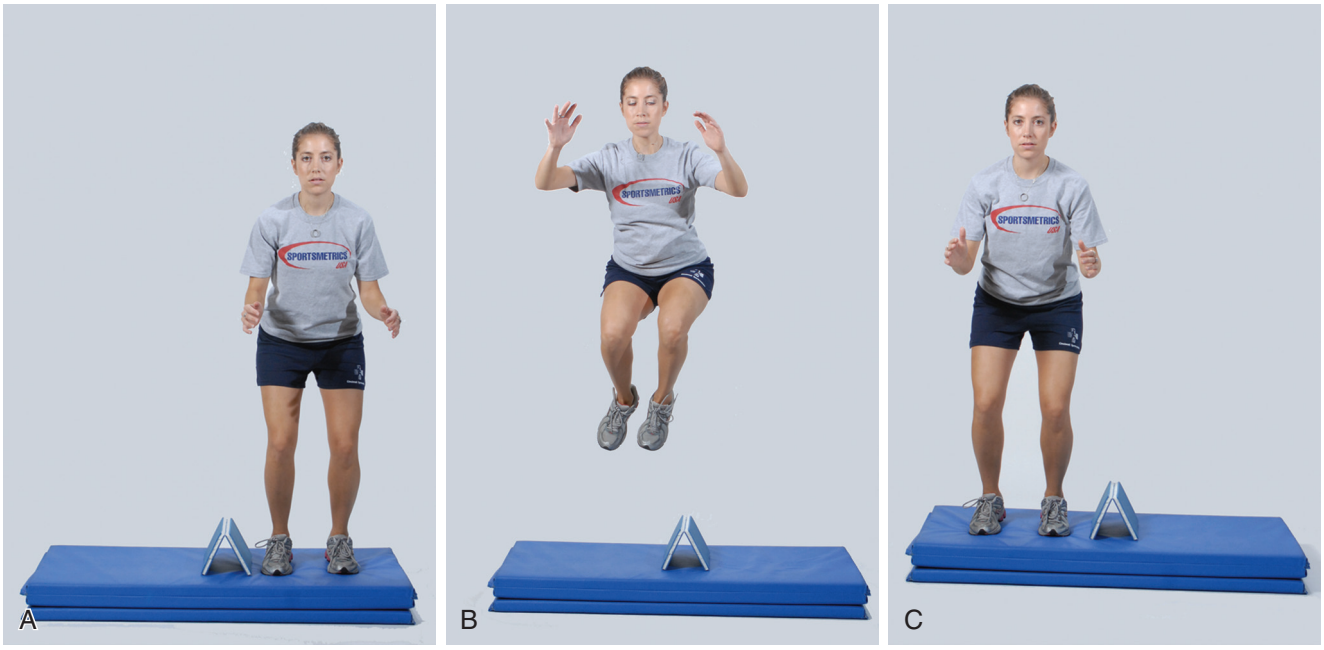


FIG 14-18 Mattress jump side to side.

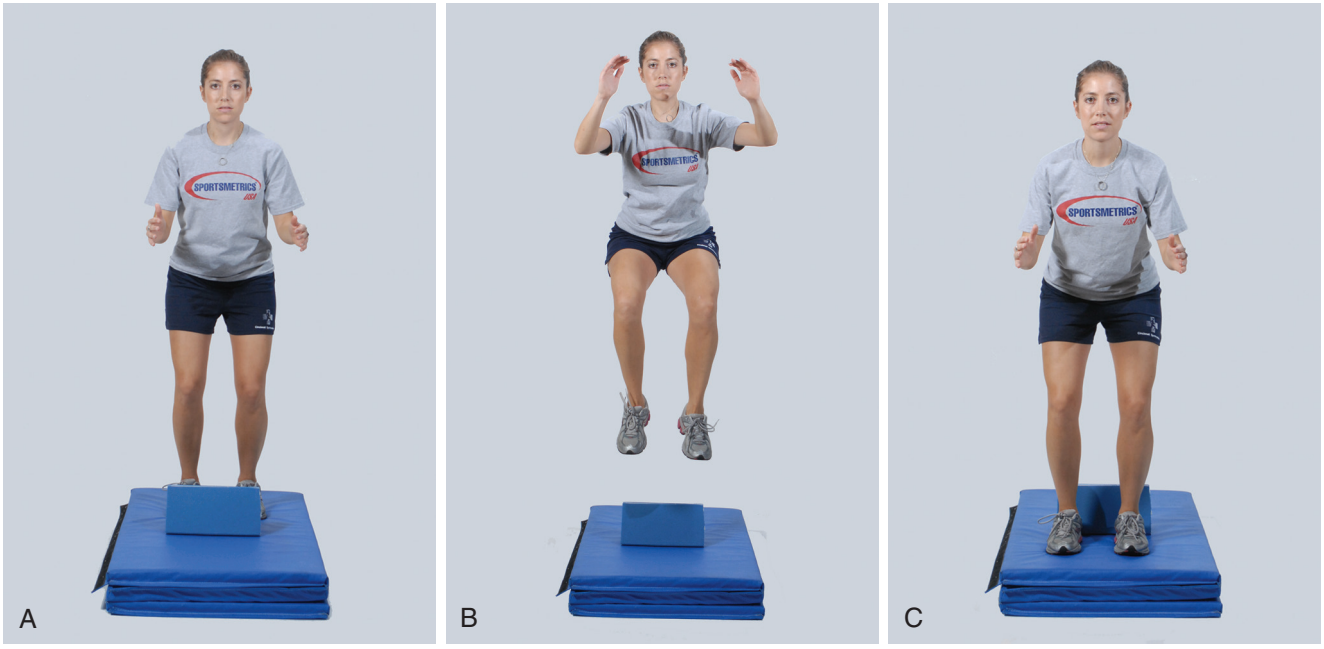


FIG 14-19 Mattress jump forward and backward.

19. **Jump into bounding** (weeks 5 and 6). The athlete jumps forward off both feet, landing on one leg with the other bent behind, and immediately begins bounding for distance.
    Mistakes to correct are performing alternating knee lifts or a simple high-knee jog, landing loudly or with wobbly knees, and keeping the knees low instead of lifting them high. The athlete should be told to land with control off the jump and immediately begin bounding, use the arms as a countermovement to progress and increase height and power, and to drive the knees upward and forward as if going for an approach vertical jump.

Strength Training

A combination of strength-training options is used to focus on the development of core strength and the improvement of overall muscular efficiency. Either isokinetic equipment or free weights may be used by the athlete, based on their availability. The lower extremity muscle groups targeted are the quadriceps, hamstrings, gluteals, and gastrocnemius. The athlete begins with 12 to 15 repetitions for each muscle group. When the athlete can perform 15 repetitions, the amount of weight is increased. The upper body muscle groups include the deltoids, pectorals, triceps, latissimus dorsi and low back, and abdominals.



FIG 14-20 Minisquat with TheraBand.

Ten to twelve repetitions are recommended initially; when the athlete can perform twelve repetitions, the amount of weight is increased. Athletes are encouraged to use 70% of their one-repetition maximum upon initiation of strength training. The overload principle is stressed. For athletes who do not have access to isokinetic equipment or free weights, exercises for strength training using body weight and a resistance band may be used, as described next.

1. **Minisquats with resistance band.** The athlete stands on the center of a strip of a resistance band with the feet shoulder width apart (Fig. 14-20, *A*). While gripping each end of the band, the athlete pulls both hands up to waist level to make the band taut. The athlete squats down into a modified 70-degree bend at the hips and knees, lowering the body against the resistance of the band (Fig. 14-20, *B*). The knees are kept over the ankles. The athlete rises back up, pushing through the heels to the starting position. This exercise is done for 30 seconds during weeks 1 to 3 and for 60 seconds during weeks 4 to 6.
   Mistakes to correct are body weight and/or knees shifting forward, slouched posture, and maintaining too much slack in the band. The athlete should be told to wiggle the toes throughout the movement and to keep the back straight, the head up, and the knees centered over the ankles.
2. **Walking lunges forward.** This exercise is similar to the lunges performed during the dynamic warmup, but a larger range of motion and slower movements are used. While keeping the entire body facing forward, the athlete steps out with one leg as far as possible. Bending the knees, the athlete lowers the back leg toward the ground, stopping just before the knee touches the ground. The front knee should stay directly over the ankle. The athlete lifts the body up to standing position by initiating the lift-up with the front leg. The back leg is brought alongside the front leg, followed by a pause, and then repeating with the opposite leg. This exercise is done for 30 seconds during weeks 1 to 3 and for 60 seconds in weeks 4 to 6.
   Mistakes to correct are bending the knee past the front toe, wobbly knees or lack of upper body control, moving fast, and pushing off from the back leg for leverage. The athlete should be told to maintain an upright posture, lift with the gluteal and quadriceps muscles on the front leg, and move slowly and deliberately.
3. **Prone hamstrings with partner resistance.** The athlete lies flat on the stomach, tightening the abdominal and gluteal muscles to press the hips into the floor. A partner places even, downward pressure on the lower calf as the athlete resists, bending at the knee so the heel comes toward the gluteal muscles without raising the hips off the floor. The athlete continues to bend and straighten the leg with control as the partner applies even, downward pressure. This exercise is repeated on each leg for 30 seconds during weeks 1 to 3 and for 60 seconds during weeks 4 to 6.
   Mistakes to correct include lifting the upper body, lifting the working hip off the ground, and the partner not resisting to create eccentric contractions. The athlete should be told to keep the hips pressed into the ground, keep the upper body relaxed, and move the leg through the full range of motion.
4. **Supine hamstring bridge.** While lying flat on the back, the athlete bends one knee and places the heel of the foot as close to the gluteus maximus as possible. The other leg is extended straight up into the air (Fig. 14-21, *A*). Pushing through the heel that is on the ground, the athlete performs small lifts, raising the gluteus maximus off the ground and taking the extended leg higher in the air with each push (see Fig. 14-21, *B*). The abdominals should be tight and the upper back in neutral position. The arms should be relaxed above the head. This exercise is repeated on each leg for 30 seconds during phase 1.
   Mistakes to correct include simply swinging the leg in the air back and forth, not raising the gluteus maximus off the ground into a bridge position, bending the leg in the air, pushing up through the toe instead of the heel, and holding the body up off the ground with the arms or hands. The athlete should be told to press the heel into the ground, keep the abdominal muscles tight and the lower back in neutral position, lift the leg straight up in the air and push the foot up toward the ceiling, keep the heel close to the gluteus maximus, and raise and lower the leg slowly and under control.

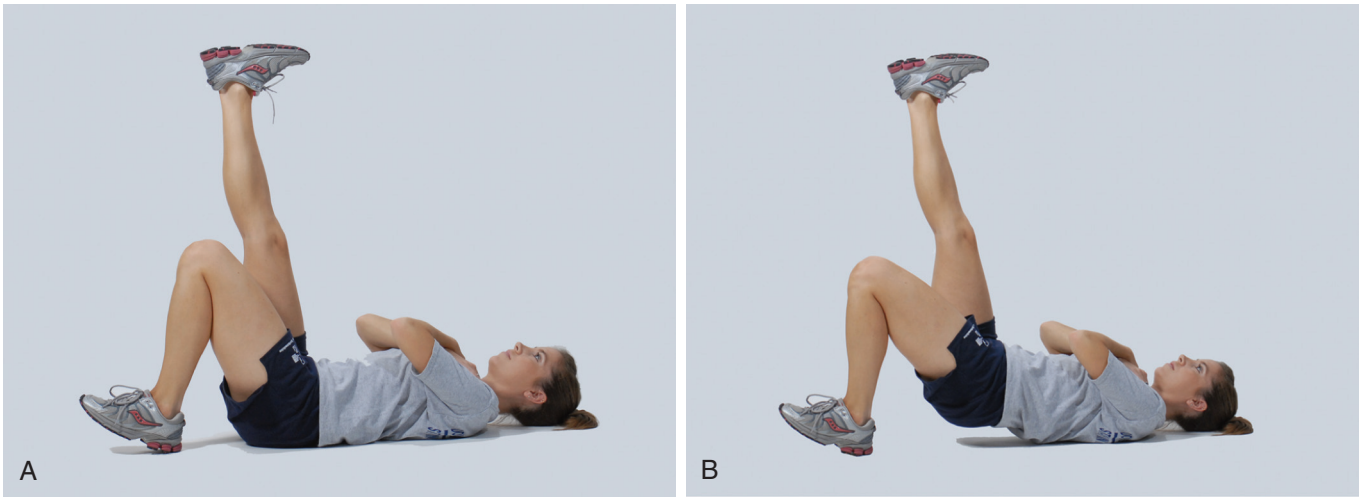


FIG 14-21 Supine hamstring bridge.



FIG 14-22 Arm swing with TheraBand.

5. **Bridge with alternating-leg hamstring glide.** This exercise is similar to the supine hamstring bridge; however, instead of extending one leg directly up from the hip, the athlete places both heels as close as possible to the gluteus maximus. The athlete slides one leg to nearly full extension, keeping the heel on the ground. The leg is returned to the starting position and repeated. This exercise is repeated on each leg for 30 seconds in phase 2.
   Mistakes to correct are not lifting and holding the hips off the ground, not moving the leg through the full range of motion, and locking the knee. The athlete should be told to relax the shoulders and keep the head on the ground, move in a slow and controlled pattern, and keep the abdominals tight.
6. **Bridge with double-leg hamstring glide.** This exercise is similar to the alternating-leg hamstring glide. The athlete begins with both heels as close to the gluteus maximus as possible. Both legs are slid to nearly full extension and then back up to the starting position. This exercise is repeated for 30 seconds in phase 3.
   Mistakes to correct include not lifting and holding the hips off the ground, not moving the legs to nearly full extension, and locking the knee. The athlete should be told to relax the shoulders and keep the head on the ground, move in a slow and controlled pattern, and keep the abdominals tight.
7. **Arm swing with resistance band.** The athlete stands on the center of a strip of a resistance band with the feet shoulder width apart. While gripping each end of the band, the athlete pulls it up to waist level so the band is taut and the elbows are at a 90-degree angle (Fig. 14-22, *A*). The arms are kept at a 90-degree angle (see Fig. 14-22, *B*) while alternatively swung from the hip to the ear, mimicking a running pattern (see Fig. 14-22, *C*). This exercise is done for 30 seconds during weeks 1 to 3 and for 60 seconds during weeks 4 to 6.

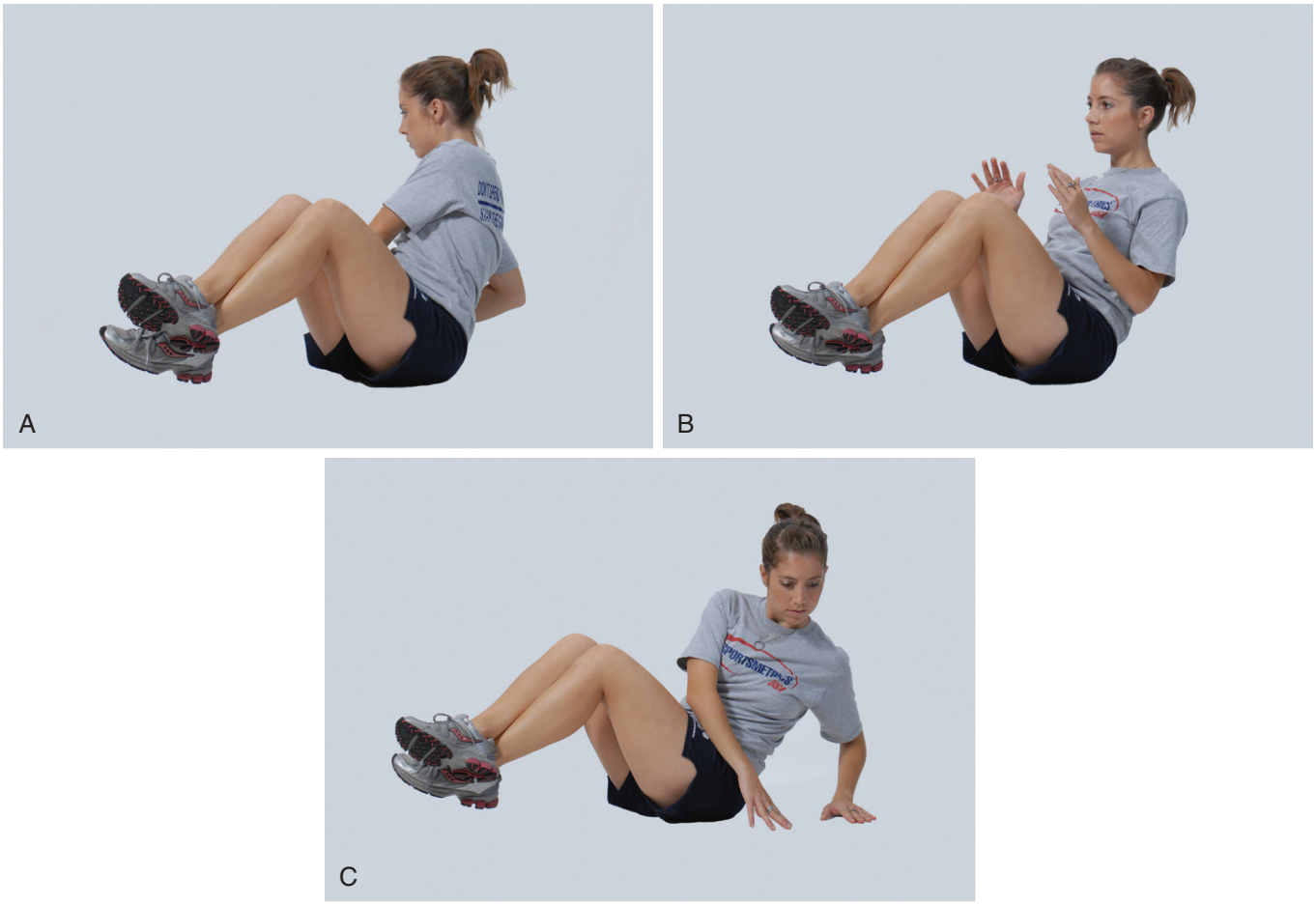


FIG 14-23 Abdominals (Russian twists).

Mistakes to correct include not keeping the arms at a 90-degree angle through the full range of motion, locking the knees, and twisting the torso. The athlete should be told to keep the head up and shoulders back, maintain an upright, neutral spine; and keep the abdominals tight.

8. **Superman (alternating arms and legs).** The athlete lies face down and places the forehead on top of the back of one hand. The other arm is extended out on the ground. The abdominal muscles are tightened, and the upper body is raised to lift the extended arm. At the same time, from the hip and gluteals, the leg opposite the extended arm is raised. The toes and fingers on the lifted leg and arm are extended. The abdominals remained tightened. This exercise is done for 30 seconds during weeks 1 to 3 and for 60 seconds during weeks 4 to 6.
   Mistakes to correct are lifting the head up, overly arching the back, and lifting the leg to the side. The athlete should be told to keep the spine as neutral as possible, focusing the eyes on the mat and/or ground directly below; lift from the trunk; lift the leg and arm only to the point of tension in the lower back; and keep the abdominals tight.
9. **Abdominals (Russian twists).** The athlete lies on the ground, bends the knees, and places the heels on the floor. The athlete bends at the hips, not at the waist, to bring the upper body to a 45-degree angle and holds this position. Moving the trunk as a unit, the athlete rotates the upper body side to side, allowing the hands to touch the ground next to the hip with each rotation (Fig. 14-23). This exercise is done 1 day each week for 30 seconds in phase 1, 60 seconds in phase 2, and 90 seconds in phase 3.
   Mistakes to correct are slouched posture, rounded shoulders, and twisting only the shoulders and not the torso. The athlete should be told to keep the back straight and shoulders relaxed, keep the upper body at a 45-degree angle, and move the trunk as a unit, making sure that both hands are touching the ground with each rotation.
10. **Abdominals (plank).** The athlete lies face down and places the elbows under the shoulders with the forearms on the floor (Fig. 14-24, *A*). The legs are placed hip distance apart, and the toes are curled under. The athlete lifts the body up onto the elbows and toes (Fig. 14-24, *B*). A neutral posture is maintained. The position is held with tight abdominals. This exercise is done 1 day each week for 30 seconds in phase 1, 60 seconds in phase 2, and 90 seconds in phase 3.
    Mistakes to correct include maintaining a slouched or arched midsection, placing the head down with the chin resting on the chest, and keeping the elbows and/or toes too close together. The athlete should be told to maintain a neutral posture, keep the neck and shoulders relaxed, keep the body in a straight line parallel to the ground, maintain the head in a neutral position, and keep the abdominals tight at all times.
11. **Abdominals (bicycle kicks).** The athlete lies on the back with the knees bent into the chest, placing the fingertips on the back of the head. The upper body is raised off the ground until the shoulders

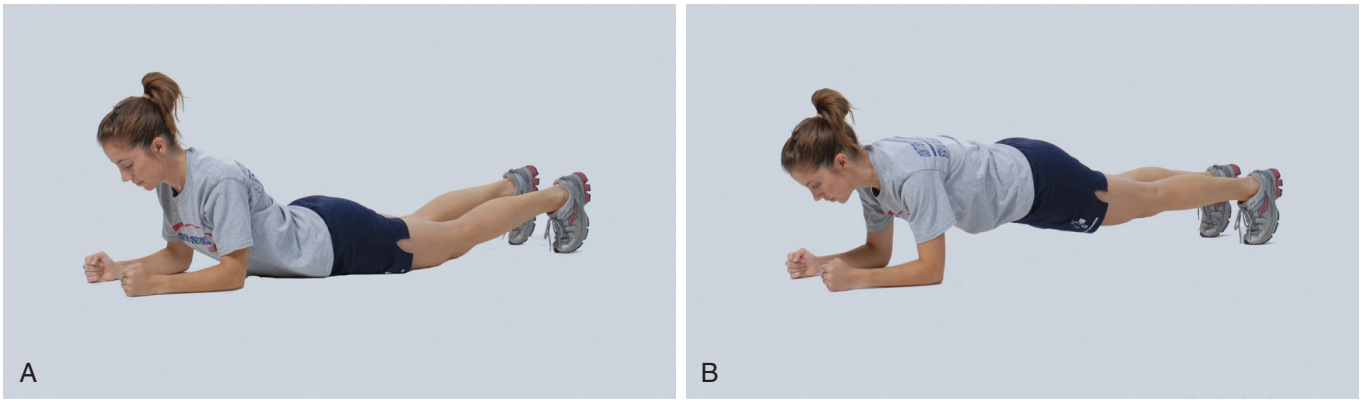


FIG 14-24 Abdominals (plank).

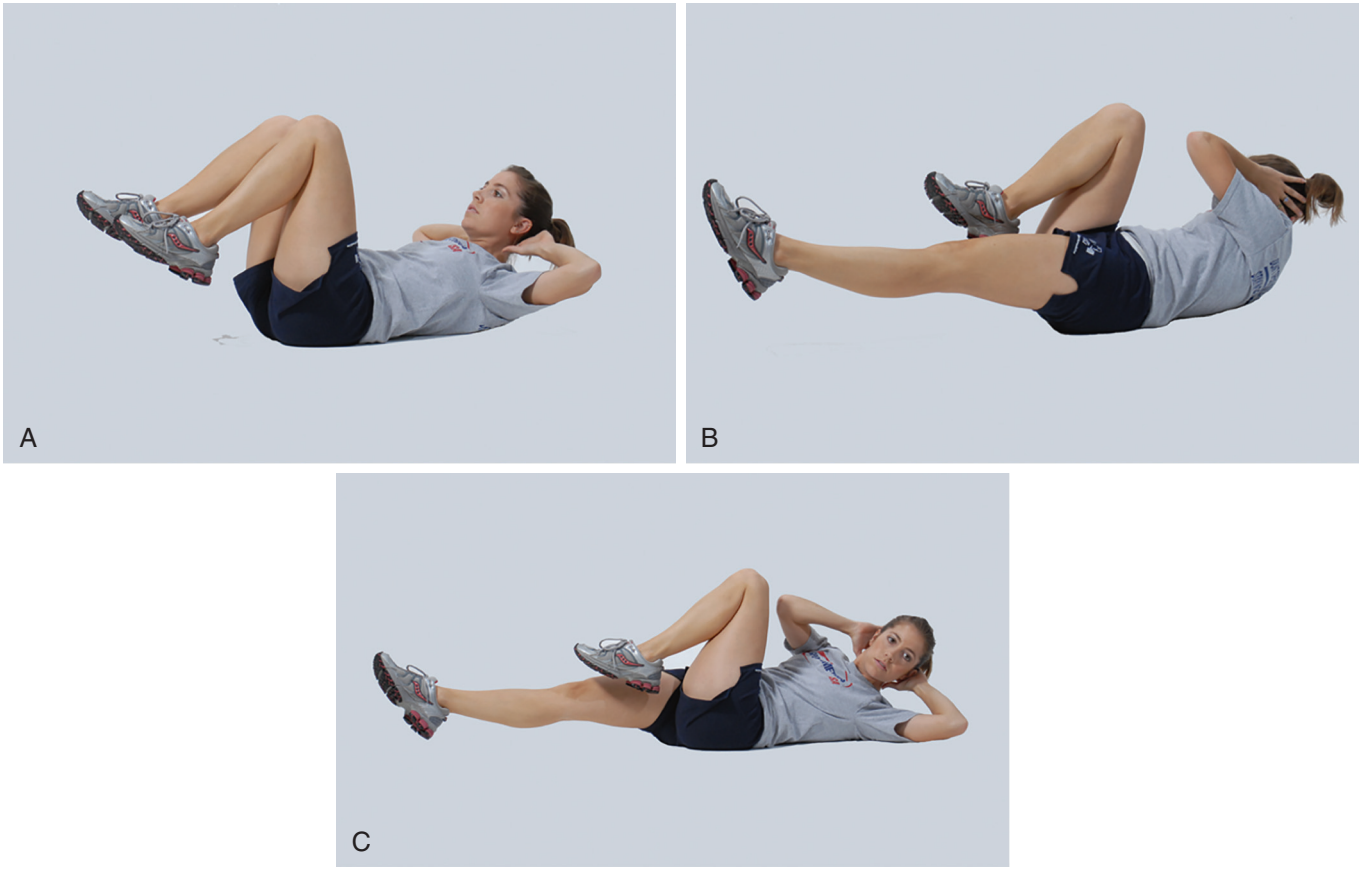


FIG 14-25 Abdominals (bicycle kicks).

no longer touch the ground, and then this position is held. The legs are moved in a cyclic motion, with the heels brought into the gluteus maximus and the legs extended out as close to the floor as possible (Fig. 14-25). This exercise is performed 1 day each week for 30 seconds in phase 1, 60 seconds in phase 2, and 90 seconds in phase 3.

Mistakes to correct include not keeping the upper body off the ground, rotating the upper body, and cycling the legs close to the body. The athlete should be told to keep the chest open and lift from the waist, keep the elbows open and upper body stationary, and fully bend and straighten the legs close to the ground.

12. **Hip flexor resistance band kicking.** The athlete places one end of a piece of a resistance band around the ankle, with the other end around the ankle of a partner or anchored to a stationary object. With the back faced to the partner or stationary object, the athlete steps forward to produce moderate tension in the band while the leg with the resistance band around it is in approximately 15 degrees of hip extension (Fig. 14-26, *A*). Then, the athlete drives the knee that is in back up and forward with maximal effort against the resistance of the band until the thigh is parallel to the ground (see Fig. 14-26, *B*). The leg is returned to a slightly extended position after each exertion. This exercise consists of 2 sets of 10 repetitions, with 30 seconds of rest between each set. A third set

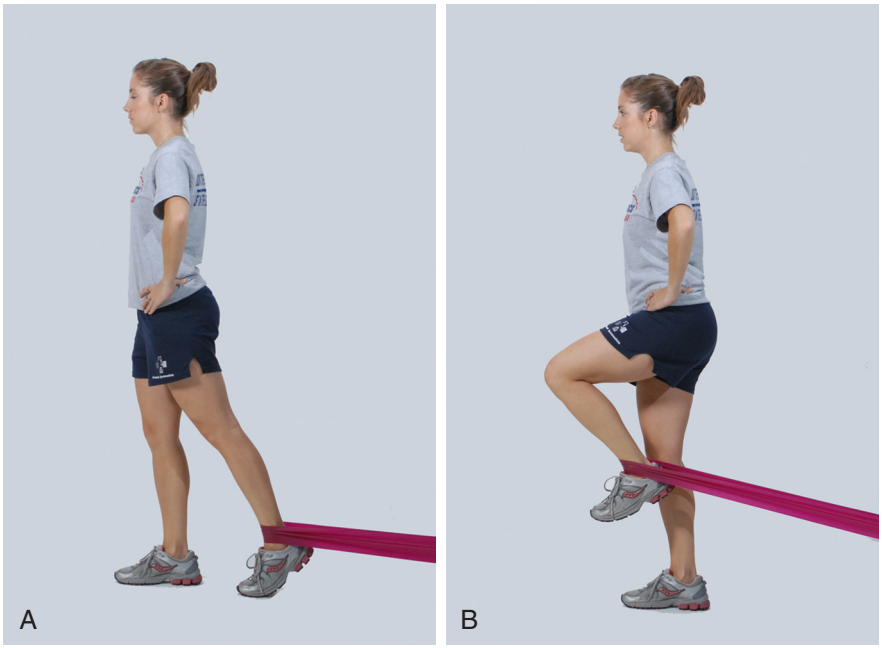


FIG 14-26 Hip flexor TheraBand kicking.

is performed of 20 repetitions in phase 1, 30 repetitions in phase 2, and 40 repetitions in phase 3.

Mistakes to correct include swinging the leg up and back, hiking the hip, and moving the torso. The athlete should be told to keep head and neck straight, look straight down, keep the shoulders and hips square, keep the upper body stationary, and always return the working leg to a slightly extended position before kicking forward again.

13. **Steamboats (hip flexion).** The athlete places a resistance band around the thighs, halfway between the hips and the knees. The exercise is begun with the feet shoulder width apart and one knee bent slightly so that the foot is off the ground. The athlete balances on the one leg that is on the ground and begins kicking forward and backward with the bent leg at the hip. The upper body is kept still and does not sway. This exercise is done for 30 seconds on each leg during weeks 1 to 3 and for 60 seconds during weeks 4 to 6. It may replace hip flexor TheraBand kicking.

    Mistakes to correct include flexing or extending at the knee, simply bending and straightening the knee and not moving at the hip, swaying the upper body back and forth with kicking movements, and not kicking forward or backward far enough to feel resistance of the band. The athlete should be told to keep the back straight, the shoulders back, and the head and eyes up; maintain a slight bend in both knees at all times; keep the upper body stationary; kick the leg back and forth through full range of motion; keep the hips level at all times; and not to hike the hip with motion.

14. **Hip abductor resistance band kicking.** The athlete places one end of a piece of a resistance band around the ankle and the other end around the ankle of a partner or anchored to a stationary object. The athlete stands in line with the partner or stationary object so that the leg with the resistance is farthest away from the partner or object (Fig. 14-27, *A*). The athlete steps sideways to produce moderate tension in the band, kicks the outside leg out sideways against the resistance of the band (see Fig. 14-27, *B*), and returns to the starting position. This exercise consists of 2 sets of 10 repetitions, with 30 seconds of rest between sets. A third set is performed of 20 repetitions in phase 1, 30 repetitions in phase 2, and 40 repetitions in phase 3. This activity is performed 2 days per week.

    Mistakes to correct are swinging the leg out and back without control and leaning the upper body to the side while kicking. The athlete should be told to keep the head and neck straight, look straight ahead, keep shoulders and hips square, keep the upper body stationary, and keep movements slow and controlled.

15. **Lateral walking with resistance band.** The athlete places a resistance band around the thighs, halfway between the hips and knees. The exercise is begun with the feet shoulder width apart. The athlete steps out to the side approximately 2 to 3 feet. Slowly and under control, the athlete follows with the other foot to regain the feet shoulder width apart position. Once finished, the athlete reverses direction so that the opposite foot leads the exercise. This exercise is done for 30 seconds during weeks 1 to 3 and for 60 seconds during weeks 4 to 6. It may replace hip abduction resistance band kicking.

    Mistakes to correct include allowing the feet to come together between steps, allowing the leg that follows to snap back to the starting position, walking with the knees locked in the straight position, bending forward at the waist, rounding the shoulders, and looking down at the feet and ground. The athlete should be told to keep the back straight, the shoulders back, and the head and eyes up; keep the steps to a distance that allows for leg control throughout the activity; keep motion slow and under control at all times; and to make sure that all motion is coming from the hips and legs.

Flexibility

Passive stretching is done at the conclusion of training, with each stretch held for 20 to 30 seconds and repeated twice on each side. Stretching is considered essential to achieving maximum muscle length to allow muscles to work with power through a complete range of

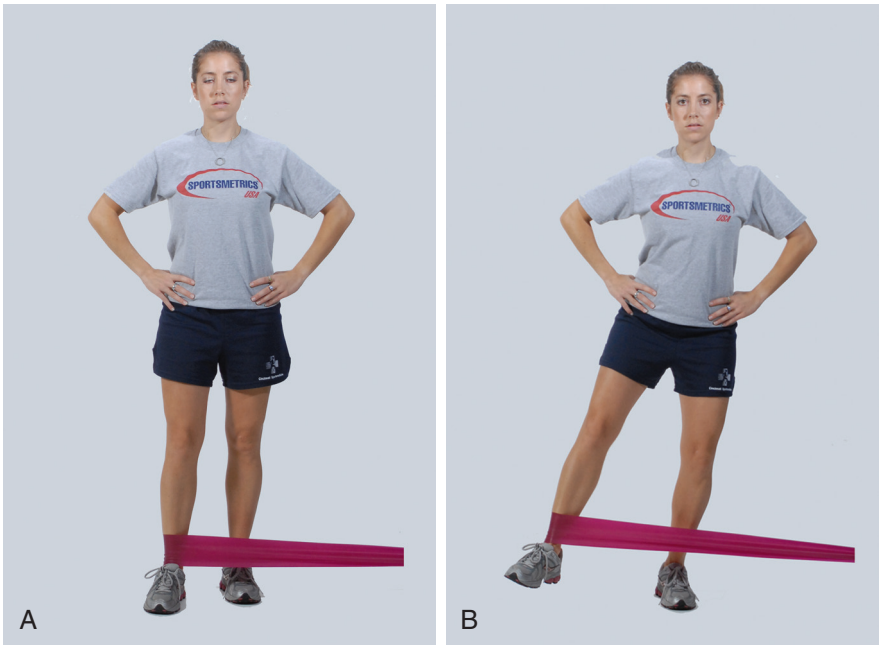


FIG 14-27 Hip abductor TheraBand kicking.

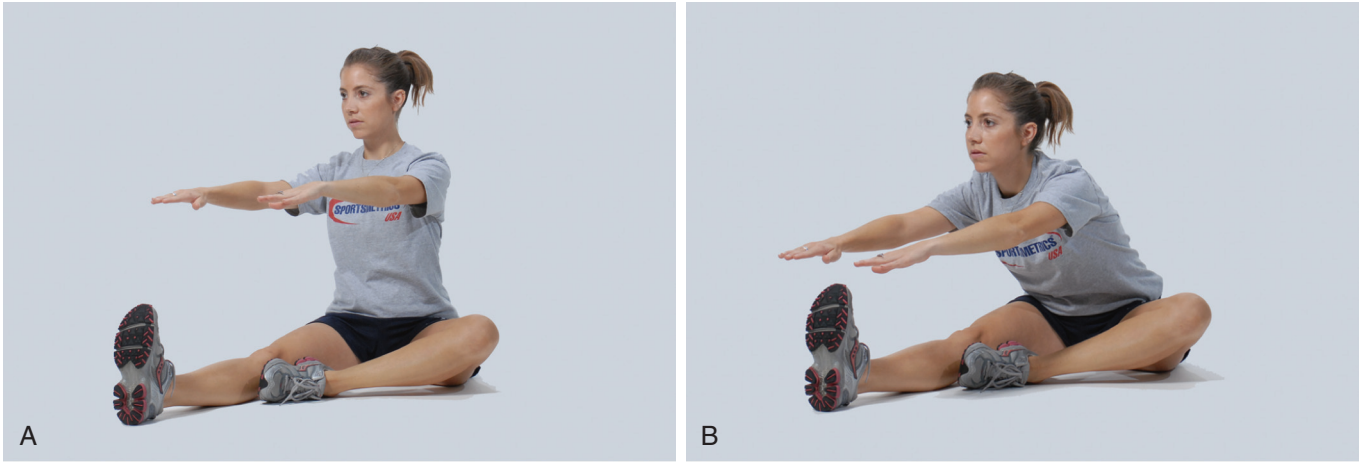


FIG 14-28 Hamstrings stretch.

motion. The major muscle groups targeted are the hamstrings, iliotibial band, quadriceps, hip flexor, gastrocnemius, soleus, deltoid, triceps, biceps, pectoralis, and latissimus dorsi.

1. **Hamstrings.** While seated, the athlete extends the right leg fully and bends the left leg, placing the inside of the foot along the left calf (Fig. 14-28, *A*). The back is kept straight, and the chest is brought toward the knee. The athlete reaches with both hands toward the toes (see Fig. 14-28, *B*). The hands are either placed on the floor alongside the legs or held on the toes.
   Mistakes to correct are rounding the shoulders when leaning into a stretch, bringing the chin into the chest when stretching, allowing the knee of the leg on the ground to bend, and bouncing into the stretch. The athlete should be told to keep the back straight when leaning forward into the stretch, bend forward at the waist, and keep the shoulders back and head up for the duration of the stretch.
2. **Iliotibial band.** While seated, the athlete bends the right knee and places the right foot flat on the floor. The left foot and ankle are placed on the right thigh just above the knee. Both hands are placed on the floor behind the hips, and the chest is pressed toward the knee and foot. The upper torso, neck, and shoulders remain neutral and open, and the upper back is not rounded (Fig. 14-29). This stretch may be performed while lying on the back to support the spine and neck.
3. **Quadriceps.** While standing, the athlete grabs the foot or ankle and lifts it up behind the body. The lower leg and foot are gently pulled up, directly behind the upper leg, with no twisting inward or outward (Fig. 14-30). The stretch is held for 20 seconds, released, and repeated.
   Mistakes to correct include allowing the foot to rest on the buttocks, pulling the leg and/or foot inward or outward, and locking the knee of the leg being used for balance. The athlete should be told to pull straight up on the foot and leg and to keep the back straight, shoulders back, and head and eyes up.
4. **Hip flexor.** The athlete stands with the feet in a lunge position and the front knee slightly bent. The athlete pushes up on the rear toe.

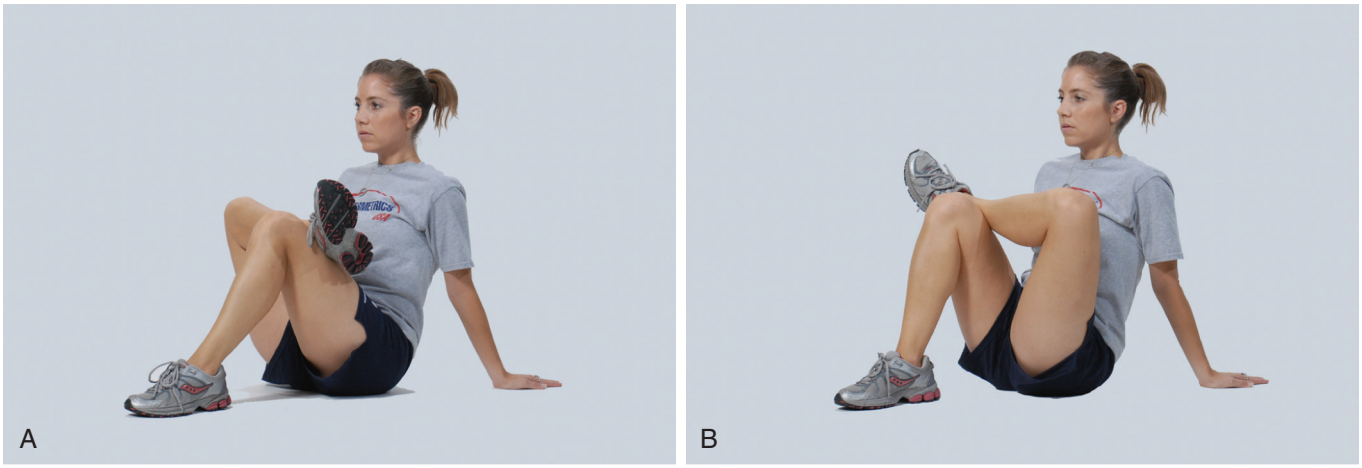


FIG 14-29 Iliotibial band stretch.



FIG 14-30 Quadriceps stretch.

The hips are pressed forward while the buttocks are tightened until a stretch is felt in the front of the hip. The upper torso remains upright and centered directly over the hips (Fig. 14-31).

Mistakes to correct include leaning the upper body forward, not pressing the hips forward, and bouncing into the stretch. The athlete should be told to keep the upper body upright and centered directly over the hips, press or rock the hips forward to initiate the stretch, and keep the back straight, shoulders back, and head and eyes up.

5. **Gastrocnemius.** The athlete stands in a long lunge position with the front knee slightly bent, but not extended past the ankle. The hands are placed on the front of the thigh, and the body is leaned forward while the back leg is kept straight. The rear heel is pressed down (Fig. 14-32). This stretch may also be done by placing both hands against a wall and leaning forward. The stretch is held for 20 seconds, released, and repeated.

   Mistakes to correct are allowing the back heel to raise off the ground, bouncing into the stretch, allowing the knee of the back leg to bend, and not maintaining upper body posture. The athlete should be told to keep the back straight, the shoulders back, and head and eyes up; keep the back leg straight; and keep the heel on the ground at all times.

6. **Soleus.** The athlete stands with one foot forward and one foot back in a short lunge position. Both knees are bent, and the athlete is instructed to sit the hips down into the back heel, with the majority of the body weight on the back leg (Fig. 14-33). The heel is kept on the floor. This stretch may be performed by placing both hands against a wall for balance.
7. **Deltoid.** While either standing or sitting, the athlete brings the left arm across the body, placing the elbow close to the chest. The palm of the hand faces the rear. The arm is clasped at the elbow and gently pressed into and across the body (Fig. 14-34). Both shoulders stay relaxed and low. The head, neck, and spine all remain neutral.
8. **Triceps, latissimus dorsi.** While either standing or sitting, the athlete extends the right arm above the head. The elbow is bent



FIG 14-31 Hip flexor stretch.



FIG 14-33 Soleus stretch.



FIG 14-32 Gastrocnemius stretch.



FIG 14-34 Deltoid stretch.

behind the head while the palm of the hand is brought toward the center of the upper back. The elbow is grasped with the left hand and gently pressed down and back (Fig. 14-35).

9. **Pectoralis, biceps.** While standing, the athlete clasps the hands behind the back. With the shoulders and neck relaxed, the elbows are extended, the chest opened, and the hands lifted up. The posture should remain upright and neutral and the knees slightly flexed (Fig. 14-36).
10. **Low back.** The athlete kneels on the floor with the hands close to the buttocks. The athlete bends forward with the arms fully extended, reaching out onto the floor. The head is lowered between the arms, with the forehead close to or resting on the floor. The hands are gradually moved out farther from the body without the athlete rising up from the heels (Fig. 14-37).

SPORTSMETRICS TRAINING PROGRAM OPTIONS

Sportsmetrics Warmup for Injury Prevention and Performance

Designed as a maintenance program, WIPP is recommended upon completion of the formal Sportsmetrics training to continue to instill the skills and techniques learned for the athlete's entire sports season. WIPP training is conducted in place of the normal warmup before a practice or game and lasts approximately 20 minutes. The program

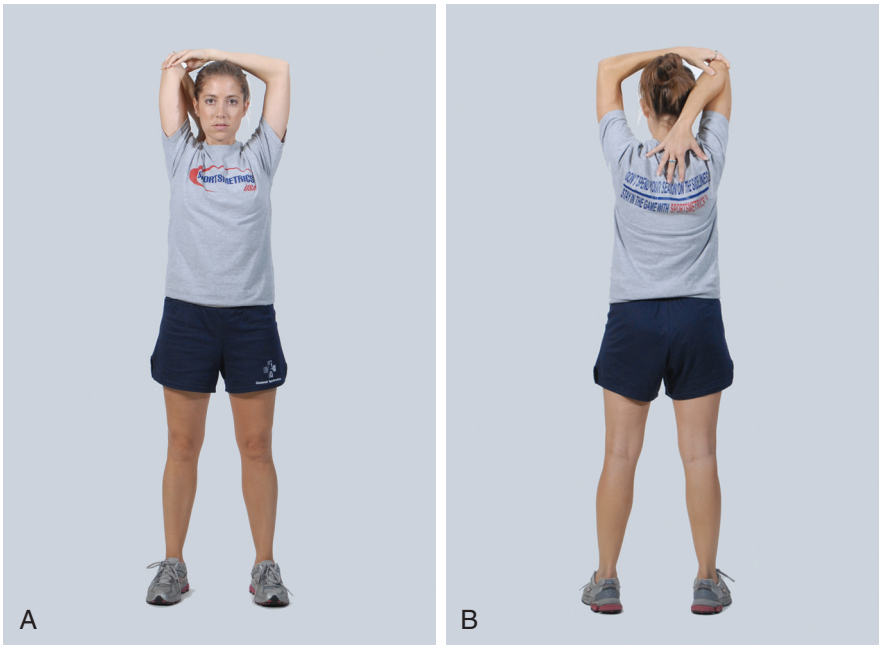


FIG 14-35 Triceps, latissimus dorsi stretch.



FIG 14-36 Pectoralis, biceps stretch.



FIG 14-37 Low back stretch.

integrates select elements from the four basic components of Sportsmetrics and focuses on the essential training concepts of control of the upper body, trunk, and lower body position on landing; increased hip and knee flexion angles on landing; and techniques to land softly to decrease ground reaction forces (Table 14-3).

Sportsmetrics Soccer, Sportsmetrics Basketball, Sportsmetrics Volleyball, Sportsmetrics Tennis

One common problem with the implementation of ACL injury prevention training is that many athletes, parents, and coaches are interested only in performance enhancement programs. In addition, coaches frequently do not want to take time away from practices, either in the preseason or during the season, solely for an injury prevention program. Therefore several sport-specific Sportsmetrics programs were created that include both the essential components of Sportsmetrics and additional exercises and drills designed to improve dynamic balance, agility, speed, strength, and aerobic conditioning. These programs begin with the dynamic warmup and plyometrics previously described. Then, sport-specific agility, speed, and aerobic conditioning exercises are performed, followed by strength and flexibility exercises. Sportsmetrics Soccer,[50] Sportsmetrics Basketball,[49] Sportsmetrics Volleyball,[48] and Sportsmetrics Tennis[3,4] have improved neuromuscular and athletic performance indices and are commonly preferred by coaches and athletes over the standard Sportsmetrics program. For all of these programs, athletes are taught techniques for agility and reaction drills that are believed to reduce the risk of a noncontact ACL injury.[1,6,12,15,38,69,73] These techniques are as follows:

1. Regardless of the direction, the first step should be short. Keep the toes pointed forward.

TABLE 14-3 Sportsmetrics Warmup for Injury Prevention and Performance Training Program

Component	Exercise	Duration (sec)	Comments	Transition Between Exercises (sec)
Dynamic warmup	Straight-leg march	20		5
Dynamic warmup	Hand walk	20		10
Dynamic warmup	Cradle walk	20		5
Dynamic warmup	Hip rotator walk	20		20
Jump training	Tuck jump	30		10
Jump training	Squat jumps	30		10
Jump training	180-degree jump	30		10
Jump training	Scissors jump	30		10
Jump training	Barrier hop side to side	30	15 sec each leg	75
Strength training	Steamboats	60	30 sec each leg	10
Strength training	Lateral step	60	30 sec each direction	40
Strength training	Supine hamstring	60	30 sec each leg	15
Strength training	Abdominal crunch	60		10
Strength training	Modified plank	60		15
Flexibility	Hamstring stretch	40	20 sec each leg	15
Flexibility	Hip flexor stretch	40	20 sec each leg	15
Flexibility	Quadriceps stretch	40	20 sec each leg	25
Flexibility	Calf stretch	40	20 sec each leg	20
Agility	Quick feet	60	30 sec each direction	20
Agility	Nebraska drill	60	30 sec each run	—

2. Maintain control of the body's center of gravity throughout the drill.
3. Keep an erect posture with a stable trunk, and avoid excessive anterior pelvic tilt and rounded shoulders.
4. Keep the head and eyes up, and look straight ahead.
5. Keep the body weight evenly distributed over the balls of the feet.
6. Maintain the same angle of hip, knee, and ankle flexion throughout the drill, including during changes in direction. Knee flexion should be greater than 30 degrees.
7. Avoid a valgus lower limb position.
8. Keep the knees over the ankles, and do not allow them to extend over the toes.
9. During deceleration, use three short steps to reduce speed instead of one step.
10. During a sidestep cut, bring the foot to the midline to plant and keep the torso upright, with no rotation, pointed in the general direction the athlete wishes to travel.[11]
11. Videotape the athlete while she or he perform drills and exercises to show techniques that require correction.
12. Use external focus cues such as cones to teach proper form.

The agility/reaction, acceleration/speed/endurance, additional jumps, and strength training components are shown in Table 14-4 for Sportsmetrics Soccer, in Table 14-5 for Sportsmetrics Basketball, in Table 14-6 for Sportsmetrics Volleyball, and in Table 14-7 for Sportsmetrics Tennis. These components have been described in detail elsewhere.[6] The effectiveness of all of these programs in improving neuromuscular and athletic performance indices has been published previously and is described briefly next. All training was accomplished by certified Sportsmetrics trainers. In addition, in the Sportsmetrics Tennis program, a tennis professional certified by the U.S. Tennis Association (elite level) was also involved.

The effectiveness of the Sportsmetrics Soccer program was tested in two phases.[50] Phase 1 consisted of a group of 62 high school female athletes who underwent the video drop-jump test, the agility *t* test, two vertical jump tests, and a 37-meter sprint test before and after 6 weeks of training. Phase 2 consisted of 62 other athletes who underwent an MSFT before and after training. There were significant improvements in the drop-jump test in the mean absolute millimeters of knee and ankle separation distance, as well as in the normalized knee separation distance (Table 14-8). There were also significant improvements in the agility *t* test, MSFT estimated maximal aerobic power, sprint test, and two-step approach vertical jump test.

Sportsmetrics Basketball was tested in 57 female high school athletes who underwent the video drop-jump test, MSFT, vertical jump test, and an 18-meter sprint test before and after 6 weeks of training.[49] There were significant improvements in the drop-jump test in the mean absolute millimeters of knee separation distance and the normalized knee separation distance, the MSFT, and the vertical jump test (Table 14-9). Improvement was noted in 91% of the subjects in the normalized knee separation distance, in 89% of the subjects in the MSFT, and in 70% of the subjects in the vertical jump test.

Sportsmetrics Volleyball was completed by 34 high school female athletes who underwent the video drop-jump test, the MSFT, the vertical jump test, and a sit-up test before and after training.[48] Significant improvements were found after 6 weeks of training in these athletes in all of the tests (Table 14-10). Improvement was found in 73% of the subjects in the MSFT and in 68% of the subjects in the vertical jump and sit-up tests.

The Sportsmetrics Tennis training program was tested in 42 players (31 females, 11 males; mean age: 14 ± 2 years).[3] Statistically significant improvements were found for all of the tests conducted, shown in Table 14-11. The percentages of the players whose test scores improved were 98% in the one-court suicide, 90% in the abdominal endurance test, 76% in the service line and single-leg hop tests, 69% to 74% in the baseline tests, and 59% to 65% in the single-leg triple-crossover hop test. There were no differences between the sexes regarding the absolute or percentage improvement in any of the tests. A subgroup of 15 players voluntarily participated in more than 1 training program to

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TABLE 14-4 Sportsmetrics Soccer

Component	Sessions	Exercise	Duration
Agility, reaction	1-3	Serpentine run	¼ field, 3 reps
	1-3	Wheel drill: listen to instructor	30 sec, 2 reps
	4-6	Modified shuttle	¼ field, 3 reps
	4-6	Sprint/stop feet: listen	30 sec, 2 reps
	7-9	Square drill	30 ft × 30 ft (9.1 m × 9.1 m) box, 2 reps
	7-9	Sprint/quick feet: listen	45 sec, 2 reps
	10-12	Nebraska drill	30 ft (9.1 m) long, 4 reps
	10-12	Reaction drill: watch instructor point	45 sec, 2 reps
	13-15	Illinois drill	15 ft × 10 ft (4.6 m × 3.0 m), 4 reps
	13-15	Reaction mirror drill, pressing	60 sec, 2 reps
	16-18	Agility *t* test: 5-10-5	4 reps
	16-18	Advanced wheel drill: listen to instructor	60 sec, 2 reps
Acceleration, speed, endurance	1-3	Partner push-offs, hold 5 seconds	5 reps
	1-3	Sprint/backpedal	½ field or 50 yards (45.7 m), 5 reps
	1-3	Jog	4 laps around field (1280 yards, 1170 m)
	4-6	Acceleration with band	Go to 10-yard line (9.1 m)
	4-6	Sprint with ground touches/backpedal	½ field or 50 yards (45.7 m), 5 reps
	4-6	100 yards (91.4 m) shuttle	3 × 100 (300 yards, 274 m), 4 reps
	7-9	Partner push-offs, hold 10 sec	5 reps
	7-9	Half-eagle into sprint, jog back	½ field or 50 yards (45.7 m), 6 reps
	7-9	50-yard (45.7-m) shuttle	Up and back × 3 (300 yards, 274 m), 4 reps
	10-12	Acceleration with band	Go to 20-yard line (18.3 m)
	10-12	Box drill, sprint/90 degrees/backpedal	½ field, 3 reps
	10-12	50-yard (45.7-m) cone drill: 10 yards (9.1 m) and back, 20 yards (18.3 m) and back, 30 yards (27.4 m) and back, 40 yards (36.6 m) and back, 50 yards (45.7 m) and back	4 reps
	13-15	Partner push-offs, hold 15 sec	5 reps
	13-15	Sprint/180 degrees/backpedal	½ field or 50 yards (45.7 m), 7 reps
	13-15	Jingle-jangle, 20 yards (18.3 m)	Up and back × 5 (200 yards, 183 m), 5 reps
	16-18	Acceleration with band	Go to 30 yard (27.4 m) line
	16-18	Sprint/360 degrees/sprint	½ field or 50 yards (45.7 m), 7 reps
	16-18	Jingle-jangle, 10 yards (9.1 m)	Up and back × 5 (100 yards, 91 m), 6 reps
Ladders, quick feet, additional jumps	1-3	Ladder: up-up and back-back	2 reps
	1-3	Dot drill: double-leg jumps	5 reps ×3
	4-6	Ladder: toe touches	2 reps
	4-6	Dot drill: add split-leg jumps	5 reps ×3
	7-9	Ladder: outside foot in	2 reps
	7-9	Dot drill: add 180-degree split-leg jump	5 reps ×3
	10-12	Ladder: in-in, out-out	2 reps
	10-12	Dot drill: add single-leg hops	5 reps ×3
	13-15	Ladder: up-up and back-back	2 reps
	13-15	Dot drill: combination of all jumps	5 reps ×3
	16-18	Ladder: 1 foot forward, 1 foot backward	2 reps
	16-18	Dot drill: combination of all jumps	5 reps ×4
Strength training	1-18	Resistance band: squats	30 sec all exercises: sessions 1-6
		Resistance band: lunges	45 sec all exercises: sessions 7-12
		Single-leg heel raise	60 sec all exercises: sessions 13-18
		Prone hamstring with partner resistance	
		Supine hamstring bridge	
		Abdominals of choice	
		Hip flexion: resistance band knee drive with partner	
		Hip abductor: resistance band kicking with partner	
		Resistance band: arm swing	
		Wall-sits	

Reps, Repetitions.

TABLE 14-5 Sportsmetrics Basketball

Component	Sessions	Exercise	Duration
Agility, reaction	1-3	Shuttle drill	2 reps
	1-3	Maze drill	3 reps
	4-6	Tip drill	3 min
	4-6	Figure-4 drill	2 reps
	7-9	Square drill	2 reps
	7-9	4-dot drill, quarter-eagles	3 reps
	10-12	Defensive slides	45 sec, 3 reps
	10-12	Shoot and sprint	3 reps
	13-15	Tip drill	4 min
	13-15	Irish "D"	4 reps
	16-18	Agility *t* tests: 5-10-5	4 reps
	16-18	Kill the grass drill	2 min
Acceleration, speed, endurance	1-3	Mountain climbers	10 sec, 5 reps
	1-3	Sprint-backpedal	5 reps
	1-3	Suicides	2 reps
	4-6	Mountain climbers	15 sec, 5 reps
	4-6	Sprint-backpedal	7 reps
	4-6	Suicides: forward and backward	2 reps
	7-9	Mountain climbers	20 sec, 5 reps
	7-9	Quarter-eagle sprint-backpedal	5 reps
	7-9	Suicides: defensive slides	2 reps
	10-12	Mountain climbers	25 sec, 5 reps
	10-12	Sprint with ground touches	5 reps
	10-12	Full-court relay	5 reps
	13-15	Mountain climbers	25 sec, 5 reps
	13-15	Sprint/180 degrees/backpedal	5 reps
	13-15	Sprint/quick feet	30 sec, 2 reps
	16-18	Mountain climbers	30 sec, 5 reps
	16-18	Sprint/360 degrees/backpedal	5 reps
	16-18	Power rebounds relay	1 rep
Ladders, quick feet, additional jumps	1-3	Ladder: high knees	4 reps
	1-3	High knee ball toss over barrier	45 sec, 2 reps
	1-3	Dot drill: double-leg jumps	5 reps ×2
	4-6	Ladder: up-up, back-back	4 reps
	4-6	Double high knee with ball toss	2 reps
	4-6	Dot drill: add split-leg jumps	5 reps ×2
	7-9	Ladder: outside foot in	4 reps
	7-9	Bleacher jumps	10 reps each leg ×2
	7-9	Dot drill: add 180 degrees split-leg jump	5 reps ×2
	10-12	Ladder: in-in, out-out	4 reps
	10-12	Instructor pointing	45 sec, 2 reps
	10-12	Dot drills: add single-leg hops	5 reps ×3
	13-15	Ladder: scissors	4 reps
	13-15	Instructor pointing with quick feet up and down	45 sec, 3 reps
	13-15	Dot drill: all jumps	5 reps ×3
	16-18	Ladder: "Ickey shuffle"	4 reps
	16-18	Single-leg squat jumps and 180-degree scissors jumps	20 sec each jump
	16-18	Dot drills: all jumps	5 reps ×3
Strength training, on the court	1-18	Squats with resistance band	30 sec all exercises: sessions 1-6
		Lunges with resistance band	45 sec all exercises: sessions 7-12
		Single-leg heel raises	60 sec all exercises: sessions 13-18
		Prone hamstring: hip extension with knee flexion	Lower extremity done on Monday and Friday
		Supine hamstring bridge	Upper extremity done on Wednesday
		Abdominals of choice	
		Hip flexion: steamboats	
		Hip abductor: lateral walk	
		Arm swing with resistance band	
		Internal rotation with resistance band with partner	
		External rotation with resistance band	
		Biceps curls with resistance band	
		Triceps extension with resistance band	
		Rows with resistance band	
		Pushups	

Reps, Repetitions.

TABLE 14-6 Sportsmetrics Volleyball

Component	Sessions	Exercise	Duration
Agility, reaction	1-3	Volleyball shuttle	3 reps
	4-6	Volleyball tip drill	2 reps
	7-9	Square drill	3 reps
	10-12	Nebraska drill	4 reps
	13-15	Illinois drill	5 reps
	13-15	Shuffle pass with partner	1 set
	16-18	Agility *t* test: 5-10-5	4 reps
	16-18	Shuffle set with partner	1 set
Acceleration, speed, endurance	1-3	Partner push-offs, hold 5 sec	5 reps
	1-3	Sprint, backpedal	5 reps
	4-6	Acceleration sprint with band, hold 5 sec	5 reps
	4-6	Sprint, backpedal	7 reps
	7-9	Mountain climbers	6 reps
	7-9	Quarter-eagle into sprint: listen to instructor	6 reps
	10-12	Partner push-off, hold 5 sec	6 reps
	10-12	Forward sprints with ground touches	5-7 reps
	13-15	Acceleration sprints with band	15 sec, 5 reps
	13-15	Sprint/180 degrees/backpedal	7 reps
	16-18	Mountain climbers	5-7 reps
	16-18	Sprint/360 degrees/backpedal	5-7 reps
Ladders, quick feet, additional jumps	1-3	Ladder: high knees	4-6 reps
	1-3	Wheel drill-listen to instructor	30 sec, 2 reps
	1-3	"Suicides"/volleyball court ×2	2 reps
	1-3	Dot drill: double-leg jumps	5 reps ×3
	4-6	Ladder: up-up/back-back	4-6 reps
	4-6	Sprint/stop feet/listen to instructor	30 sec, 2 reps
	4-6	Suicides/forward/backward, volleyball court ×2	2 reps
	5-7	Dot drill: add split-leg jumps	5 reps ×3
	7-9	Ladder: outside foot in	4-6 reps
	7-9	Sprint/quick feet/listen to instructor	30 sec, 2 reps
	7-9	Suicides/lateral shuffle, volleyball court ×2	2 reps
	7-9	Dot drill: add 180-degree jumps	5 reps ×3
	10-12	Ladder: in-in/out-out	4-6 reps
	10-12	Reaction drill/watch instructor point	45 sec, 2 reps
	10-12	Jingle-jangle	10 yards (9.1 m) up-back, 4-6 reps
	10-12	Dot drill: add single-leg hops	5 reps ×3
	13-15	Ladder: scissors	4-6 reps
	13-15	Reaction mirror drill/partner pressing	45 sec, 1 reps
	13-15	Jingle-jangle	20 yards (18.3 m) up-back, 4-6 reps
	16-18	Ladder: "Ickey shuffle"	4-6 reps
	16-18	Reaction instructor pointing/quick feet + up/down with pushup	45 sec, 2 reps
	16-18	Power rebounds relay	1 set
Strength training, on the court	1-18	Squats with resistance band	30 sec all exercises: sessions 1-6
		Power lunges (pulsating)	45 sec all exercises: sessions 7-12
		Single-leg heel raises	60 sec all exercises: sessions 13-18
		Supine hamstring bridge, single leg	
		Seated scapular retraction	
		Seated latissimus pull with resistance band	
		Seated scapular protraction with resistance band	
		Seated external rotation with resistance band	
		Partner internal rotation with resistance band	
		Abdominals of choice	
		Hip flexor resistance band kicking with partner	
		Steamboats (hip flexion)	
		Hip abductor resistance band kicking with partner	
		Lateral walking with resistance band	

Reps, Repetitions.

TABLE 14-7 Sportsmetrics Tennis

Component	Session no.	Exercise	Duration
Agility, reaction	1-3	Shadow swing baseline: forehand, backhand	2 sets × 10 reps each side
	1-3	Alternating short and deep balls: forehand, backhand	1 set × 10 reps each side
	4-6	Alternating short and deep balls: forehand, backhand	2 sets × 8 reps each side
	4-6	Resistance belt forehand and backhand	1 set × 10 reps each side
	7-9	Alternating short and deep balls: forehand, backhand	2 sets × 8 reps each side
	10-12	Rapid drop feed: forehand, backhand	2 sets × 8 reps each side
	13-15	Forehand, backhand reaction: facing net	2 sets × 8 reps each side
	13-15	Forehand, backhand reaction: facing fence	2 sets × 10 reps each side
	13-15	Rapid return serve feeds: forehand, backhand	2 sets × 8 reps each side
	16-18	Up-up, back-back, sprint to ground stroke, sprint to volley (forehand, backhand)	90 sec each side
Acceleration, speed, endurance	1-3	"Suicides," 1-court	2 reps
	4-6	Net zigzag	2 reps
	4-6	Partner push-offs	5 sec, 5 reps
	7-9	Forehand, backhand wide continuous hitting	8-6-6-8 reps
	7-9	Net zigzag	3 reps
	7-9	Partner push-offs	10 sec, 3 reps
	10-12	Baseline random feed: forehand, backhand	1 min, 2 min
	10-12	Net zigzag	3 reps
	10-12	Sprint/quick feet/listen to instructor	60 sec, 2 reps
	13-15	Suicides, 1-court	2 reps
	13-15	Suicides, 2 courts	1 rep
	13-15	Sprint/quick feet/listen to instructor	60 sec, 3 reps
	16-18	Forehand, backhand wide continuous hitting	6-4-4-6 reps
	16-18	Suicides, 1-court	4 reps
	16-18	Suicides, 2 courts	1 rep
Ladders, additional jumps	1-3	Up-up, back-back, sprint to cone, backpedal	2 reps
	4-6	Patterns 1 and 2	25 sec each
	7-9	Up-up, back-back, sprint to cone, backpedal	3 reps
	7-9	Patterns 3 and 4	25 sec each
	10-12	Up-up, back-back, sprint to cone, backpedal	2 reps
	10-12	Patterns 5 and 6	25 sec each
	13-15	Up-up, back-back, sprint to cone, backpedal	3 reps
	13-15	Patterns 7 and 8	25 sec each
	16-18	Patterns 9 and 10	25 sec each
Strength training, on the court	1-6	Medicine ball forehand	2 sets × 8 reps
	1-6	Medicine ball backhand	2 sets × 8 reps
	1-3	Medicine ball overhead	2 sets × 8 reps
	4-6	Medicine ball backwards, between legs	2 sets × 8 reps
	4-6	ETCH-Swing forehand and backhand	1 set × 10 shots each side
	7-9	ETCH-Swing forehand, backhand, serve	2 sets × 15 shots each side
	16-18	Medicine ball twisting lunges	2 sets × 16 reps
	1-18	Backward lunge, add hand weight day 4	1 full court × 2-4 reps
	1-18	Single-leg toe raise, add hand weight day 4	3 sets × 10-20 reps each leg
	1-18	Seated press-ups	10-20 reps
	1-18	Regular or wall pushups	3 sets × 10-20 reps
	1-18	Wall-sits	3 sets × 45-60 sec
	1-18	Wall-sits, ball pressed between legs	3 sets × 45-60 sec
	1-18	Abdominals, choose variety	150-300 reps
	1-18	Resistance band hip abduction, adduction	2-3 sets × 10-15 reps each side
	1-18	Tennis ball small circles	30-60 circles each arm
	1-18	Medicine ball overhead dribble	30-60 reps
	1-18	Medicine ball sideways core toss against wall	2 sets × 10-15 reps each side

Reps, Repetitions.

TABLE 14-8 Results of the Sportsmetrics Soccer Training Program

Test	Pretrain, Mean ± SD	Posttrain, Mean ± SD	Difference, Mean ± SD	*P* Value	Effect Size
Video drop-jump test					
Absolute knee separation distance (cm)	14.6 ± 3.6	23.1 ± 6.4	8.5 ± 6.2	<.0001	0.63
Absolute ankle separation distance (cm)	27.3 ± 6.3	34.6 ± 6.0	7.3 ± 6.3	<.0001	0.51
Normalized knee separation distance (%)	35.9 ± 7.4	54.2 ± 13.7	18.3 ± 13.8	<.0001	0.64
Agility *t* test (s)	12.05 ± 0.87	11.31 ± 0.69	0.75 ± 0.75	<.0001	0.43
Multistage fitness test (estimated VO_2max)*	37.9 ± 4.5	40.1 ± 4.7	2.2 ± 4.0	<.0001	0.23
37-meter sprint (s)	6.11 ± 0.43	5.99 ± 0.38	0.12 ± 0.39	.02	0.14
Vertical jump (cm)					
Two-step approach	40.7 ± 8.9	42.1 ± 8.3	1.3 ± 5.1	.04	0.08
Countermovement	32.9 ± 6.7	32.6 ± 25.8	–0.3 ± 4.6	NS	0.02

*In milliliters per kilogram per minute.
NS, Not significant; *SD,* standard deviation; *VO_2max,* maximal oxygen consumption.

TABLE 14-9 Results of the Sportsmetrics Basketball Training Program

Test	Pretrain, Mean ± SD	Posttrain, Mean ± SD	Difference, Mean ± SD	*P* Value	Effect Size
Video drop-jump test					
Absolute knee separation distance (cm)	18.5 ± 7.4	31.8 ± 10.36	13.2 ± 11.8	<.0001	0.59
Normalized knee separation distance (%)	44.9 ± 17.2	74.2 ± 18.8	29.2 ± 26.2	<.0001	0.63
Multistage fitness test (VO_2max)*	34.6 ± 4.5	39.5 ± 5.7	4.9 ± 4.6	<.0001	0.43
Vertical jump (cm)	26.2 ± 12.3	28.5 ± 12.0	2.3 ± 3.4	<.0001	0.09
18-meter sprint (sec)	3.54 ± 0.30	3.53 ± 0.42	–0.01 ± 0.29	NS	0.01

*In milliliters per kilogram per minute.
NS, Not significant; *SD,* standard deviation; *VO_2max,* maximal oxygen consumption.

TABLE 14-10 Results of the Sportsmetrics Volleyball Training Program

Test	Pretrain, Mean ± SD	Posttrain, Mean ± SD	Difference, Mean ± SD	*P* Value	Effect Size
Video drop-jump test					
Absolute knee separation distance (cm)	21.1 ± 8.2	25.9 ± 5.2	4.7 ± 7.7	.002	0.70
Normalized knee separation distance (%)	56.3 ± 19.1	63.3 ± 12.7	6.9 ± 18.2	.04	0.43
Multistage fitness test (VO_2max)*	39.4 ± 4.8	41.4 ± 4.0	2.2 ± 3.2	<.001	0.45
Abdominal strength (reps)	37.7 ± 5.3	40.5 ± 5.9	2.7 ± 4.8	.03	0.50
Vertical jump (cm)	40.1 ± 7.1	41.5 ± 4.5	1.2 ± 5.2	.05	0.24

*In milliliters per kilogram per minute.
SD, standard deviation; *VO_2max,* maximal oxygen consumption.

TABLE 14-11 Results of the Sportsmetrics Tennis Training Program

Test	Pretrain, Mean ± SD	Posttrain, Mean ± SD	Difference, Mean ± SD	*P* Value	Effect Size
One-court suicide(s)	18.55 ± 1.68	16.04 ± 1.23	–2.51 ± 1.18	<.0001	1.70
Abdominal endurance(s)	87 ± 56	162 ± 98	74 ± 75	<.0001	0.94
Baseline backhand (# reps)	8.5 ± 0.9	9.2 ± 0.7	0.7 ± 0.7	<.0001	0.88
Baseline forehand (# reps)	8.6 ± 1.0	9.3 ± 0.8	0.7 ± 0.9	<.0001	0.77
Baseline backhand distance (m)	42.8 ± 4.6	46.3 ± 3.6	3.5 ± 3.8	<.0001	0.85
Baseline forehand distance (m)	43.2 ± 5.1	46.8 ± 4.2	3.6 ± 4.7	<.0001	0.77
Service line (# reps)	22.4 ± 2.9	24.5 ± 2.2	2.1 ± 2.6	<.0001	0.82
Service line distance (m)	89.4 ± 11.8	97.8 ± 8.9	8.4 ± 10.9	<.0001	0.80
Single-leg hop, right leg (cm)	128.2 ± 28.5	141.8 ± 22.8	13.7 ± 21.3	.0004	0.53
Single-leg hop, left leg (cm)	129.5 ± 27.1	138.3 ± 26.0	8.9 ± 14.6	.0007	0.33
Single-leg triple-crossover hop, right leg (cm)	340.7 ± 71.9	373.6 ± 70.1	32.8 ± 68.9	.006	0.46
Single-leg triple-crossover hop, left leg (cm)	340.5 ± 77.6	374.3 ± 78.4	33.8 ± 67.2	.004	0.43

Positive values indicate improvements, except for the one-court suicide, where the negative mean difference represents improved speed.

TABLE 14-12 Improvements in Speed, Agility, and Abdominal Endurance in Players Who Completed Multiple Training Programs

	ONE-COURT SUICIDE(S)			BASELINE FOREHAND (M)			BASELINE BACKHAND (M)			SERVICE LINE (M)			ABDOMINAL ENDURANCE(S)		
Training Session	Mean ± SD	*P* Value	ES	Mean ± SD	*P* Value	ES	Mean ± SD	*P* Value	ES	Mean ± SD	*P* Value	ES	Mean ± SD	*P* Value	ES
First	2.56 ± 1.17	<.0001	1.63	4.6 ± 3.9	.0004	1.01	4.8 ± 3.2	<.001	1.07	12.3 ± 11.3	<.001	1.30	84 ± 98	.005	1.02
Second	1.11 ± 1.07	.0003	1.36	2.6 ± 3.5	.01	0.73	1.6 ± 4.2	NS	0.46	3.2 ± 9.9	NS	0.32	70 ± 89	.01	1.20
Third	0.96 ± .032	.004	0.73	3.8 ± 2.9	.02	1.33	2.7 ± 2.3	.02	0.89	11.6 ± 10.8	.03	0.73	111 ± 86	.02	0.95

Data represent the difference between tests conducted before and on completion of each training session. Positive values indicate improvements, except for the one-court suicide, where the negative mean difference represents improved speed.
ES, Effect size; *NS,* not significant; *SD,* standard deviation.

prepare for high school or tournament competition. Statistically significant improvements and large or moderate ESs were found for the speed and agility and abdominal endurance tests after the first, second, and third training programs among these players (Table 14-12).

Sportsmetrics Return to Play

The Sportsmetrics Return to Play program was developed as an end-stage component for rehabilitation in athletes who have sustained an ACL injury or undergone ACL reconstruction. The following are the indications to initiate the Return to Play program:

1. Negative pivot-shift test
2. Three millimeters or less increase anterior tibial translation on Lachman test
3. Less than 20% deficit peak torque hamstrings and quadriceps on isokinetic test
4. Less than 20% deficit in the distance hopped between the reconstructed and contralateral legs: single-leg hop for distance test and single-leg triple-hop for distance test
5. Successful completion *running program* with no pain, swelling, or giving-way
6. Successful completion *beginning plyometric training* with therapy staff: level surface box hops using both legs from front to back and side to side, diagonal hops using both legs, single-leg surface box hops using vertical box hops

In this program, the athlete conducts Sportsmetrics training at home using instructional videotapes but must see the physical therapist before training begins, 2 weeks later before the start of the second phase of Sportsmetrics, and then another 2 weeks later before the start of the third phase of training. In this manner, the therapist can watch and educate the athlete regarding proper form and positioning for each jump.

STRATEGIES FOR IMPLEMENTATION OF NEUROMUSCULAR TRAINING

Widespread Implementation of Neuromuscular Training

The widespread implementation of ACL injury prevention programs requires efforts at multiple levels and includes many disciplines. We identify the following as important areas to achieve success:

1. Disseminate and integrate information on ACL intervention programs to individuals directly involved with athletes, including coaches, physical education teachers, athletic trainers, strength and conditioning specialists, school administrators, primary care physicians, and pediatricians. Include the entire tier of the sports hierarchy, from local clubs and schools to national sports organizations.
2. Target governing bodies of sports organizations to facilitate or regulate the integration of ACL injury prevention training principles into routine team practices.
3. Request financial assistance from major sports organizations, sports industry for-profit companies, sports medicine organizations, national orthopedic and sports medicine research organizations, and individual philanthropists.
4. Target insurance and hospital organizations to participate in local prevention programs aimed at decreasing knee injuries in the communities they serve.
5. Continue to study risk factors and develop high-risk biomechanical profiles using findings from collaborative multisite studies. Develop screening procedures that can be used during routine preparticipation physical examinations.

To implement Sportsmetrics on a widespread basis, a formal course was devised at our institution to educate and certify health care professionals and coaches who wish to conduct training in their communities. The 13-hour formal course teaches the following:

1. The theories of why female athletes have an increased incidence of serious knee ligament injuries compared with males.
2. The scientific basis of Sportsmetrics.
3. The necessity for neuromuscular training versus plyometric performance enhancement training.
4. The verbal cues and methods required to teach the program to produce changes in landing mechanics and body positioning.
5. The differences between Sportsmetrics and other neuromuscular training programs.
6. Marketing strategies and ways to implement training in the community.
7. The necessity to conduct sports injury testing and produce research data.
8. For those involved in rehabilitation clinics, the implementation of Sportsmetrics as a component of rehabilitation after ACL reconstruction.

Participants are given a detailed demonstration of every jump and spend a few hours practicing the jumps themselves and conducting mock instructions for the teaching staff. Each participant is taken through the SIT and given step-by-step instruction on the video drop-jump test.[47] A formal written examination is conducted to ascertain that the participant has adequate knowledge of knee anatomy and strength training and plyometric concepts. A practical examination is done in which the participant trains a local athlete to demonstrate to our staff that they understand the correct verbal cues and training methodology to produce the desired result of proper body positioning and landing mechanics. Information regarding this course may be obtained at www.sportsmetrics.org.

Problems Encountered and Suggested Solutions

In our experience, young athletes are easily convinced to participate in performance enhancement training. However, unless they or someone they know has gone through a serious knee ligament injury, they simply do not comprehend the consequences of such an injury. It takes considerable effort on the part of the health care professional to educate and motivate athletes to undergo 6 weeks of training (3 times/week) to prevent an injury. In a similar manner, coaches are difficult to convince unless they have lost a number of athletes to ACL injuries. The development of the sport-specific Sportsmetrics programs, with their proven effectiveness in improving athletic performance indices, has helped this problem. The marketing strategy used involves the explanation of these improvements, with the added benefit of an ACL injury prevention component.

Because not all athletes have access to a certified instructor, a two-volume instructional DVD set and detailed manual are available. The first volume focuses on technique and teaching the proper form for body positioning and landing position. The second volume provides a step-by-step analysis of the training program and includes the dynamic warmup, jumps, and flexibility exercises.

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Video Content

Video 11-4

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15

Function of the Posterior Cruciate Ligament and Posterolateral Ligament Structures

Frank R. Noyes, Sue D. Barber-Westin

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INTRODUCTION

This chapter provides a summary of the important biomechanic principles gained from our publications and other investigations regarding the posterior cruciate ligament (PCL) and posterolateral structures (PLSs). The primary PLSs of the knee joint are the fibular collateral ligament (FCL) and popliteus muscle-tendon-ligament unit (PMTL), including the popliteofibular ligament (PFL) and posterolateral capsule (PLC). Additional PLSs that may be injured and require repair are iliotibial band femoral and tibial attachments, meniscal tibial and femoral attachments (including fascicles), the fabellofibular ligament, and the lateral capsule, including the anterolateral ligament. All of these structures are illustrated in Chapter 2. Data from these investigations provide the basis for the diagnosis of abnormal knee motion limits in single and combined ligament injuries and allow the surgeon to plan the appropriate ligament repair and reconstructive procedures.

EFFECT OF SECTIONING THE PCL AND PLSs ON THE LIMITS OF KNEE MOTION

A series of studies were conducted in cadaveric knees to measure the limits of anteroposterior (AP) translation, internal-external tibial rotation, and varus-valgus rotation (using a six-degrees-of-freedom electrogoniometer) under specific forces and moments with a verified testing apparatus previously described.[10,29,30,36,75,115]

The PCL and PLSs were sectioned in 15 knees, first separately and then in combination, to measure the resultant abnormal knee motion limits to simulate isolated and combined ligament ruptures.[30] The PLSs in this investigation included the FCL, PMTL, and PLC. A 100-N force was applied to determine the AP limits; 5 N-m was used for internal-external rotation limits; and 20 N-m was used for adduction-abduction (varus-valgus) limits from 0 to 100 degrees of knee flexion.

In these ligament-cutting experiments, the popliteus tendon was sectioned from the femoral attachment, which effectively removed the entire popliteus muscle tendon and PFL static function. In other experiments to be described,[78] the PFL was sectioned independently of the popliteus tendon attachment to investigate the individual function of this ligament. The PLC was removed, including all soft tissue structures posterior to the FCL, to ensure that the individual soft tissue components were removed. This included, in addition to the PLC, other tissue components compromising the fabellofibular ligament and capsular arm of the biceps femoris short head.

Effect on Limits of Extension

The normal fully hyperextended knee position averaged 5.6 ± 3.8 degrees. After sectioning the PCL or PLS alone, only slight and clinically insignificant increases in hyperextension were noted (such as 2.6 ± 0.09 degrees when the PLS was cut). When both the PCL and PLS were sectioned, the increase in hyperextension was 4.0 ± 1.4 degrees.

CRITICAL POINTS Effect of Sectioning the Posterior Cruciate Ligament and Posterolateral Structures on the Limits of Knee Motion

Limits of AP translation, internal-external tibial rotation, varus-valgus rotation under specific forces and moments were measured in cadaveric studies.

100-N force applied to determine the AP limits, 5 N-m for internal-external rotation limits, 20 N-m for adduction-abduction (varus-valgus) limits from 0 degrees to 100 degrees of knee flexion.

Effect on Limit of Knee Extension

- No primary restraint to hyperextension, structures work together: entire posterior knee capsule, oblique popliteal ligament, fabellofibular ligament, PCL, and ACL.

Effect on AP Translation Limits

- PCL primary restraint to posterior tibial translation throughout knee flexion.
- Increased posterior translation at 30 to 45 degrees flexion associated with injury to PLS, medial ligament structures.

Effect on Internal-External Tibial Rotation Limits

- No increase in external tibial rotation PCL cut alone.
- PLS primary restraint external tibial rotation low knee flexion positions; test 20-40 degrees of flexion.
- Increases in external tibial rotation at 90 degrees indicate injury to PLS and PCL

Effect on Adduction-Abduction Rotation Limits

- PLS primary restraint adduction (varus) rotation limits.
- Loss PLS converts both cruciate ligaments into primary restraints for varus loading.
- Combined rupture PCL/PLS requires surgical restoration of all structures.
- Abnormal medial or lateral joint opening (gap test) at arthroscopy: concurrent medial or lateral ligament reconstruction.

The data indicate that there is no primary restraint in the knee that resists hyperextension. Many structures work in synergy to resist hyperextension, and it is therefore not surprising that sectioning the PLS or PCL results in only a small increase. Other structures anatomically positioned to resist hyperextension include the entire posterior knee capsule (femoral-meniscal tibial attachments), oblique popliteal ligament, fabellofibular ligament, and posterior fibers of the PCL and anterior cruciate ligament (ACL). A reconstructive procedure is described in Chapter 17 for knees with severe knee hyperextension. This procedure is performed in addition to other required ligament reconstructive procedures.

Effect on Anteroposterior Translation Limits

The normal anterior and posterior translation knee limits are shown in Figure 15-1, *A*. The increase in these limits when the PCL is cut are shown in Figure 15-1, *B*, and the further increase in these limits when the PLSs are also sectioned is shown in Figure 15-1, *C*. The values for the increase in motion limits are given in Table 15-1.

The data show that the PCL is a primary restraint to posterior tibial translation throughout knee flexion, with the exception of a small increase in posterior translation at full extension when the PLSs are cut. The clinical finding of a knee with increased posterior translation at 30 to 45 degrees of knee flexion, similar to the posterior translation limit at 90 degrees (Fig. 15-2), indicates associated injury to the PLSs and the medial structures.

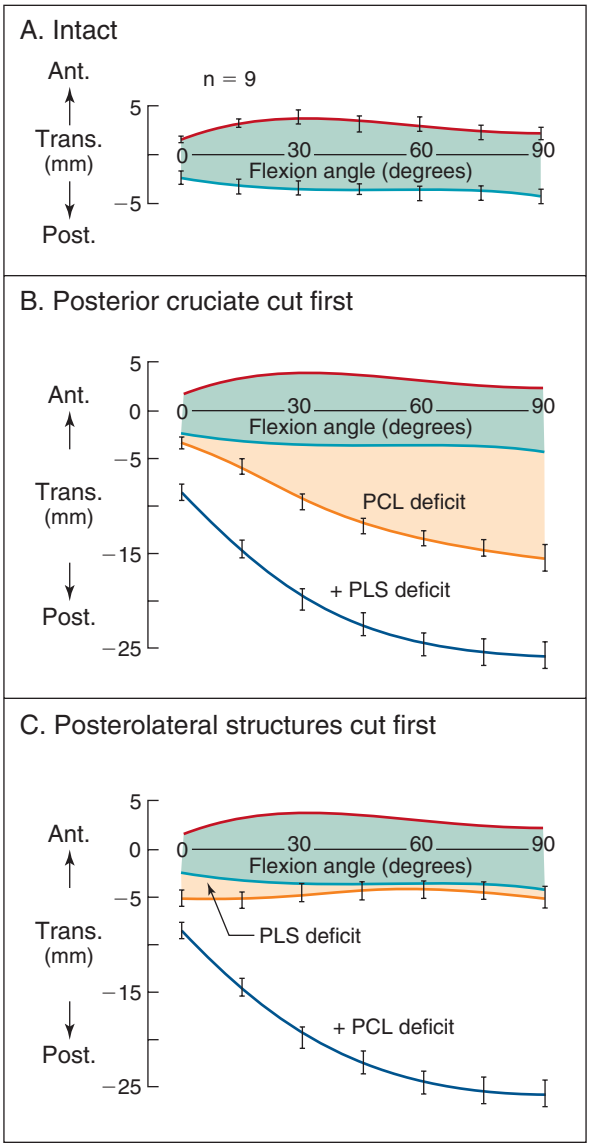


FIG 15-1 Limits of anterior *(ant.)* and posterior *(post.)* translation (vertical axis) when a 100-N anteroposterior (AP) force is applied. **A,** Intact knees. The curves show the average limits of motion and the standard deviation for nine knees. The range of total AP translation of the intact knee is shaded green. **B,** The posterior cruciate ligament (PCL) is cut first. The increase in posterior translation after cutting the PCL is shown in the area shaded in orange (PCL deficit). The limit of posterior translation, and therefore the amount of increase, is controlled by the remaining intact structures. The unshaded portion (+ posterolateral structure [PLS] deficit) shows the added increase when the PLSs (fibular collateral ligament, capsule, popliteus muscle-tendon-ligament) were cut after the PCL had first been removed. A concurrent external rotation took place with this cut. **C,** The PLSs are cut first. There was only a small increase (PLS deficit) in the posterior limit near full extension when the posterolateral structural elements were cut first. A concurrent external rotation was also present. (From Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee: effect of sectioning the posterior cruciate ligament and posterolateral structures. *J Bone Joint Surg Am.* 1988;70:88-97.)

It should be noted that a complete description of the translation limits requires an anatomic measurable point on the tibia, which is selected at the central coronal point on the tibia. The limits of posterior translation to the medial and lateral tibiofemoral joints are described in a subsequent study.[75]



FIG 15-2 Severe posterior tibial subluxation is shown in a chronic posterior cruciate ligament–deficient knee, which is caused either by physiologic laxity of the remaining secondary restraints or as the result of a traumatic injury.

TABLE 15-1 Increased Motion Compared With Normal Motion That Occurred When the Indicated Structures Were Sectioned

	ANGLE OF FLEXION (DEGREES)				
	0	15	30	60	90
Anterior Limit (mm)					
All cut	0.5 ± 0.8	0.6 ± 0.6	0.7 ± 0.7	0.4 ± 1.3	0.8 ± 1.0
Posterior Limit (mm)					
PCL cut	1.0 ± 1.6	3.6 ± 1.6	6.4 ± 1.5	9.6 ± 1.3	11.4 ± 1.9
PLS cut	3.1 ± 0.7	1.9 ± 0.8	1.4 ± 1.1	0.7 ± 0.8	0.5 ± 0.7
All cut	6.6 ± 2.7	11.3 ± 3.1	15.8 ± 3.0	20.7 ± 3.4	21.5 ± 3.4
External Rotation Limit (Degrees)					
PCL cut	0.4 ± 0.5	0.2 ± 0.5	0.2 ± 0.6	0.4 ± 0.9	0.6 ± 1.2
PLS cut	8.5 ± 2.6	11.8 ± 3.0	13.0 ± 2.3	5.2 ± 9.0	5.3 ± 2.6
All cut 1	10.5 ± 4.0	14.2 ± 3.7	18.0 ± 3.8	21.0 ± 3.1	20.9 ± 2.8
Varus Angulation Limit (Degrees)					
FCL cut	2.5 ± 0.4	4.5 ± 0.4	5.7 ± 0.2	5.5 ± 0.6	4.3 ± 0.9
PCL cut	0.4 ± 0.6	0.4 ± 0.6	0.4 ± 0.6	0.8 ± 0.6	1.4 ± 0.6
PLS cut	6.4 ± 2.3	7.9 ± 2.0	9.0 ± 2.0	8.3 ± 3.7	6.8 ± 4.5
All cut	8.1 ± 2.5	11.3 ± 3.0	14.2 ± 3.3	18.9 ± 3.4	21.2 ± 3.0
Valgus Angulation Limit (Degrees)					
PCL cut	0.3 ± 0.6	0.3 ± 1.0	0.5 ± 1.7	0.7 ± 1.9	0.5 ± 1.0

All values are given as mean ± standard deviation.
FCL, Fibular collateral ligament; *PCL,* posterior cruciate ligament; *PLS,* posterolateral structures (FCL, capsule, popliteus muscle-tendon-ligament).

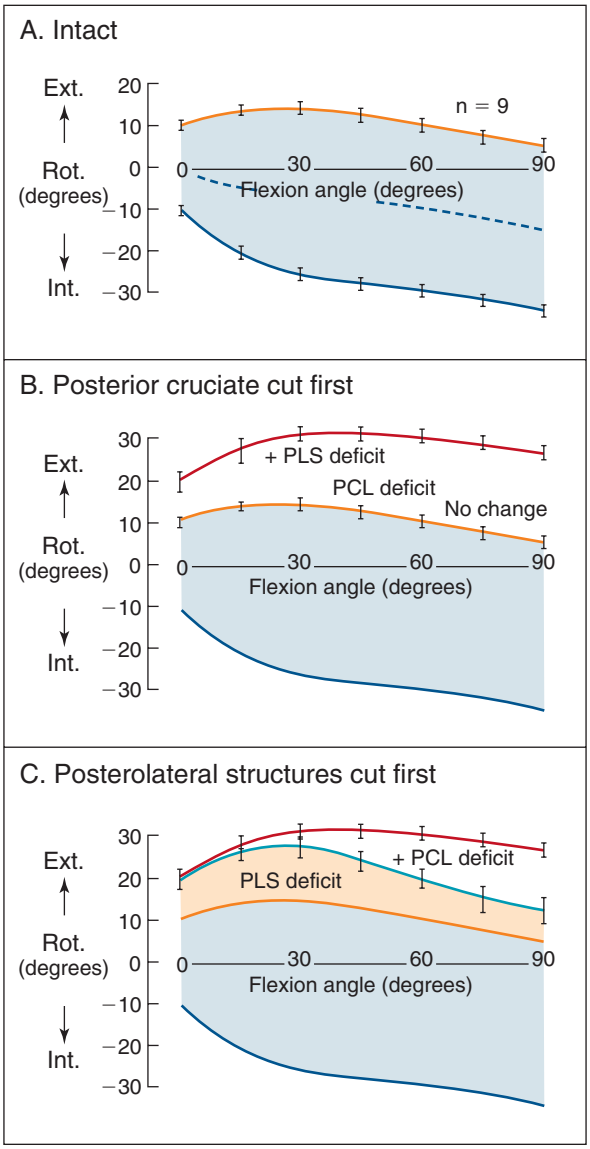


FIG 15-3 The limits of internal *(int.)* and external *(ext.)* rotation *(rot.)* of the tibia when a 5-N torque is applied. The fully extended position, measured in the intact knee, was used as the zero-rotation reference. **A,** Intact knees. The upper curve shows the limit of external rotation. The dashed line shows the average position of the knee during passive flexion with the tibia hanging freely. The range of tibial rotation in the intact knee is shaded. **B,** The posterior cruciate ligament (PCL) is cut first. No change was found in external tibial rotation. **C,** Posterolateral structures (PLS; fibular collateral ligament, capsule, popliteus muscle-tendon-ligament) are cut first. Increases in external tibial rotation occurred at low flexion angles. With added PCL sectioning, the increase in external tibial rotation occurred at high flexion angles. (From Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee: effect of sectioning the posterior cruciate ligament and posterolateral structures. *J Bone Joint Surg Am.* 1998;70:88-97.)

In a knee with a combined deficiency of the PCL and PLS, the abnormal posterior tibial translation is at least four to five times the normal limit throughout knee flexion.

Effect on Internal-External Tibial Rotation Limits

The normal knee motion limits to internal and external tibial rotation are shown in Figure 15-3, *A*. There is no increase in external tibial rotation when the PCL is cut alone (see Fig. 15-3, *B*). This finding demonstrates that the PLSs are the primary restraint for external tibial rotation throughout knee flexion. When only the PLSs are sectioned, an increase in external tibial rotation occurs (see Fig. 15-3, *C*), which is greatest at 30 degrees of knee flexion. The amount of external tibial rotation decreases as the knee is flexed, showing the influence of the PCL in limiting external tibial rotation after the PLSs are sectioned.

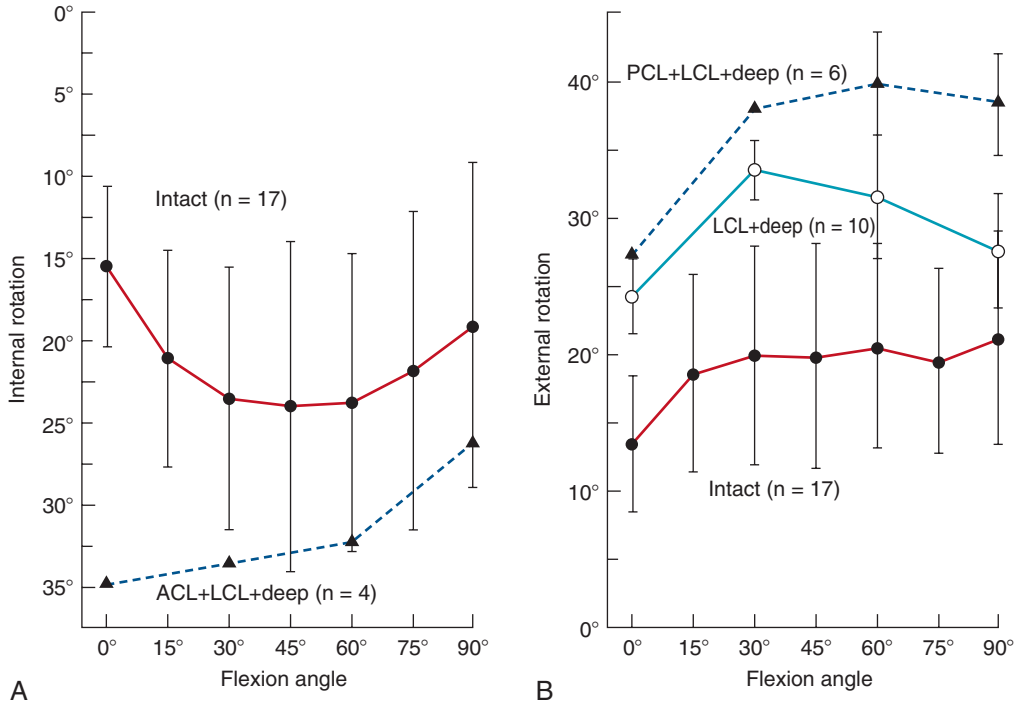


FIG 15-4 Primary internal and external tibial rotations resulting from 4.5 N-m of internal and external tibial torque in intact knees and after ligament sectioning. **A,** Increased internal rotation occurred only with combined section of the lateral collateral ligament (LCL), deep structures, and anterior cruciate ligament (ACL). **B,** Increased external rotation occurred at all angles of flexion with combined section of the LCL and deep structures, with additional increases at 60 degrees and 90 degrees when the posterior collateral ligament (PCL) was sectioned. The dashed lines indicate a lack of statistical difference from the adjacent curve unless otherwise stated. *(From Gollehon DL, Torzilli PA, Warren RF. The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study. J Bone Joint Surg Am.* 1987;69:233-42.)

These data indicate that the PLSs provide the primary restraint to external tibial rotation at low knee flexion positions and therefore should be tested in this range (20-40 degrees of flexion). Increases in external tibial rotation at 90 degrees indicate injury to both the PLS and PCL, consistent with the dial test (see Chapter 17). The data are in disagreement with the classic interpretation of the posterolateral drawer test at 90-degree flexion, indicating injury to only the PLS. The resisting function of the FCL, popliteus tendon, and PFL is described in separate studies mentioned later in this chapter.

Gollehon and coauthors[26] reported similar results showing an increase in external tibial rotation of 20-degree flexion after sectioning the PLS at 30 degrees of flexion. Sectioning of the PCL along with the PLS did not produce further significant increases in external tibial rotation (Fig. 15-4).

Effect on Adduction-Abduction Rotation Limits

The normal limits of adduction and abduction rotation are shown in Figure 15-5, *A*. Sectioning the PCL produces very small changes in these limits (see Fig. 15-5, *B*). When the PLSs are sectioned alone, large increases in adduction occur (see Fig. 15-5, *C*), indicating that these structures are the primary restraint to this knee motion. Once the PLSs are removed, the PCL becomes a primary restraint and large increases in the adduction limit occur with knee flexion.

The limits to adduction (varus angulation) after sectioning the FCL, the PLS (PMTL and PLC), and all structures (PCL, FCL, PMTL, and PLC) are graphed in Figure 15-6.[30] The data demonstrate that the FCL is the primary restraint for lateral joint opening, with further increases after the remaining PLSs are sectioned.

Markoff and associates[63] developed an in vitro system in cadaveric knees in which load transducers were used to measure ACL and PCL forces under different loading situations. After sectioning the FCL and the other PLSs, large increases were noted in resisting tensile forces in both cruciate ligaments under varus loading (Fig. 15-7) and in the PCL under posterior tibial loads and external tibial torques (Fig. 15-8). These findings are in agreement with prior studies, because the loss of the PLS converts both cruciate ligaments into primary restraints for varus loading, in which the ligaments are poorly positioned with small lever arms to resist this motion.

The importance of load-sharing of the PLS with the PCL has been demonstrated in many studies, which reinforces the need, in knees with combined PCL-PLS ruptures, to also perform posterolateral reconstructive surgery. An abnormal medial or lateral joint opening (gap test) to varus or valgus loading at arthroscopy indicates the necessity for concurrent medial or posterolateral ligament reconstruction. Otherwise, the majority of forces are placed on the ACL or PCL grafts, which may stretch out or fail postoperatively. The goal is to restore normal load-sharing in which the majority of varus-valgus loads and internal-external rotation torques are placed on the medial and lateral structures and not the cruciate ligaments.

One problem with cadaveric studies in which knee motion limits after ligament sectioning are measured is that the resulting millimeters of anterior or posterior translation (subluxation) of the medial and

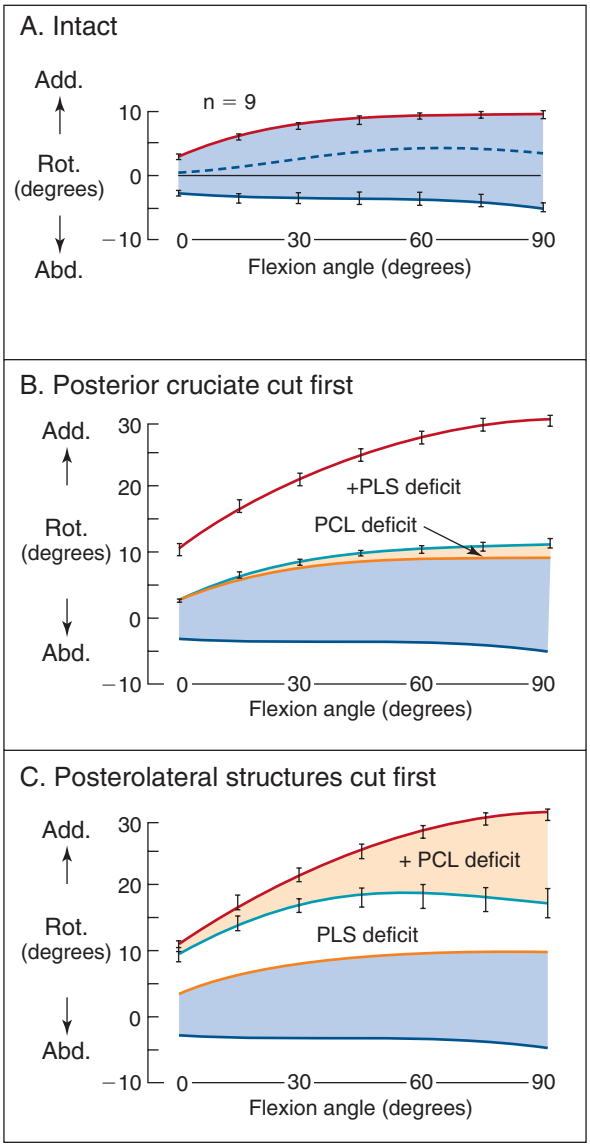


FIG 15-5 The limits of adduction *(add.)* and abduction *(abd.)* rotation *(rot.)* when a 20 N-m moment is applied. The fully extended position, measured in the intact knee, was used as the zero-rotation reference. **A,** Intact knees. The upper curve shows the limit of adduction rotation, and the lower curve shows the limit of abduction rotation. The dashed line shows the amount of adduction when the knee is passively flexed, with the tibia upside down to ensure tibiofemoral contact in both the medial and lateral compartment. **B,** The posterior cruciate ligament (PCL) is cut first. **C,** Posterolateral structures (fibular collateral ligament, capsule, popliteus muscle-tendon-ligament) are cut first. (From Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee: effect of sectioning the posterior cruciate ligament and posterolateral structures. *J Bone Joint Surg Am.* 1998;70:88-97.)

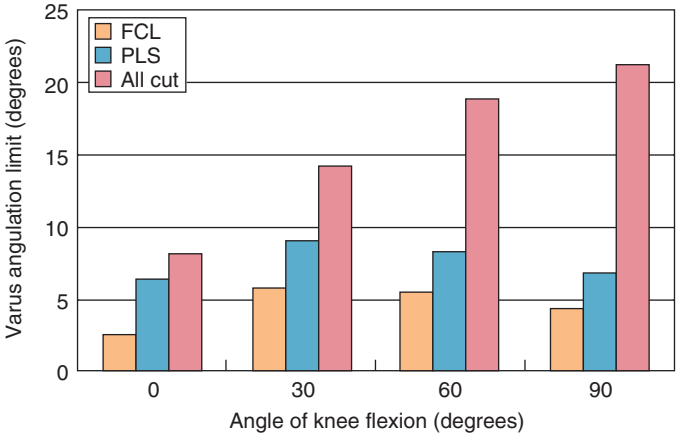


FIG 15-6 Increases in the limits to adduction (varus angulation) are shown after sectioning the fibular collateral ligament (FCL), the posterolateral capsule (PLC; popliteus muscle-tendon-ligament [PMTL] and posterolateral capsule [PLC]), and all structures (PCL, FCL, PMTL, and PLC). The data demonstrate that the FCL is the primary restraint for lateral joint opening, with further increases after the remaining posterolateral structures are sectioned. *PLS,* Posterolateral structures. (From Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee: effect of sectioning the posterior cruciate ligament and posterolateral structures. *J Bone Joint Surg Am.* 1998;70:88-97.)

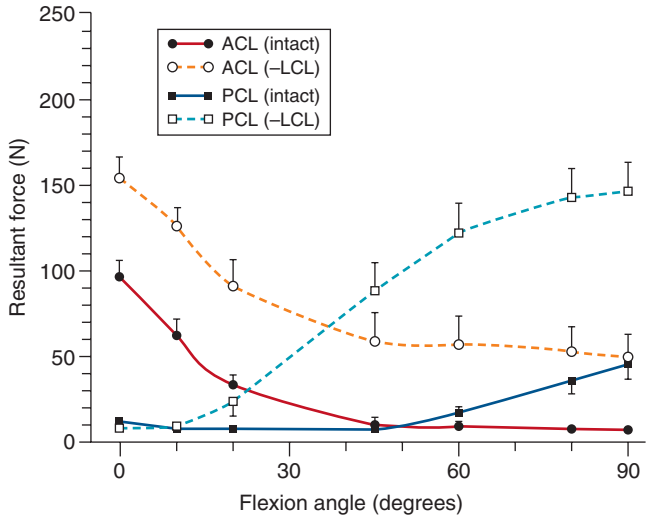


FIG 15-7 The forces generated in the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) by 10.0 N-m of applied varus bending moment before (intact) and after sectioning of the lateral collateral ligament (LCL). The increases in the mean force in the ACL after ligamentous section were significant at all angles of flexion; the increases in the mean force in the PCL were significant from 45 to 90 degrees of flexion. The mean values for eight specimens are shown; the error bars indicate the standard error of the mean. (From Markolf KL, Wascher DC, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part II: the effect of section of the posterolateral structures. *J Bone Joint Surg Am.* 1993;75:387-94.)

lateral tibiofemoral compartments are not measured or described. For example, when 15 degrees of increased external tibial rotation is measured after cutting the PLS, the resultant abnormal millimeters of posterior translation of the lateral tibial condyle are unknown. This is because it is also necessary to measure and compute the center of tibial rotation to determine the effect of the increase in degrees of external tibial rotation on the lateral and medial tibiofemoral compartment translation or position. Limited published data exist on tibial translations or subluxations of the medial and lateral compartments (rotatory subluxations) after knee ligament injuries, discussed in further detail in this chapter.[75]

ROLE OF THE POSTERIOR OBLIQUE LIGAMENT

Petersen and colleagues,[80] using a robotic testing system in a cadaveric study, examined the restraint of the superficial medial collateral

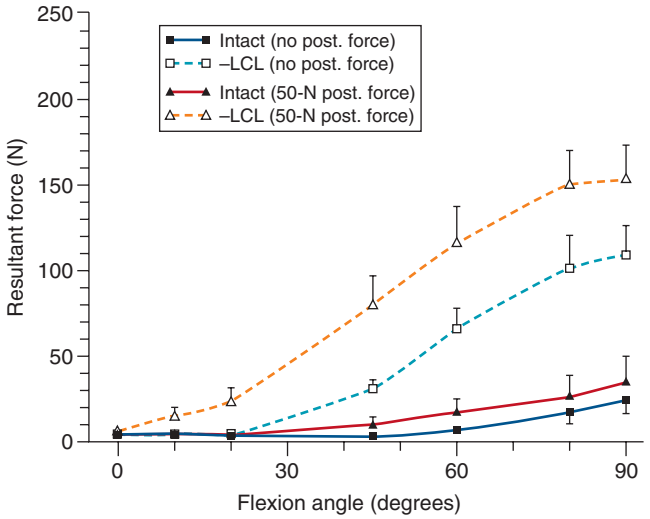


FIG 15-8 The forces generated in the posterior cruciate ligament (PCL) by 50 N of posterior *(post.)* tibial force, with the tibial rotated externally by 7 N-m of applied tibial torque. Application of the 50-N posterior tibial force had no significant effect on the mean force in the PCL in the intact specimens (intact). After ligamentous section (lateral collateral ligament [LCL], fibular collateral ligament), the posterior tibial force increased the mean force in the PCL at all angles except full extension. The mean values for eight specimens are shown; the error bars indicate the standard error of the mean. (From Markolf KL, Wascher DC, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part II: the effect of section of the posterolateral structures. *J Bone Joint Surg Am.* 1993;75:387-94.)

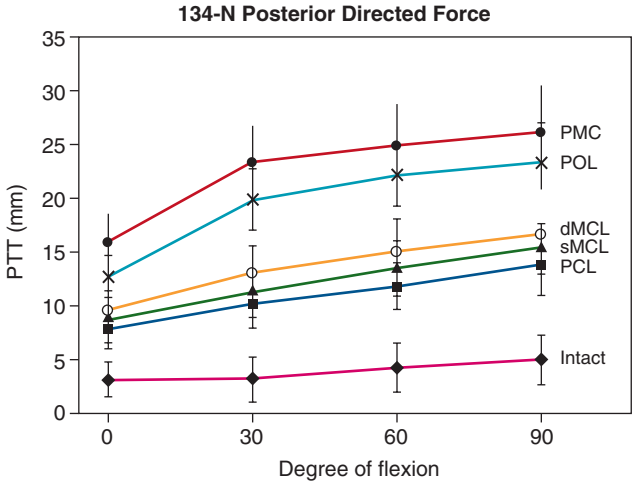


FIG 15-9 Posterior tibial translation (PTT) in response to a posterior load of 134 N (mean ± standard deviation). The effect of sectioning the secondary medial restraints resulted in a marked increase in posterior tibial translation. (From Petersen WJ, Loerch S, Schanz S, et al. The role of the posterior oblique ligament in controlling posterior tibial translation in the posterior cruciate ligament deficient knee. *Am J Sports Med.* 2008;36:495-501.)

ligament (SMCL), the deep medial collateral ligament (DMCL), the posterior oblique ligament (POL), and the posteromedial capsule (PMC) in resisting posterior tibial translation after PCL sectioning. The data shown in Figure 15-9 demonstrate the increase in posterior tibial translation after sequential ligament sectioning of the medial and posteromedial structures. The authors concluded that the POL has a much larger role than the SMCL and DMCL in resisting posterior tibial translation and internal tibial rotation. It should be noted that these two structures were first sectioned, and no studies were done when the POL was sectioned first. This indicates that there could be a sectioning artifact introduced in the study. Even so, there are posteromedial oblique capsular fibers from the medial femoral condyle to the tibia, just posterior to the SMCL, which resist internal tibial rotation and posterior tibial translation (after PCL sectioning). These authors concluded that discrete oblique fibers form the middle arm of the POL described by Hughston and Eilers.[41] Of interest in this cadaveric study was the finding that a valgus loading of the knee joint close to knee extension (with PCL deficiency) produced an increased posterior tibial translation of the medial compartment with absence of the POL and PMC.

Robinson and coworkers[85] conducted a cadaveric study of the medial and posteromedial structures and could not identify a distinct separate POL structure, but they did find an oblique portion of the PMC where fibers could be tensioned under internal tibial rotation loading. Robinson and associates[84] and Haimes and colleagues[36] studied the contribution of the PMC, which included the POL. Robinson and associates[84] reported that the PMC resisted 28% of the posterior tibial load when the tibia rotated freely in the extended knee, which rose to 42% when the tibia was subjected to internal rotation. These authors concluded the PMC resisted posterior tibial translation close to full extension and less so with knee flexion, which relaxes the PMC. With knee flexion, the SMCL resisted posterior tibial translation.

In knees with chronic PCL instability and associated medial and posteromedial ligament and capsular injury, the integrity of all the structures should be restored. Increased internal tibial rotation is assessed with the dial test. The problem is that the tibia drops posteriorly with PCL deficiency, and it is difficult to judge the added posterior subluxation on internal tibial rotation that tests the role of the PMC (including the POL).

FUNCTION AND ROLE OF THE PMTL

The PMTL includes (1) the muscular tibial origin, (2) the fibular origin (PFL), (3) the merging of both of these components to the popliteal tendon inserting on the lateral femoral condyle, (4) the inferior and superior popliteomeniscal fascicles forming the popliteal hiatus, and (5) the soft tissue attachments to the lateral meniscus and posterior tibia. The static stabilizing function of the PMTL that requires surgical reconstruction has been debated.[48,70,78] Studies from our laboratory advanced the hypothesis that the PFL has a secondary role in that it provides a functional attachment of the popliteus tendon to the fibula. However, removal of this fibular attachment has little effect on the limits of motion, as long as the popliteal tendon femoral and tibial attachments remain intact.[78] This hypothesis questions the success of operations in posterolateral rotational instability in which only the PFL is reconstructed, without attention to the FCL or popliteus tendon femoral and tibial attachments.[65,90,98]

As previously described, Grood and coauthors[30] reported increases in external tibial rotation (posterior subluxation lateral tibial plateau) that is highly dependent on the order of sectioning of the PLSs. The last remaining PLS sectioned will, in general, provide the largest effect in terms of increased knee motion limits after the other primary and secondary restraints have been sectioned. Therefore the experimental design on the order of ligament sectioning may induce an artifact and an incorrect assignment of a primary restraining role to a soft tissue structure. Shahane and associates,[90] in a cadaveric study, concluded that the PMTL was the primary restraint to external tibial rotation and

CRITICAL POINTS Function and Role of the Popliteus Muscle-Tendon-Ligament Unit

PMTL includes:

1. Muscular tibial origin
2. Fibular origin (PFL)
3. Merging of these components to popliteal tendon inserting on the lateral femoral condyle
4. Inferior and superior popliteomeniscal fascicles forming the popliteal hiatus.
5. Soft tissue attachments to lateral meniscus and posterior tibia

All PLSs provide restraint to external tibial rotation.

PFL has a secondary role; removal has little effect on the limits of motion (popliteal tendon femoral and tibial attachments intact).

Application to Surgical Reconstruction

- FCL, PMTL, posterolateral capsular structures function as a unit to resist external tibial rotation and varus rotation.
- FCL, PMTL act together at low- to mid-flexion positions.
- Reconstructing only PMTL can lead to failure if FCL is deficient.
- Reconstructing only FCL can lead to failure if PMTL is deficient.

the FCL was a secondary restraint. However, their study did not include sectioning the FCL first to determine whether increases in external tibial rotation occurred before sectioning the PMTL. In contrast, Veltri and colleagues[108,109] reported that sectioning the PFL (after first sectioning the FCL, popliteus tendon intact) resulted in only small and minor increases in external tibial rotation.

In their cadaveric study, Pasque and coworkers[78] implemented an experimental system similar to that already described,[29,30] in which an instrumented spatial linkage and loading of the knee joint was used with a 100-N posterior force, a 10 N-m varus force, and a 5 N-m external moment from 0 to 120 degrees of knee flexion. The ligament sectioning of the PLS was varied to more precisely define the restraining function of the individual structures. The results are shown in Figures 15-10 and 15-11. Sectioning the PFL in the intact knee produced no statistically significant changes in motion limits, whereas sectioning both the popliteus tendon and PFL together (removing the function of the PMTL) produced a small increase in external rotation from 3 to 5 degrees.

In another group of knees, the PCL, FCL, and PLC were first sectioned, followed by the PFL and then the popliteus tendon. Only small increases were noted after sectioning the PFL, as long as the popliteus tendon attachments remained intact.

In a separate study, Wroble and associates[115] reported the effect on external tibial rotation when only the popliteus tendon was sectioned in ACL-deficient knees (Fig. 15-12) and when only the FCL was sectioned along with the iliotibial band and lateral capsule (Fig. 15-13). Consistent with the studies previously discussed, only small increases in external tibial rotation were found when individual PLSs were sectioned.

All of the PLSs provide important restraints to external tibial rotation, whereas the PFL serves as a secondary restraint in providing a fibular origin to the PMTL. In acute knee injuries, all of the soft tissue structures including this fibular attachment should be repaired in addition to an FCL graft reconstruction (see Chapter 17). The FCL functions to limit external tibial rotation, particularly at low knee flexion angles, and is an important structure to reconstruct in posterolateral injuries. Sugita and Amis[99] measured the orientation of the FCL and PFL in cadaveric knees and reported that the

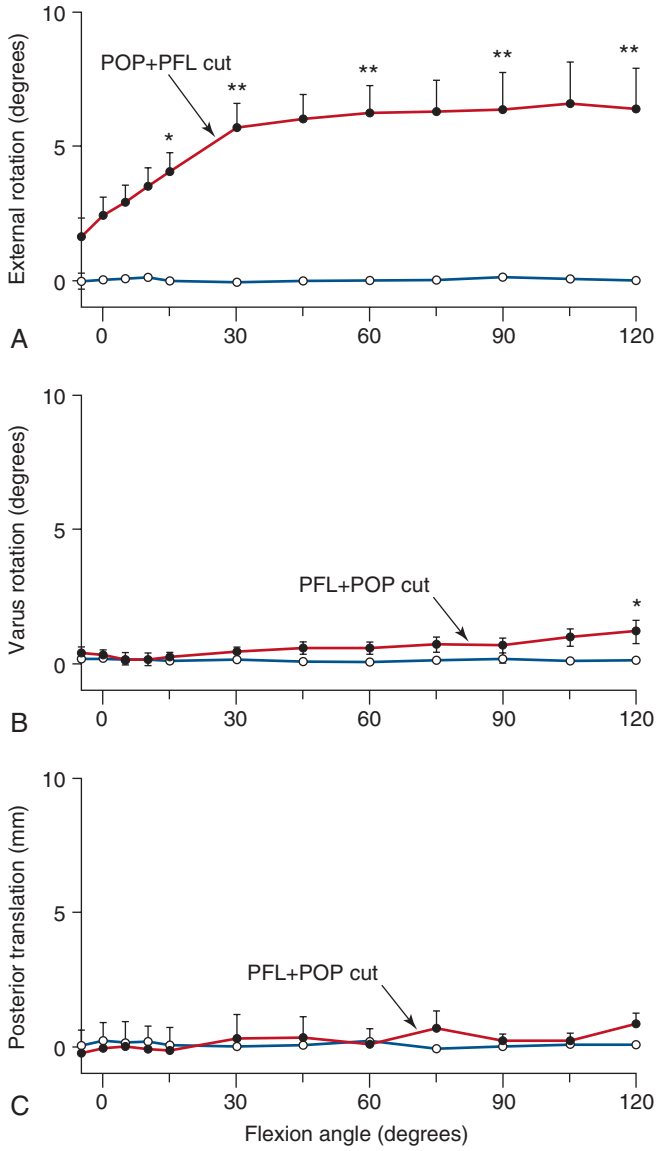


FIG 15-10 The increase in external rotation (**A**), varus rotation (**B**), and posterior translation (**C**) from the intact knee when the popliteofibular ligament (PFL) and popliteus (POP) tendon were sectioned. The data are given as the mean ± standard error of the mean. $*P < .05$, $**P < .001$ by one-tailed test after correction of multiple comparisons. (From Pasque C, Noyes FR, Gibbons M, et al. The role of the popliteofibular ligament and the tendon of popliteus in providing stability in the human knee. *J Bone Joint Surg Br.* 2003;85:292-298.)

FCL slackened with increasing knee flexion, achieving a vertical position at 70 degrees of flexion, which decreased its ability to resist external tibial rotation. The PTML maintained an oblique orientation, which allowed effective resistance of external tibial rotation with increasing knee flexion, indicating the importance of restoring PTML function.

LaPrade and coworkers[49] conducted an in vitro cadaveric knee study in which a specially designed buckle transducer was attached to the FCL, popliteus tendon, and PFL. The knee joints were subjected to AP forces (67 N), varus-valgus torques (12 N-m), and internal-external rotation torques (6 N-m). A reciprocal relationship of load-sharing with knee flexion was found, because the FCL had higher loads resisting the external rotation torque at low flexion positions and the

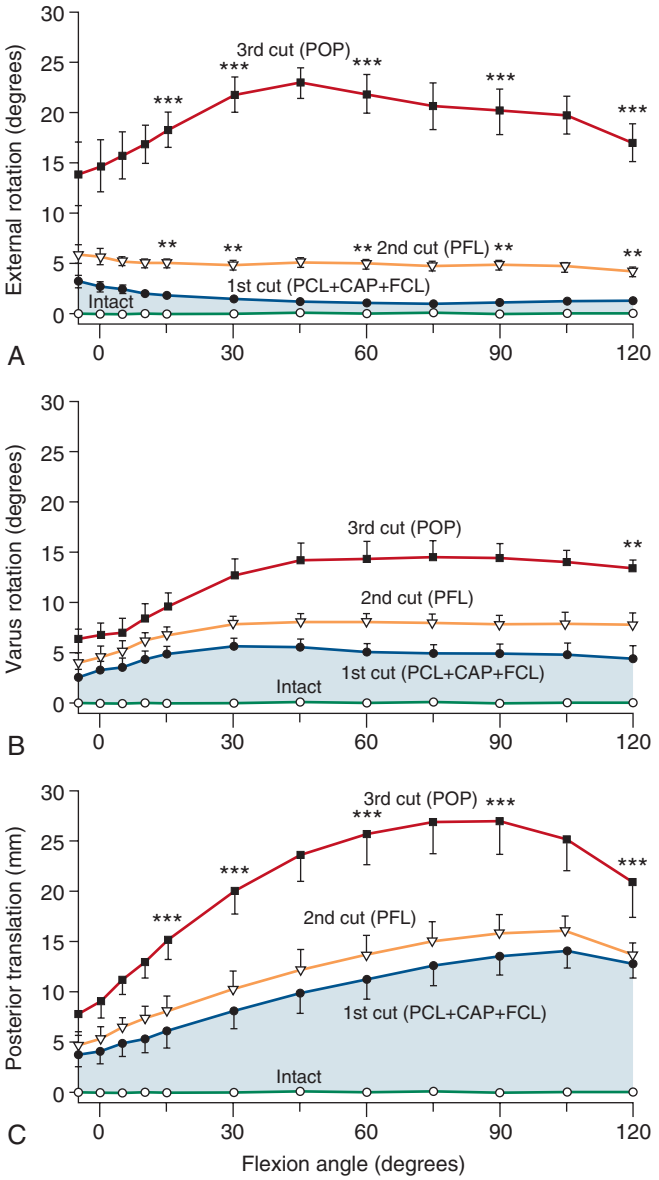


FIG 15-11 The increase in motion limits from the intact knee after external rotation (**A**), varus rotation (**B**), and posterior translation (**C**). The open circles represent the intact knee. The solid circles represent sectioning of the posterior cruciate ligament (PCL), fibular collateral ligament (FCL), and posterolateral capsule (CAP). This denotes that multiple ligaments have been sectioned, leaving only the popliteofibular ligament (PFL) and popliteus tendon (POP) structures remaining. Only small increases were noted after the PFL had been cut (triangles). Subsequent sectioning of the POP (squares) resulted in large increases in movement limits. Data are given as the mean ± standard error of the mean. $*P \leq .01$ and $***P \leq .001$ after correction for multiple comparisons (one-tailed *t* test). (From Pasque C, Noyes FR, Gibbons M, et al. The role of the popliteofibular ligament and the tendon of popliteus in providing stability in the human knee. *J Bone Joint Surg Br.* 2003;85:292-298.)

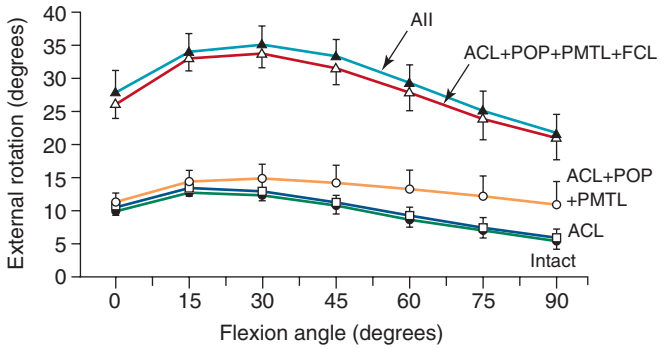


FIG 15-12 Limits of external rotation with 5 N-m moment for intact specimens and with structures cut. "All" included the anterior cruciate ligament (ACL), popliteus tendon (POP), popliteus muscle-tendon-ligament unit (PMTL), fibular collateral ligament (FCL), and iliotibial band and anterolateral capsule (ALS). Statistically significant increases in external rotation were found in the ACL + POP + PMTL cut state at 60 degrees of flexion and higher. Statistically significant increases in external rotation were found at all flexion angles for the ACL + POP + PMTL + FCL and the "all" cut states. The intact FCL limits external rotation at all flexion angles after the ACL + POP + PMTL was sectioned. (From Wroble RR, Grood ES, Cummings JS, et al. The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee. *Am J Sports Med.* 1993;21:257-263.)

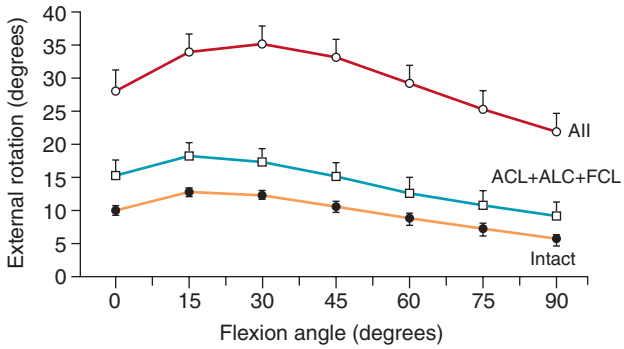


FIG 15-13 Limits of external rotation with 5 N-m moment for intact specimens and with anterior cruciate ligament (ACL) + iliotibial band and anterolateral capsule (ALC) + fibular collateral ligament (FCL) and "all" structures (ACL + ALC + FCL + popliteus muscle-tendon-ligament unit [PMTL] + popliteus tendon [POP]) cut. Statistically significant increases were found at all flexion angles for both cut states. The difference between the ACL + ALC + FCL and "all" curves represents the restraining function of the PMTL and POP toward external rotation. Note that increases occur at all flexion angles. (From Wroble RR, Grood ES, Cummings JS, et al. The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee. *Am J Sports Med.* 1993;21:257-263.)

popliteus complex had higher loads at 60 degrees and 90 degrees of knee flexion (Fig. 15-14). Even though buckle transducers have inherent problems in truly measuring ligament tensile-resisting loads, the results show that all three structures are important in resisting external tibial rotation loads and the importance of anatomic reconstruction of these structures when deficient.

Application to Surgical Reconstruction

These studies provide the surgeon with important principles for the surgical restoration of function in acute and chronic injuries to the PLS. The FCL, PMTL, and PLC function as a unit in resisting external tibial rotation and varus rotation. As such, no individual structure is the primary restraint in resisting these motions. The PLC slackens with knee flexion, providing less of a contribution to resisting these motions. The FCL and PMTL provide important contributions and act together at low- to mid-flexion positions. The FCL provides a higher contribution to varus rotation, and the PMTL provides a higher contribution

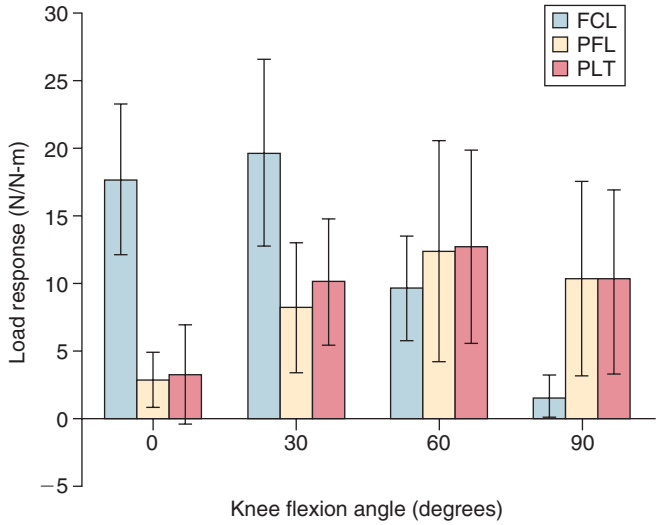


FIG 15-14 Forces in the fibular collateral ligament (FCL), popliteus tendon (PLT), and popliteofibular ligament (PFL) during application of an external rotation torque of 6 N-m. (From LaPrade RF, Tso A, Wentorf FA. Force measurements on the fibular collateral ligament, popliteofibular ligament, and popliteus tendon to applied loads. *Am J Sports Med.* 2004;32:1695-1701.)

to resisting external tibial rotation and posterior tibial translation with knee flexion.

We have encountered knees requiring revision of a failed posterolateral surgical procedure in which only the PMTL was reconstructed, leaving a partially or completely insufficient FCL. The abnormal lateral joint opening places high tensile forces on the PMTL, which is not designed to resist varus moments (in the absence of a functional FCL). Similarly, performing only an FCL reconstruction in knees with a complete PMTL disruption subjects the FCL graft to external tibial rotation moments without the added load-sharing of the PMTL. At surgery, there may exist a false sense of restoring stability when reconstructing only the FCL or PMTL that will initially eliminate the abnormal motions of lateral joint opening and external tibial rotation. However, the single reconstruction will be subjected to much higher in vivo loading conditions without the added load-sharing of the other PLSs, and there is an increased risk of failure and a return of knee instability. An anatomic reconstruction of the PLS (with the goal of restoring the PLC and meniscus attachments, PMTL, and FCL) is described in Chapter 17.

All of the biomechanic studies show the effects of the PLS at the maximum limits of internal-external rotation under defined torques. Within this envelope of motion, the resisting effect of the FCL and other PLS changes as already described, depending on many factors, including degrees of internal-external rotation, the AP tibiofemoral displacements with knee flexion, and imposed loads that lead to an increase or decrease in femoral-fibular attachment distances and tensioning or slackening of the ligament structures. Normal anatomic variations in the position of the tibiofibular joint may occur with a more posterior fibula position, increasing the FCL orientation. These variables produce subtle differences in measured FCL function in cadaveric studies and account for the large standard deviations commonly found.

POSTERIOR SUBLUXATION OF THE MEDIAL AND LATERAL TIBIOFEMORAL COMPARTMENTS

The millimeters of posterior subluxation of the medial and lateral tibiofemoral compartments after sectioning the PCL and PLS were measured in whole cadaver lower limbs in a testing apparatus previously described.[75] The position of the lateral and medial tibial plateaus was determined by three reference points: the AP translation of a point located at the center of each plateau, and the medial and lateral locations of points located midway between the tibial edges and joint centers.

The purposes of this investigation were, first, to determine the AP position of the medial and lateral tibia plateaus when a known external rotation torque was applied at 30 degrees and 90 degrees of knee flexion and, second, to measure how the positions of the lateral and medial tibial plateaus change and the magnitude of this change (subluxation) after sectioning the PLS alone and in combination with the PCL. The anterior meniscofemoral ligament (AMFL) and posterior meniscofemoral ligament (PMFL) were also sectioned when present. Studies have shown that these structures are not the primary restraints for posterior tibial translation or external rotation and provide a restraint only after the PCL has been removed.[34,39,50] The study also determined the effect of physiologic joint laxity, or preexisting ligament laxity, on the magnitude of rotatory subluxation

CRITICAL POINTS Posterior Subluxations of the Medial and Lateral Tibiofemoral Compartments

Posterior subluxation medial and lateral tibiofemoral compartments measured after sectioning PCL, PLSs.

Sectioning only PLSs: mean increase posterior translation lateral tibial plateau, 8.0 mm (30 degrees of flexion) over intact state.

Posterior Tibial Translation

- Sectioning PCL and PLSs: increases posterior translation medial and lateral tibial plateaus (30 degrees, 90 degrees of flexion).
- Sectioning PLSs: significant increases external tibial rotation (30 degrees, 90 degrees of flexion).
- Sectioning PCL and PLSs: further increase in external tibial rotation (30 degrees, 90 degrees of flexion).

External Tibial Rotation

- Classification of rotatory subluxations is based on final position (translation, millimeters) of medial and lateral tibial plateaus under defined loading conditions.
- In normal knees (5 N-m external tibial rotation, 100-N posterior force, 30 degrees of flexion), lateral tibial plateau displaces mean 7.5 ± 2.9 mm. PLSs sectioned: further increase to 15.5 ± 3.5 mm.
- PCL, PLSs sectioned: mean posterior translation, 25.3 ± 5.2 mm.

Effect of Physiologic Laxity

- Substantial differences in clinical tests "tight-jointed" versus "loose-jointed" knees. Determines amount of displacement before other secondary ligament restraints block further joint displacements.
- Some "tight" knees may have substantial damage to PLSs, demonstrate minimal increases in posterolateral tibial subluxation on external tibial rotation owing to secondary resistance provided by PCL.
- In knees with physiologic laxity, large increases in posterior tibial plateau subluxation may be detected after isolated PLS rupture because there is little resistance provided by the PCL.
- Diagnosis of injury to PLSs based on the final posterior position of the lateral tibial plateau, not on the degrees of external tibial rotation.
- Examiner palpates the position of the medial and lateral tibial plateaus to qualitatively determine the anterior and posterior position of the medial and lateral tibial plateaus with tibial rotation.

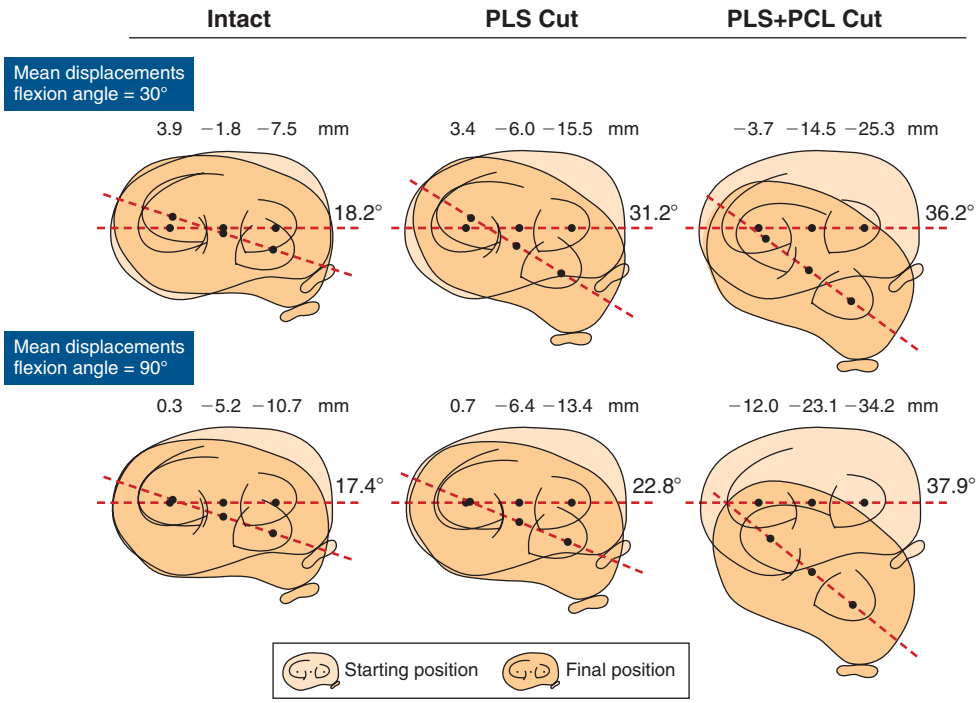


FIG 15-15 The mean values of external tibial rotation and the millimeters of anteroposterior (AP) translation for medial, central, and lateral tibial reference points are shown for 30 degrees and 90 degrees of knee flexion under the predetermined loads applied to the knee joint (100-N posterior load, 5 N-m external rotation torque). The neutral position (0-degree rotation, 0-mm AP translation) was determined in the intact knee by allowing the tibia to hang vertically by its own weight. *PCL,* Posterior cruciate ligament; *PLS,* posterolateral structures. (From Noyes FR, Stowers SF, Grood ES, et al. Posterior subluxations of the medial and lateral tibiofemoral compartments. An in vitro ligament sectioning study in cadaveric knees. *Am J Sports Med.* 1993;21:407-414.)

of the tibia after sectioning the PLS alone and in combination with the PCL.

Posterior Tibial Translation

The mean values of AP translation and external tibial rotation are shown in Figure 15-15 for intact knees and after sectioning the PLS and PLS/PCL. Sectioning only the PLS resulted in a mean increase in posterior translation of the lateral tibial plateau of 8.0 mm at 30 degrees of flexion over the intact state ($P < .01$) and a smaller increase of 2.7 mm at 90 degrees of flexion. There was no significant increase in posterior translation of the medial tibial plateau at either flexion angle. There was a large range of posterior tibial subluxations at both 30 degrees (Fig. 15-16) and 90 degrees (Fig. 15-17) of knee flexion.

Sectioning both the PCL and PLS caused significant increases in posterior translation of both the medial and lateral tibial plateaus at 30 degrees and 90 degrees of flexion ($P < .01$). The increase in posterior translation of the lateral tibial plateau compared with the intact state averaged 17.8 and 23.5 mm at 30 and 90 degrees of flexion, respectively. The increase in posterior translation of the medial tibial plateau over the intact state averaged 7.6 and 12.3 mm at 30 and 90 degrees of flexion, respectively.

External Tibial Rotation

The mean values of the external tibial rotation limits for the intact knees and after sectioning the PLS and PLS/PCL are shown in Table 15-2. Cutting the PLS caused a significant increase ($P < .01$) in external tibial rotation at both 30 degrees (mean increase, 13.0 degrees) and 90 degrees (mean increase, 5.4 degrees) of flexion. Sectioning the PCL along with the PLS caused a further increase in external tibial rotation at 30 degrees (mean increase, 5.0 degrees; not significant) and at 90 degrees of flexion (mean increase, 15.1 degrees; $P < .01$). Considerable variability was present among specimens in the amount of measured external tibial rotation at 30 degrees (see Fig. 15-13) and 90 degrees (see Fig. 15-14) of flexion.

On the basis of these data, a classification system of rotatory subluxations was devised based on two concepts: the final position of the medial and lateral tibial plateaus under defined loading conditions (such as with either internal or external tibial rotation at a defined knee flexion angle) and the position of each plateau. There are three possible positions for each plateau: anterior subluxation, normal position, or posterior subluxation. For each of these positions of the lateral tibial plateau, there exists three corresponding positions for the medial tibial plateau (Fig. 15-18).

This study showed that in normal knees under the conditions of external tibial rotation (5 N-m) and a posterior force (100 N) at 30 degrees of flexion, the lateral tibial plateau displaced a mean of 7.5 ± 2.9 mm. After sectioning the PLS, a further increase to 15.5 ± 3.5 mm was noted, representing an increase of 8 mm of posterior tibial subluxation of the lateral tibia plateau from normal. This is the amount that the clinician may palpate on the lateral tibiofemoral step-off with external tibial rotation in knees with ruptures to the PLS (compared with the opposite knee). After sectioning the PCL (in addition to the PLS), a mean posterior translation of 25.3 ± 5.2 mm was demonstrated, representing a 17.8-mm increase from normal.

Under the same loading conditions at 90 degrees of flexion, sectioning only the PLS resulted in a small (2.7-mm) increase in posterior translation of the lateral tibial plateau. These data agree with the external tibial knee motion limits previously reported,[30] where small and

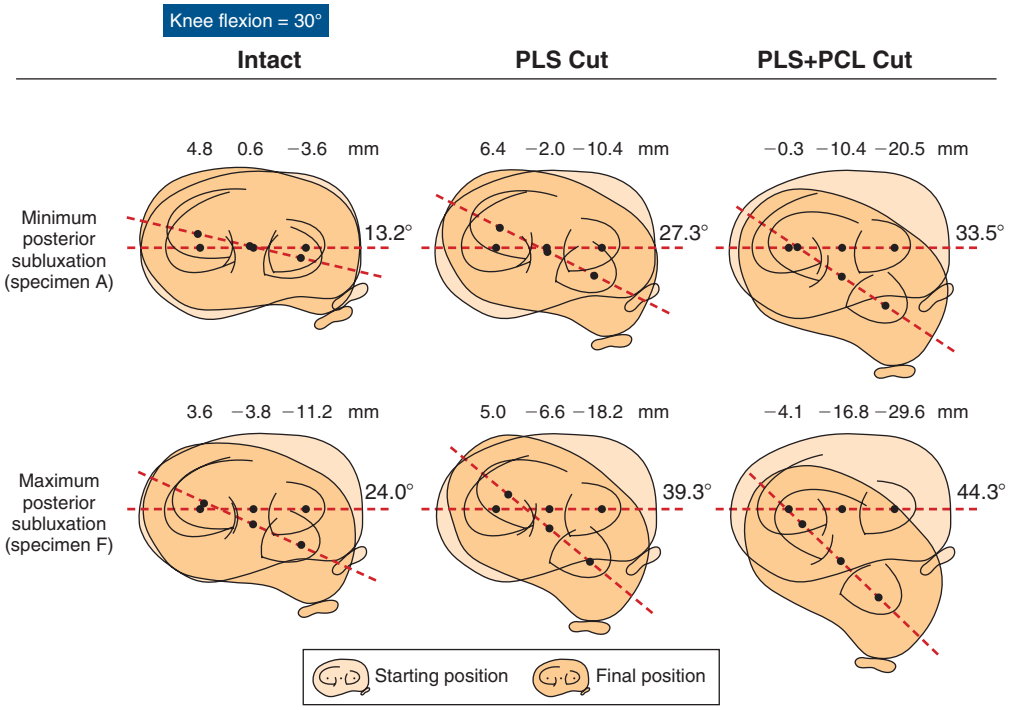


FIG 15-16 Tibiofemoral position at 30 degrees of knee flexion. The degrees of external rotation and the millimeters of anteroposterior translation for the medial, central, and lateral points are shown for two specimens, one with the least posterior tibial subluxation and one with the greatest posterior tibial subluxation (100-N posterior load, 5 N-m external rotation torque). *PCL,* Posterior cruciate ligament; *PLS,* posterolateral structures. (From Noyes FR, Stowers SF, Grood ES, et al. Posterior subluxations of the medial and lateral tibiofemoral compartments. An in vitro ligament sectioning study in cadaveric knees. *Am J Sports Med.* 1993;21:407-414.)

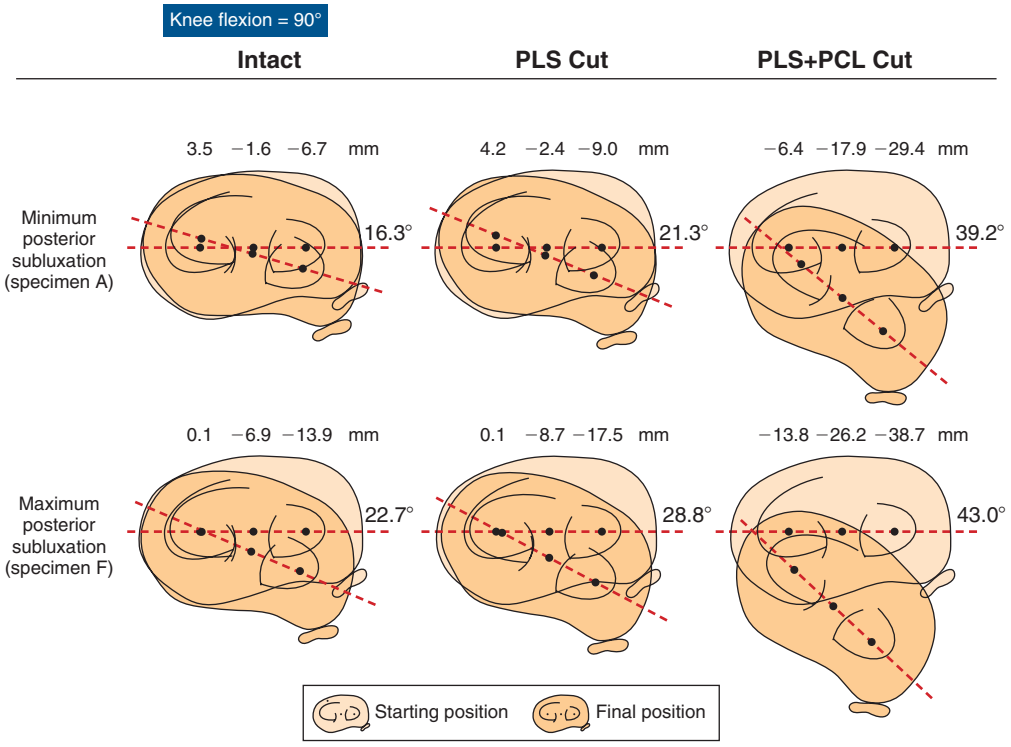


FIG 15-17 Tibiofemoral position at 90 degrees of flexion. The degrees of external rotation and the millimeters of anteroposterior translation for medial, central, and lateral points are shown for two specimens, one with the least posterior tibial subluxation and one with the greatest posterior tibial subluxation. *PCL,* Posterior cruciate ligament; *PLS,* posterolateral structures. (From Noyes FR, Stowers SF, Grood ES, et al. Posterior subluxations of the medial and lateral tibiofemoral compartments. An in vitro ligament sectioning study in cadaveric knees. *Am J Sports Med.* 1993;21:407-414.)

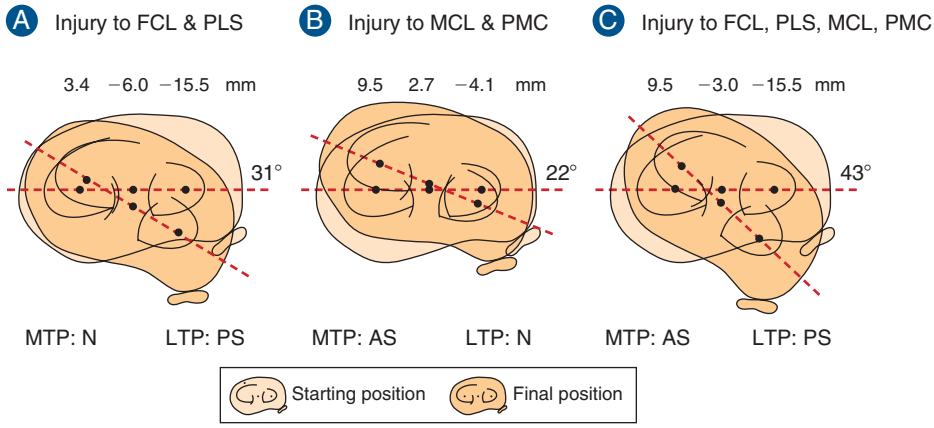


FIG 15-18 Three types of tibiofemoral situations observed with increased external tibial rotation. **A,** Abnormal posterior translation of the lateral tibial plateau (at 30 degrees of knee flexion under the loading conditions described in the study). **B,** Abnormal anterior translation of the medial tibial plateau under loading conditions of 5 N-m (at 30 degrees of knee flexion). **C,** Abnormal posterior translation of the lateral tibial plateau plus abnormal anterior translation of the medial tibial plateau after sectioning both the medial and lateral ligament structures. *AS,* Anterior subluxation; *FCL,* fibular collateral ligament; *LTP,* lateral tibial plateau; *MCL,* medial collateral ligament; *MTP,* medial tibial plateau; *N,* normal position; *PLS,* posterolateral structures (FCL, PMTL); *PMC,* posterior medial capsule; *PS,* posterior subluxation. (From Noyes FR, Stowers SF, Grood ES, et al. Posterior subluxations of the medial and lateral tibiofemoral compartments. An in vitro ligament sectioning study in cadaveric knees. *Am J Sports Med.* 1993;21:407-414.)

TABLE 15-2 External Rotation Limits (100-N Posterior Force, 5 N-m External Moment)

Flexion	External Rotation (Degrees; Mean ± SD)
30 Degrees	
Intact	18.2 ± 3.9
PLS cut	31.2 ± 5.0
PLS, PCL cut	36.2 ± 4.7
90 Degrees	
Intact	17.4 ± 3.5
PLS cut	22.8 ± 5.0
PLS, PCL cut	37.9 ± 3.0

PCL, Posterior cruciate ligament (and ligaments of Humphry and Wrisberg cut in addition to the PLS and FCL); *PLS,* posterolateral structures including fibular collateral ligament (FCL); *SD,* standard deviation.

insignificant increases in external tibial rotation occurred at 90 degrees after PLS sectioning. When the PCL was also sectioned, the lateral tibial plateau demonstrated a gross posterior subluxation, with a mean posterior translation of 34.2 ± 3.5 mm (23.5 mm from normal).

Effect of Physiologic Laxity

Normal knees that had greater physiologic laxity (greater posterior tibial translation and degrees of external rotation) had larger amounts of posterior subluxation of the lateral tibial plateau when the PLSs were sectioned. It is important to note that the posterior subluxation of the lateral tibial plateau varied from 10 mm to 18 mm at 30 degrees of flexion and from 9 mm to 18 mm at 90 degrees of flexion. This represents the displacement required to tense the PCL to resist further posterior subluxation of the lateral tibial plateau. In intact knees that had low values for posterior tibial displacements, ligament cutting resulted in a small increase in posterior subluxation, which was often lower than that measured in the normal "physiologically loose" knees.

From a clinical standpoint, knees that normally have low values for posterior subluxation that have substantial damage to the PLS may demonstrate only minimal increases in posterior tibial subluxation on external tibial rotation because of the secondary resistance provided by the PCL. Conversely, in knees with physiologic laxity, large increases in posterior tibial plateau subluxation may be detected after isolated PLS rupture because there is little resistance provided by the PCL. This finding explains the importance of individualizing the examination to each patient and determining his or her laxity profile. The surgeon should expect substantial differences in ligament stress tests in "tight-jointed" versus "loose-jointed" knees, which determines the amount of displacement before other secondary ligament restraints block further joint displacements.

The data in this experiment confirm the significant increase in posterior subluxation of the lateral tibial plateau at 30-degree knee flexion after sectioning the PLS, but not at 90-degree flexion. In addition, the data show that there is no significant increase in external tibial rotation after the PCL is sectioned and the PLSs are intact. The data also confirm that the diagnosis of injury to the PLS is based on the final posterior position of the lateral tibial plateau and not on the degrees of external tibial rotation. This is because an increase in external tibial rotation may occur with anterior subluxation of the medial tibial plateau when damage to the medial ligamentous structures is present.

In a prior study, the senior author and others[73] reported that the clinician may diagnose a posterolateral ligament injury when the increase in external tibial rotation is caused by a medial collateral ligament injury. For this reason, during clinical testing with the dial test for tibial rotatory subluxation, the examiner must palpate the position of the medial and lateral tibial plateaus to qualitatively determine if an anterior position of the medial plateau or a posterior position of lateral tibial plateau occurs with external tibial rotation. This is why the dial rotation test should be performed with the patient in the supine position (not in the prone position) as the senior author described to

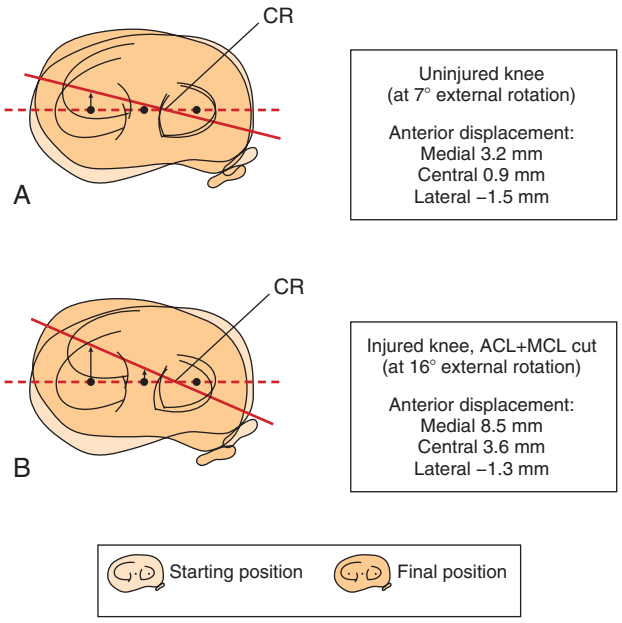


FIG 15-19 The external rotation dial test in the normal uninjured knee (**A**) and after sectioning the anterior cruciate ligament (ACL) and medial collateral ligament (MCL) (**B**). The increase in external tibial rotation from 7 degrees to 16 degrees is shown, along with an increase in anterior translation of the medial tibial plateau and shift in the axis of tibial rotation. *CR,* Center of rotation. (From Noyes FR, Cummings JF, Grood ES, et al. The diagnosis of knee motion limits, subluxations and ligament injury. *Am J Sports Med.* 1991;19:163-171.)

enable the examiner to observe and palpate the relative step-off of the medial and lateral tibial plateaus at 30 degrees and 90 degrees of flexion. Still, it may be difficult to quantify the amount of posterior subluxation of the lateral tibial plateau with PLS injuries, and additional tests such as lateral joint opening under varus loading and varus recurvatum are needed to confirm the diagnosis.

In Figure 15-19, the external rotation dial test is shown for a cadaveric knee measured with a 3-dimensional goniometer with 5 N-m load under conditions already described.[73] The increase in the external rotation limit and anterior translation of the medial tibial plateau is shown in the normal knee and then after sectioning the ACL and SMCL. The tibial rotation increased from 7 to 16 degrees and was associated with a lateral shift in the axis of tibial rotation. This resulted in an increase in anterior translation of the medial tibial plateau from 3.2 to 8.5 mm (anteromedial subluxation). In this study, examinations of cadaveric knees were performed by 11 experienced knee surgeons who were blinded as to the sectioned ligaments and asked to determine a diagnosis. More than one-half of the surgeons misinterpreted the increase in external tibial rotation as an injury to the PLS. This indicates that tests for rotatory subluxations of the knee joint are limited by the ability to quantitatively determine the millimeters of AP translation of the medial or lateral tibiofemoral joint under external rotation loads, and variability among examiners should be expected.

EFFECT OF PCL AND POSTEROLATERAL RECONSTRUCTION ON RESTORING NORMAL KNEE MOTION LIMITS

Isolated Posterior Cruciate Ligament Reconstructions

There still exist few studies and incomplete data to completely guide the surgeon on time-zero kinematics of single- and double-bundle PCL grafts (Table 15-3). As already discussed, there is a theoretic advantage of using two PCL grafts, owing to the substantial collagen material that is required, given the total cross-sectional area of the native PCL attachment. In addition, a second graft decreases the total forces a single graft is subjected to, because both grafts share the load (although in different percentages). The data presented show the difference in load-sharing between two grafts placed in the distal two-thirds of the PCL attachment compared with grafts placed in a distal and proximal manner. Other unanswered questions concern the amount of tension to be placed on PCL grafts and the appropriate knee flexion angle.

Kennedy and associates[45] performed a biomechanic study on a single-bundle anterolateral PCL reconstruction in nine cadaveric knees in which the graft was tensioned to 88 N and fixed at 75, 90, and 105 degrees. A posterior load of 134 N was applied, and knee laxity was determined at 0 to 120 degrees and 5 N-m external, 5 N-m internal, and 10 N-m valgus rotation torques. Each fixation angle had comparable time-zero loads; however, a residual average of 4.1 mm of posterior translation occurred. The authors did not provide a justification for selecting the 88-N initial graft tension, and the observation is made that a higher initial graft tension would most likely be necessary, as shown in published data already presented. The difference in methodology regarding the initial graft tension is important. Rather than selecting an arbitrary graft tension, an alternative approach is to tension the graft to a certain knee flexion angle (e.g., 90 degrees), which provides data on the amount of graft tension required to restore time-zero stability, and then examine the change in graft forces at different knee flexion positions.

In a second study, Kennedy and colleagues[46] performed an anatomic double-bundle PCL reconstruction to examine time-zero graft forces. In this study, the investigators used a higher overall total graft tension (initial tension anteromedial bundle of 88 N, posterolateral bundle at 67 N, total of 135 N) and reported a mean residual posterior translation of 1.5 mm at 90 degrees of flexion. Difficulties arise in comparing these results with single-bundle anterolateral bundle PCL data previously described (overall graft tension of 88 N), owing to the overall higher graft tension in the double-bundle study. The study recommended that the posterolateral bundle graft be tensioned at 0 degrees instead of 15 degrees and that the anterolateral bundle graft be tensioned at 90 to 105 degrees (compared with 75 degrees) to minimize higher graft tensions with knee flexion.

In two cadaveric knee studies,[57,61] Markolf and coworkers reported that a single-bundle PCL graft placed in the anterolateral femoral attachment produced a laxity profile that better replicated the normal knee, had better graft isometricity, and resulted in lower PCL graft forces than a double-bundle reconstruction (Fig. 15-20). The posteromedial graft overconstrained the knee from 30 degrees to 0 degrees (Fig. 15-21) and did not provide resistance to posterior tibial translation at higher flexion angles. Note that Markolf and coworkers used a

CRITICAL POINTS Effect of Posterior Cruciate Ligament and Posterolateral Reconstruction on Restoring Normal Knee Motion Limits

- Studies show the dependence of posterolateral reconstructions on a functional PCL or PCL reconstruction.
- PCL reconstruction may fail if concurrent injury to the PLS is not diagnosed and surgically addressed.
- All functional components of the posterolateral structures should be restored at surgery.

TABLE 15-3 Effect of Posterior Cruciate Ligament Reconstruction on Biomechanical Properties and Knee Motion Limits

Study	No. Specimens, Patient Age	Grafts, How Placement Was Determined	Results	Conclusions
Benedetto et al[5] (2014)	5 pairs, 65-85 yr	QT-PB, arthroscopic inlay. Anatomic PCL tibia footprint marked, remnants fibrous attachments left intact. Group A: tibial footprint positioned onto center of proximal margin of remnants (ALB). Group B, footprint center placed at most distal edge of remnants (PMB).	No difference in displacement at 5, 500, 1000 cycles. Significant difference in yield strength (N): group A, 201 ± 35; group B, 500 ± 186. Failure load (N): group A, 338 ± 130; group B, 564 ± 212. Stiffness (N/mm): group A, 74 ± 16; group B, 56 ± 13 ($P < .05$ all comparisons).	Replicating anatomic PCL footprint at posterior edge of the posterior tibial facet results in higher pullout strength compared with tunnel position at center of tibial facet. Bias of added backup fixation in group B.
Kennedy et al[45] (2014)	9, 29-63 yr	AT allograft, single strand, transtibial. Tibial tunnel: 1 cm medial to tibial tuberosity, 6 cm distal to joint line. ALB femoral footprint, centered, fixed at 75 degrees, 90 degrees, 105 degrees.	No difference in posterior translation for 3 fixation methods, but all residual increases compared with intact (5.3-5.4 mm). No difference in IR, ER, valgus rotation for 3 fixation methods.	All fixation angles significantly reduced posterior translation compared with intact, but residual translation existed.
Kennedy et al[46] (2014)	9, 29-63 yr	AT (ALB), anterior tibialis (PMB) allografts. Two strands. Fixation options (PMB/ALB): • 0 degrees/75 degrees • 0 degrees/90 degrees • 15 degrees/75 degrees • 15 degrees/90 degrees • 15 degrees/105 degrees	All methods significantly reduced posterior translation; mean residual laxity = 1.5 mm. Fixation PMB at 15 degrees resulted in significantly larger graft forces compared with fixation at 0 degrees during posterior, IR, ER, valgus rotation loading. Fixation ALB at 75 degrees resulted in larger forces than at 90 degrees or 105 degrees.	Fix PMB at 0 degrees and ALB at 90 to 105 degrees to reduce posterior translation to intact state and not result in increased graft loads.
Tompkins et al[100] (2013)	10 pairs, age unknown	OI vs. IO femoral drilling. CT scans used to compare 2 techniques; goal to place femoral tunnel aperture within anatomic femoral PCL footprint, determine tunnel orientation within medial femoral condyle.	OI technique placed 70.4% of the tunnel within native femoral footprint; IO placed 79.8%. IO technique created femoral tunnels with more vertical and anterior orientation.	Either technique can be used, but IO technique with knee hyperflexed during drilling likely produces "gentler graft bending angles."
Tsukada et al[112] (2012)	8, 52-77 yr	Two-strand (2 femoral, 2 tibial tunnels) reconstruction compared with single-strand AL reconstruction and single-strand PM reconstruction. STG for AL, ST for PM. AL fixed on tibia 90 degrees of flexion, PM bundle fixed at 0 degrees.	At 60 and 90 degrees, posterior translation single-strand PM reconstruction significantly greater than other 2 reconstructions, but no difference at 0 and 30 degrees flexion. No difference for all 3 reconstructions in posterior load + ER for all flexion angles.	Recommend 2-strand reconstruction; however, "cannot confirm superiority."
Weimann et al[113] (2012)	10, 55-78 yr	Single-strand STG. MCL and POL reconstructed with ST graft. 134 N posterior load, 10 N-m valgus torque, 5 N-m internal torque 0, 30, 60, 90 degrees of flexion. PTT measured robotic system.	PCL + posteromedial structures cut, PTT significantly increased all flexion angles. Knees with PCL + PM injuries had decreased PTT over PCL alone; however, still residual abnormal PTT (~5 mm).	Reconstruction POL contributed to normalizing PTT in knees with combined PCL-PM injuries. However, experimental bias of residual abnormal PTT.

Continued

TABLE 15-3 Effect of Posterior Cruciate Ligament Reconstruction on Biomechanical Properties and Knee Motion Limits—cont'd

Study	No. Specimens, Patient Age	Grafts, How Placement Was Determined	Results	Conclusions
Markolf et al[61] (2010)	10, 21-45 yr	Single-strand, 2-strand (narrow tunnel separation), 2 femoral tunnels, 1 tibial tunnel; 2-strand (wide tunnel separation) 2 femoral tunnels, 1 tibial tunnel; AT allograft.	Tunnel separation distance no difference in mean laxities, graft forces, tibial rotations. PM graft tightened from 30 to 0 degrees and developed high graft forces.	Need for PM graft questioned; high graft forces at 0 degrees may cause elongation with time. No biomechanic advantage to 2-strand reconstruction in making bone bridge between tunnels <3 mm.
Ahn et al[2] (2009)	20, 49-78 yr	Single-strand AT. Anteromedial cortex tibial tunnel (tip guide pin aimed 2.5 cm inferior from tibial tuberosity) vs. AL cortex tibial tunnel (1.5 cm lateral to tibial tuberosity). Both transtibial tunnel technique, 10-mm reamer drilled to tibial PCL insertion site.	Mean cortex-tunnel angles: 47.5 ± 9.3 degrees anteromedial vs. 28.3 ± 7.4 degrees AL ($P < .01$). Mean long tunnel diameter 10.6 ± 1.0 mm anteromedial vs. 14.0 ± 1.5 mm AL ($P < .01$). Maximal load at failure 385.4 ± 139.7 N anteromedial vs. 225.1 ± 144.1 N anterolateral ($P < .05$).	Anterolateral approach resulted in tunnel with wider entrance, more acute cortex-tunnel angle, and lower maximal load at failure. May require additional fixation.
Schoderbek et al[88] (2009)	8, 42-65 yr	3 femoral tunnel techniques compared: OI, IO at 90 degrees, IO at 120 degrees.	Mean graft-femoral tunnel angle: OI, 34.4 ± 14.4 degrees; IO, 120 degrees flexion, 52.3 ± 14.1 degrees; IO 90 degrees flexion, 74.4 ± 11 degrees. Angle smaller OI technique vs. both IO techniques ($P < .05$).	IO at 90 degrees produced high graft/femoral tunnel angle. OI produced lowest critical corner angle.

AL, Anterolateral; *ALB,* anterolateral bundle; *AT,* Achilles tendon; *CT,* computed tomography; *ER,* external rotation; *IO,* inside-out; *IR,* internal rotation; *MCL,* medial collateral ligament; *OI,* outside-in; *PCL,* posterior cruciate ligament; *PM,* posteromedial; *PMB,* posteromedial bundle; *POL,* posterior oblique ligament; *PTT,* posterior tibial translation; *QT-PB,* quadriceps tendon-patellar bone; *ST,* semitendinosus; *STG,* semitendinosus-gracilis.

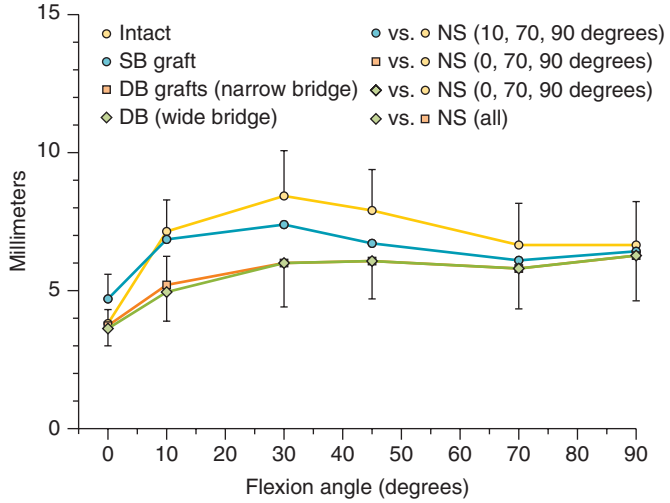


FIG 15-20 Mean anteroposterior (AP) laxities (at ±100 N) vs. knee flexion angle for the intact knee and after a single-bundle (SB) reconstruction and double-bundle (DB) reconstructions with narrow and wide bone bridges. Mean laxities are shown, and error bars indicate 1 standard deviation. Mean values are significantly different at each flexion angle unless indicated by *NS* (not significant). (From Markolf KL, Jackson SR, McAllister DR. Single- versus double-bundle posterior cruciate ligament reconstruction. Effects of femoral tunnel separation. *Am J Sports Med.* 2010;38:1141-1146.)

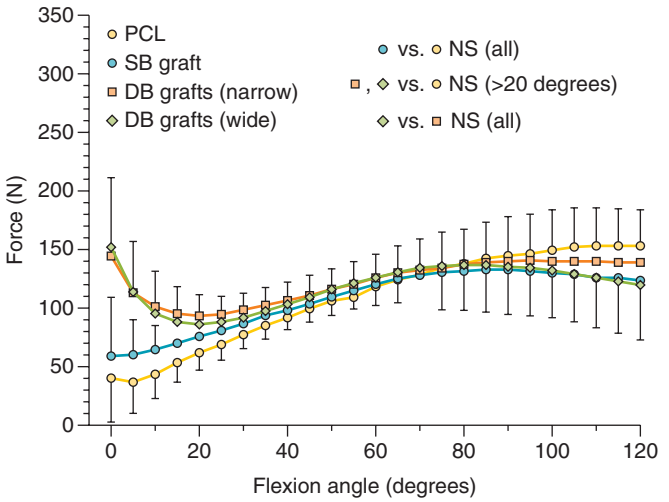


FIG 15-21 Mean curve of 100 N posterior tibial force vs. knee flexion angle for the intact posterior cruciate ligament (PCL), single-bundle anterolateral graft (SB), and double-bundle (DB) grafts with narrow and wide bone bridges; sample standard deviations are indicated by error bars. All mean graft forces are significantly different from corresponding PCL forces unless indicated by NS (not significant). (From Markolf KL, Jackson SR, McAllister DR. Single- versus double-bundle posterior cruciate ligament reconstruction. Effects of femoral tunnel separation. *Am J Sports Med.* 2010;38:1141-1146.)

PCL graft tensioning technique in which the graft was tensioned under measured loads to restore posterior knee translation to normal values at 90-degree knee flexion, in contrast to the studies of Kennedy and colleagues.[45,46] More conclusive studies regarding PCL graft positioning and tensioning are necessary in the future from both laboratory kinematic and clinical standpoints.

Combined Posterior Cruciate Ligament-Posterolateral Reconstructions

Sekiya and coworkers[89] conducted an in vitro cadaveric study using a robotic testing system in which the PCL was reconstructed with a two-strand construct (Achilles and semitendinosus tendons), the PFL was reconstructed with a gracilis tendon, and the popliteus tendon was reattached to its femoral origin. The specimens were subjected to a 134-N posterior tibial load and a 5 N-m external tibial torque at multiple flexion angles. The authors reported that the forces in the posterolateral grafts were significantly higher than those in the native PLS. A possible explanation for the increased loads on the posterolateral reconstruction is the fact that the two-strand PCL reconstruction did not restore normal posterior tibial translation, because significant increases in posterior tibial translation were detected from 0 to 90 degrees of flexion compared with intact knees. The PCL grafts were tensioned to a defined load, but not to the load required to reduce posterior tibial translation to normal; therefore the PCL reconstruction forces were low after the reconstruction. For this reason, additional loads were placed on the posterolateral grafts.

The data from the investigation by Sekiya and coworkers[89] and a subsequent study[37] show the dependence of posterolateral reconstructions on a functional PCL reconstruction. Harner and associates[37] studied the effect of deficiency of the PLSs on PCL Achilles tendon graft reconstructions in 10 cadaveric knees. The authors reported that a functional PCL reconstruction (posterior tibial translation restored to within 2.4 ± 1.4 mm of the intact knee, 90 degrees of flexion) subjected to sectioning of the PLS resulted in a significant increase in posterior tibial translation (6.0 ± 2.7 mm at 30 degrees, 4.6 ± 1.5 mm at 90 degrees; $P < .05$). In addition, the forces in the PCL graft were significantly increased for posterior tibial load, external tibial torque, combined posterior and external torque, and varus torque. These data support other studies in which researchers have concluded that a PCL reconstruction may stretch out or fail if a concurrent injury to the PLS is not diagnosed and concurrently surgically addressed.[63,71]

LaPrade and colleagues[48] conducted a biomechanic analysis of an anatomic posterolateral reconstruction in which a two-graft technique was used to replace the FCL, popliteus tendon, and PFL. The reconstructions were performed using Achilles tendon-bone constructs in 10 cadaveric knees aged 62 to 74 years (Fig. 15-22). It should be noted that in the reconstruction described by LaPrade and colleagues,[48] the PFL does not attach to the popliteus tendon at its normal anatomic attachment, and therefore this represents an anatomic reconstruction of the popliteus tendon and FCL. The knees were tested under a 5 N-m varus moment and 5 N-m external rotation torque, first with the PLSs intact; second with the FCL, popliteus tendon, and PFL sectioned; and

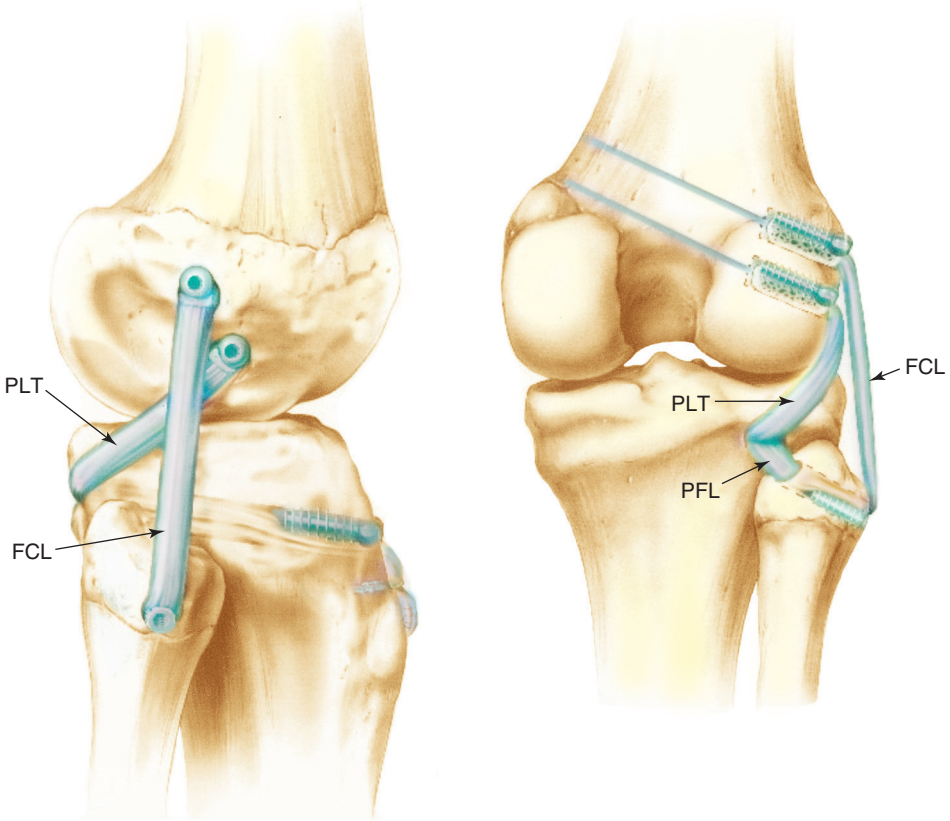


FIG 15-22 The posterolateral knee reconstruction described by LaPrade. *Left,* Lateral view, right knee. *Right,* Posterior view, right knee. *FCL,* Fibular collateral ligament; *PFL,* popliteofibular ligament; *PLT,* popliteus tendon. (From LaPrade RF, Johansen S, Wentorf FA, et al. An analysis of an anatomical posterolateral knee reconstruction. An in vitro biomechanical study and development of a surgical technique. *Am J Sports Med* 2004;32:1405-1414.)

third after the posterolateral reconstruction. There was no significant difference between the intact and reconstructed knees for varus translation at 0, 60, or 90 degrees of flexion or for external tibial rotation at 0, 30, 60, or 90 degrees of flexion. The authors concluded that this technique restored static stability and provides the scientific basis for patient outcome studies. We agree with this conclusion, because both the popliteus tendon (static attachments) and FCL were reconstructed.

Apsingi and coworkers[3] reported on the kinematics of cadaveric knees with a combined PCL and posterolateral ligament deficiency. The authors used both a single-bundle and double-bundle PCL reconstruction that was combined with a femoral-fibular graft reconstruction for the PLS. The combined PCL and posterolateral reconstruction restored all the laxity limits to normal, and the double-bundle PCL reconstruction was not reported to have an advantage over the single-bundle reconstruction. Of importance, the nonanatomic femoral-fibular reconstruction involved two femoral tunnels with the graft passed in an anterior-to-posterior direction through the fibula. The location of the two femoral tunnels was determined by selecting isometric points on the lateral femoral condyle and not by attaching the two graft arms to any specific anatomic location. The two graft ends passed through the two femoral tunnels were tensioned independently to restore the adduction and external rotation limits to normal. The anterior limb was tensioned at 20 degrees of flexion to match the laxity of the intact knee to varus loading. The posterior limb was tensioned at 90 degrees of flexion to match the intact knee motion limit to external rotation torque. Each graft arm was only 5 mm in diameter. The data from this study and others on femoral-fibular reconstructions may suggest that the more simplified femoral-fibular reconstruction is all that is required for posterolateral insufficiency, instead of the more complex anatomic reconstruction recommended by the senior author (F.R.N.) and LaPrade and colleagues.[48] It is true that in a time-zero cadaveric study, a single graft appropriately tensioned will restore varus and external rotation motion limits to normal.

Two points are worthy of emphasis. First, Apsingi and coworkers[3] did not measure the effects of the femoral-fibular reconstruction on decreasing or unloading the PCL graft. Markolf and associates[60] showed that an FCL reconstruction alone was insufficient to decrease or unload PCL graft forces. The Markolf and associates[60] data provide added support to the concept of restoring all of the functional components of the PLS at the time of surgery. Second, a small-diameter graft passed through the fibula and secured to the femoral condyle may be insufficient to resist the large adduction and external rotation loads that occur postoperatively. The anatomic reconstruction advocated by Noyes[72] and LaPrade[48] places two larger-diameter grafts at both the femoral, fibular, and tibial attachment sites of respective PLSs. The graft function therefore does not depend only on a fibular attachment site, and the popliteus tendon graft is passed through a distal tibial tunnel.

A third point on the application of biomechanic studies to clinical cases involves whether to select an isometric point on the femur for the FCL and popliteus tendon[60,94] or, as described by some authors, to select the anatomic attachment site to restore native anatomy.[48,72] Sigward and associates[94] reported, on the basis of a cadaveric knee study, the femoral fixation sites for isometry of posterolateral reconstructions. A coordinate grid system was located across the lateral femoral condyle, permitting the placement of 21 holes in the femur, 5 mm apart, for the measurement of suture length changes with knee flexion. The authors did compute a mean location for the FCL and popliteus tendon attachment; however, the femoral isometric points showed major differences among knees. This wide variability among specimens indicates that one mean value for the ideal isometric point for a graft placement would most likely be incorrect for knees undergoing surgery. Future clinical studies are necessary to determine the ideal success rates for knees in which either an isometric point is selected at surgery or an anatomic attachment site is selected. Until these studies are available, we recommend anatomic attachment points and an anatomic reconstruction for posterolateral instability as described in Chapter 17.

CLINICAL EFFECTS OF POSTERIOR TIBIAL SUBLUXATION OF THE PCL-DEFICIENT KNEE

Morrison[69] and Denham and Bishop[19] estimated that PCL forces up to 50% body weight occur during level walking. Even higher PCL forces have been calculated during stair-climbing, ascending stairs, and descending stairs.[6] (See Chapter 18 for other studies on estimated PCL forces during activity.) In a study done at our laboratory and involving 10 patients with complete PCL ruptures, the amount of posterior tibial translation that occurred during a double-stance static squat test was measured.[12] A lateral radiograph was obtained of both lower limbs, which was used to compute the amount of posterior tibial translation and sagittal plane forces on the PCL-deficient knee and a normal knee. A stress radiograph was taken with an 11-kg (108-N) posterior force to provide an objective measurement of the amount of posterior translation in the PCL-deficient knee compared with the opposite, normal knee. In low knee flexion angles, only 3 of the 10 knees had a posterior subluxation (from 5 to 9 mm) during the squat test. However, in high knee flexion positions, nine knees had an abnormal posterior tibial subluxation (mean, 5.9 ± 2.8 mm; range, 3-12 mm).

Logan and coworkers[52] used an open-access magnetic resonance imaging (MRI) system that allowed full weight bearing (squatting) by six patients with isolated PCL ruptures and measured tibiofemoral motion from 0 to 90 degrees of flexion (Table 15-4). The investigation found significantly increased, persistent posterior subluxation (~5 mm) of the medial tibia throughout knee motion. The authors concluded that the "fixed" anterior subluxation of the medial femoral condyle and posterior subluxation of the medial tibial plateau could explain the clinical observation of medial compartment osteoarthritis in PCL-deficient knees.

In several investigations, researchers have found significant differences in knee kinematics at higher knee flexion angles during a

CRITICAL POINTS Clinical Effects of Posterior Tibial Subluxation of the Posterior Cruciate Ligament-Deficient Knee

- PCL forces up to 50% of body weight occur during level walking.
- Higher PCL forces occur during stair-climbing, ascending stairs, descending stairs.
- Posterior tibial subluxation occurs in PCL-deficient knees during activities of daily living in high knee flexion positions, but not at low flexion positions in which smaller posterior shear forces are present.
- High PCL forces occur during a single-leg lunge between 60 and 120 degrees of flexion.
- Quadriceps neutral angle may vary from 60 to 90 degrees between knees; not objective measurement diagnosis of posterior tibial subluxation.
- PCL-deficient patients frequently note an anterior shifting of the tibia, as the tibial moves forward from its subluxated position, when they attempt to stand from a seated position.
- Significantly increased contact pressures in medial tibiofemoral and patellofemoral compartments occur in PCL-deficient knees.

TABLE 15-4 In Vivo Effects of Posterior Cruciate Ligament Deficiency

Study	Subjects	Methods	Results	Conclusions
Chandrasekaran et al[13] (2012)	10 isolated PCL injured knees, 10 controls	Supine leg press, 150-N load, MRI sagittal images 0-90 degrees. Tibiofemoral contact, flexion facet center measured from posterior tibial cortex.	Significant difference in medial compartment PCL-deficient compared with controls for contact pattern (greatest differences occurred at 75 degrees flexion of 4 mm and 90 degrees flexion of 5 mm) and flexion facet center (75 degrees flexion, 3 mm).	Significant difference medial compartment in sagittal plane articulation of TF joint in subjects with isolated PCL injury. TF contact and flexion facet center move more anteriorly on the tibia as the knee flexes in PCL-deficient knees.
von Eisenhart-Rothe et al[110] (2012)	12 isolated PCL injured knees, 20 controls	MRI supine, with and without isometric muscle contractions, 0 to 90 degrees of flexion.	Significant differences at 90 degrees, femur anterior in relation to tibia, patellar tilt and patellar shift positioned laterally. Isometric muscle contractions caused anterior translation of femur compared with muscle relaxation.	Significant changes in TF and patellofemoral joint kinematics occur in patients with isolated PCL deficiency >30 degrees flexion; may explain development of OA.
Goyal et al[27] (2012)	9 isolated PCL grade II injured knees, contralateral normal knees	Level running, stair ascent. Dynamic stereo x-rays taken, 3-D reconstruction knee anatomy created from CT scans. Model-based tracking used to align x-ray with CT bone models.	Running: swing phase: PCL-deficient tibia 2 mm posteriorly subluxated, had anterior velocity relative to the femur 40 mm/s greater than contralateral knee. Stair ascent: terminal swing and early stance phases: PCL-deficient tibia 4 mm posteriorly subluxated. Between foot strike and time of peak ground reaction force, tibia translated anteriorly relative to femur with velocities 3-4 times greater than contralateral knee.	Significant changes in knee kinematics during stair ascent may result in high shear forces that may expose the joint to potentially damaging forces.
Gill et al[25] (2009)	7 isolated PCL injured knees, contralateral normal knees, 2-year post-PCL single-bundle AT allograft reconstruction	Single-leg lunge, MRI and dual fluoroscopy used to create series of knee models to assess tibiofemoral and patellofemoral kinematics from 0 to 120 degrees of flexion.	TF: 75 to 120 degrees of flexion: both PCL-deficient and PCL-reconstructed knees significantly increased lateral tibial translation, abnormal patellar rotation, and tilt.	Single-bundle reconstruction restored normal anteroposterior translation; however, was not able to restore normal mediolateral tibial translation (small changes, 1-15 mm), patellar rotation, and patellar tilt.
Kozanek et al[47] (2009)	14 isolated PCL injured knees, contralateral normal knees	Single-leg lunge, MRI and dual fluoroscopy used to create series of knee models from 0 to 120 degrees. Length of posterolateral structures measured from models.	Significant increases in length of FCL, greatest at 120 degrees (injured, 51.6 ± 6.1 mm; normal, 48.2 ± 6.1 mm) and PMT unit, greatest at 30 degrees flexion (injured, 110.4 ± 10.2 mm; normal, 101.2 ± 9.3 mm).	PCL deficiency increases length patterns of FCL, PMT during weight-bearing flexion.
Van de Velde et al[104] (2009)	14 isolated PCL injured knees, contralateral normal knees	Single-leg lunge, MRI and dual fluoroscopy used to create series of knee models to assess location and magnitude of peak cartilage deformation in the tibiofemoral compartments from 0 to 120 degrees flexion.	Medial compartment: more anterior and medial location of peak cartilage deformation on tibial plateau compared with normal knees between 75 and 120 degrees flexion. Greater deformation of cartilage in medial compartment from 75 to 120 degrees flexion. No differences in lateral compartment.	PCL deficiency results in shift of TF contact and an increase in cartilage deformation in the medial TF compartment beyond 75 degrees of flexion.

Continued

TABLE 15-4 In Vivo Effects of Posterior Cruciate Ligament Deficiency—cont'd

Study	Subjects	Methods	Results	Conclusions
Van de Velde et al[105] (2009)	10 isolated PCL injured knees, contralateral normal knees	Single-leg lunge, MRI and dual fluoroscopy used to create series of knee models to assess patellofemoral kinematics and cartilage contact from 0 to 120 degrees flexion.	Significant differences 90 to 120 degrees of flexion: patellar flexion angle (mean, 10.7 degrees), decreased lateral shift (mean, –1.9 mm), decreased patellar tilt (mean, –2.7 degrees), decreased valgus rotation (mean, –1.8 degrees). Significant changes patellofemoral cartilage contact: distal (mean, –3.3 mm) and medial (mean, 2.7 mm) shift.	Significant differences occurred between 90 and 102 degrees flexion that might predispose patellofemoral joint to degeneration. Avoid deep squats in patients with PCL deficiency.
Li et al[51] (2008)	8 isolated PCL injured knees, contralateral normal knees	Single-leg lunge, MRI and dual fluoroscopy used to create series of knee models to assess translation and rotation from 0 to 105 degrees flexion.	≥90 degrees PCL-injured knees had significantly less anterior tibial translation (3.5-4.3 mm), greater lateral tibial translation (1.1 mm), lower varus rotation (mean, 0.6 degrees). All flexion angles >30 degrees, increased posterior tibial translation.	PCL functions to constrain posterior tibial translation, lateral tibial translation, and tibial rotation during weight-bearing flexion.
Logan et al[52] (2004)	6 isolated PCL injured knees, contralateral normal knees	Weight-bearing squats (0, 20, 45, 90 degrees flexion) and non-weight-bearing images (90 degrees flexion), vertical open double-doughnut MRI configuration.	Weight bearing: 5-mm increased posterior subluxation medial tibial plateau and anterior subluxation medial femoral condyle throughout arc of flexion.	During weight bearing, tibia subluxated posteriorly on femur in medial compartment.

AT, Achilles tendon; *CT,* computed tomography; *FCL,* fibular collateral ligament; *MGH,* Massachusetts General Hospital; *MRI,* magnetic resonance imaging; *OA,* osteoarthritis, *PCL,* posterior cruciate ligament; *PMT,* popliteus-muscle-tendon; *TF,* tibiofemoral.

single-leg lunge between PCL-deficient and contralateral normal knees using knee models created by MRI and dual fluroscopy.[25,47,104,105,110] For instance, Gill and colleagues[25] reported that PCL-deficient knees had significantly increased posterior tibial translation between 60 and 120 degrees of flexion compared with normal knees (mean difference, 3.5 ± 1.1 mm; $P < .05$). Significant decreases in patellar rotation and tilt were also observed between PCL-deficient knees and normal knees between 75 and 120 degrees of knee flexion.

These data support the concept that posterior tibial subluxation occurs in PCL-deficient knees during activities of daily living in high knee flexion positions, but not usually at low flexion positions, where smaller posterior shear forces are present. In strenuous activities such as sudden stopping, deceleration, or walking down a ramp, a posterior subluxation of the tibia is expected to occur. If the subluxation reaches 8 to 10 mm, minimal function of the menisci occurs (particularly the medial meniscus) and increased tibiofemoral stresses may be expected. As the tibia becomes more vertical with knee flexion, an increase in tibiofemoral compressive forces occurs from increased quadriceps and patellar tendon forces. However, the increased tibiofemoral compressive forces are not sufficient to overcome the posterior tibial shear forces, and a resultant abnormal posterior tibial translation occurs.

As noted by Daniel and colleagues,[17] the quadriceps neutral angle is the angle of knee flexion at which the course of the patellar tendon is perpendicular to the articular surface of the tibia. The neutral knee flexion angle may vary from 60 to 90 degrees, with a mean of 71 degrees. Below this angle, the patellar tendon lies anterior to the tibial tubercle and produces a posterior tibial shear force. Conversely, at a greater flexion angle, the patellar tendon has a line of action coursing posterior to the attachment to the tibial tubercle, producing an anterior tibial shear force. The quadriceps neutral angle varies sufficiently among knees and is not an objective measurement in terms of the diagnosis of posterior tibial subluxation. However, patients with PCL-deficient knees frequently note an anterior shifting of the tibia from its posterior subluxated position when they attempt to stand from a seated position, which can easily be demonstrated in the clinic.

Experimental studies have documented significantly increased contact pressures in the medial tibiofemoral and patellofemoral compartments after PCL sectioning.[24,53,96] Skyhar and coworkers[96] reported that PCL sectioning caused significant increases in contact pressure on the medial tibiofemoral compartment at all knee flexion angles compared with intact specimens (29.1 ± 11.6 Pa and 19 ± 3.4 Pa, respectively; $P < .05$). A significant elevation in contact pressure in the patellofemoral compartment was found only at 60 degrees of flexion. Gill and associates[24] analyzed patellofemoral contact pressures under simulated muscle loads in both PCL-sectioned and PCL-reconstructed cadaver knees (Achilles tendon single-bundle allograft). Significantly greater peak contact pressures were measured in the PCL-deficient knees than in the intact knees under both an isolated quadriceps (400 N) and a combined quadriceps and hamstrings (400 N/200 N) load. The PCL-reconstructed knees also had elevated pressures, which were not significantly different from those measured in the PCL-deficient specimens. There was no effect of knee flexion angle on these findings.

More recently, the location and magnitude of articular cartilage deformation in the tibiofemoral compartment was measured by Van de Velde and coworkers in 14 patients with isolated PCL deficiency

during a single-leg lunge.[104] Three-dimensional knee models of the bone and cartilage were derived from MRI sequences and were used to reproduce in vivo knee positions from 0 to 120 degrees of flexion. The location and magnitude of peak cartilage deformation were significantly altered in the PCL-deficient knees between 75 and 120 degrees of flexion. There was a more anterior (mean, 2.4 ± 0.4 mm) and medial (mean, 1.9 ± 0.4 mm) location of cartilage deformation on the tibial plateau, as well as increased deformation. There were no significant differences in the lateral tibiofemoral compartment for these values. In another investigation by Van de Velde and colleagues,[105] changes in patellofemoral joint kinematics and cartilage deformation were measured in 10 patients with isolated PCL ruptures during a single-leg lunge. Between 90 and 120 degrees of flexion, the PCL-deficient knees had a significantly increased patellar flexion angle (mean, 10.7 degrees), decreased lateral shift (mean, –1.9 mm), decreased patellar tilt (mean, –2.7 degrees), and decreased valgus rotation (mean, –1.8 degrees). There was a distal (mean, –3.3 mm) and medial (mean, 2.7 mm) shift of cartilage contact from 75 to 120 degrees of knee flexion. Chandrasekaran and associates[13] reported significant differences in medial compartment contact points and flexion facet centers (measured from the posterior tibial cortex) in 10 PCL-deficient knees compared with healthy knees during a supine leg press against a 150-N load. The tibiofemoral contact points and the flexion facet centers moved more anteriorly in the PCL-deficient knees, which were significantly increased compared with the healthy knee from 45 to 90 degrees of flexion. At 90 degrees of flexion, the mean difference in the tibiofemoral contact points was 5 mm and the mean difference in the flexion facet centers was 2 mm.

MENISCOFEMORAL LIGAMENTS

Gupte and colleagues[33] conducted an analysis of 16 anatomic studies involving 1022 cadaveric knees and reported that 91% had at least one MFL. The AMFL was identified in 390 knees (48%); the PMFL was identified in 569 knees (70%); and both the AMFL and PMFL were found in 257 knees (32%). It is important to identify the AMFL and PMFL (when present) to determine the PCL anatomic footprint for graft placement, particularly when a two-strand graft construct is used.[35] The anatomic attachment of the AMFL is distal to the PCL attachment (Fig. 15-23), which gives the appearance that the PCL footprint is adjacent to the articular cartilage when, in fact, the true PCL attachment is a few more millimeters proximal.

The cross-sectional area of the AMFL ranges from 6.8 to 7.8 mm^2, and the cross-sectional area of the PMFL ranges from 6.7 to 12.7 mm^2.[33]

CRITICAL POINTS Meniscofemoral Ligaments

- Most knees have at least one MFL.
- One-third of knees have both MFLs.
- Insufficient data to support a functional role of these structures.
- Identify AMFL and PMFL (when present) to determine true PCL anatomic footprint for graft placement.
- In some knees with isolated PCL ruptures, secondary ligament restraints including the MFL structures resist posterior tibial subluxation, particularly at low knee flexion angles.
- 90 degrees of knee flexion, neutral tibial rotation best position to test for maximum posterior translation.
- Amount of posterior translation determined by secondary restraints will vary depending on physiologic laxity.

For the surgeon, this indicates that these structures will be encountered at the time of PCL surgery. The mean ultimate loads of the AMFL and PMFL have been reported to be 265 ± 152 N and 443 ± 287 N, respectively.[43] A comparison of the ultimate strength of the MFLs and the PCL is not possible, because published cadaveric data are from older specimens tested at failure loads less than expected.

Gupte and colleagues[33] reviewed the numerous theories and evolutionary perspectives on the function of the MFL and concluded that there are insufficient data to support a functional role of these structures in humans. In animals such as sheep, horses, and dogs, the lateral meniscus posterior horn is attached by virtue of the PMFL without a separate posterior tibial attachment. In humans, the posterior horn of the lateral meniscus has two separate attachments into the tibia and, when the PMFL is present, an additional attachment into the femur. In rare cases, the posterolateral meniscus tibial attachment is absent and attaches only by the femoral PMFL, which must be preserved with any surgical procedure such as PCL reconstruction. The Wrisberg-type discoid lateral meniscus may have the PMFL as the only attachment, with an absent posterior tibial attachment. Gupte and colleagues[33]

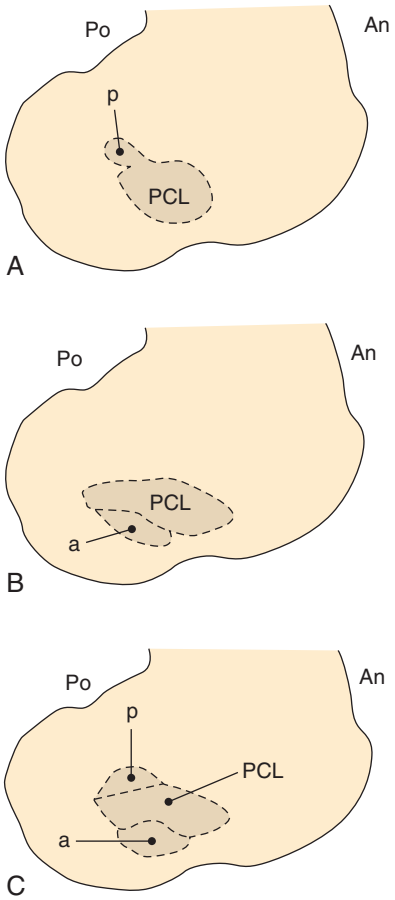


FIG 15-23 Femoral insertions of the meniscofemoral ligaments in relation to the insertion of the posterior cruciate ligament (PCL). Diagrammatic views of the left lateral femoral condyle in sagittal section demonstrate its anterior (An) and posterior (Po) aspects. **A,** Specimen with posterior meniscofemoral ligament (p) and PCL. **B,** Specimen with anterior meniscofemoral ligament and PCL. **C,** Specimen with PCL and coexisting anterior and posterior meniscofemoral ligaments. (From Gupte CM, Bull AM, Thomas RD, Amis AA. A review of the function and biomechanics of the meniscofemoral ligaments. *Arthroscopy.* 2003;19:161-171.)

noted that the PMFL is tight in both knee extension and deep knee flexion. It has been theorized that the PMFL may pull the lateral meniscus into the joint during flexion, causing clicking and snapping symptoms and leading to meniscus deteroriation.[20] It is possible that the PMFL provides additional resistance to posterior displacement of the lateral meniscus posterior horn during maximum external rotation tibia; however, this has not been experimentally proven.

The effect of the MFLs acting as a secondary restraint to posterior tibial translation was investigated by Gupte and coworkers[32] in cadaveric knees. The authors postulated that the MFLs provide to the PCL a "synergistic reinforcement" in resisting posterior tibial translation. In this study, the PCL was first divided and the increase in posterior tibial translation measured; then the MFLs were divided (Figs. 15-24 and 15-25). The data showed that the MFLs contributed 28% of the restraining force at 90 degrees of knee flexion without any restraint for rotatory subluxations. The data show that partial or isolated tears of the PCL may be supported in part by intact MFL structures, resulting in less overall posterior tibial translation. This

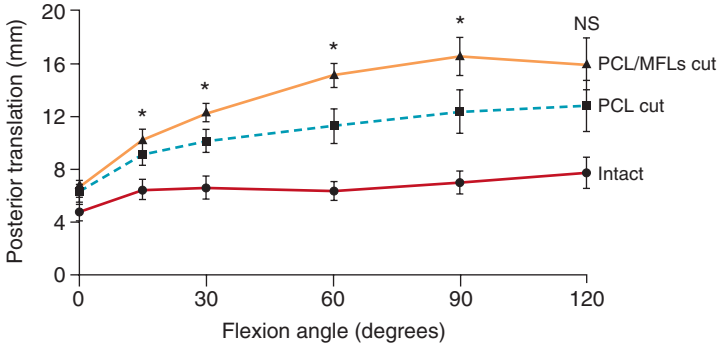


FIG 15-24 The effect of division of the posterior cruciate ligament (PCL) on posterior laxity in the intact knee, and the effect of division of the meniscofemoral ligaments (MFLs) in the PCL-deficient knee. Division of the PCL resulted in an increase in posterior translation at all angles of flexion in the intact knee (paired *t* test and analysis of variance; $P < .005$). Division of the MFLs resulted in an increase in posterior translation in the PCL-deficient knee between 15 and 90 degrees of flexion (*$P < .005$). Bars are standard error of the mean. *NS*, not significant. (From Gupte CM, Bull AM, Thomas RD, Amis AA. The meniscofemoral ligaments: secondary restraints to the posterior drawer. Analysis of anteroposterior and rotatory laxity in the intact and posterior cruciate-deficient knee. *J Bone Joint Surg Br.* 2003;85:765-773.)

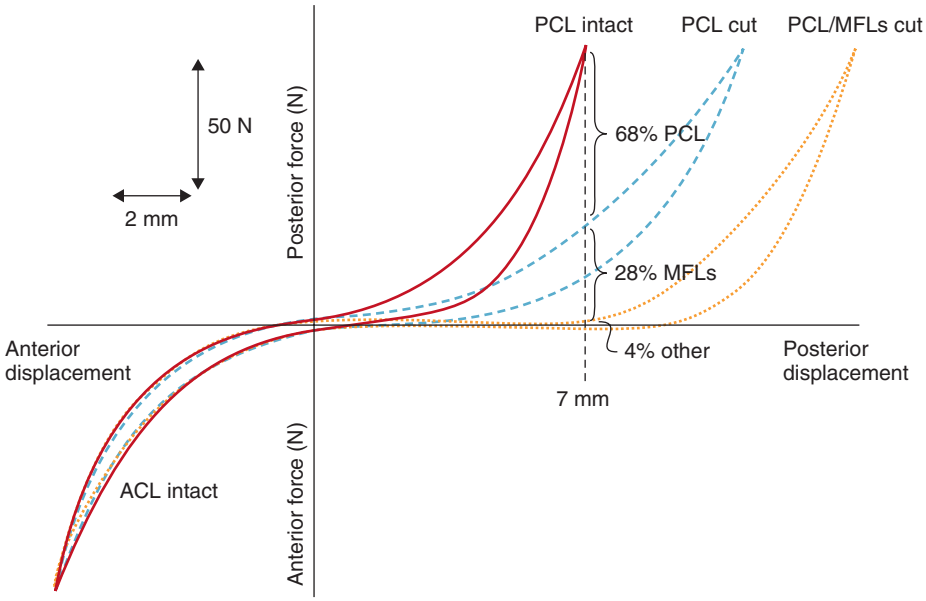


FIG 15-25 Mean load-displacement curves for intact, posterior cruciate ligament (PCL)-deficient and PCL/meniscofemoral ligament (MFL)-deficient knees tested at 90 degrees of flexion. Note the hysteresis effect of the anteroposterior (AP) drawer cycle. Note also the relative percentage contributions of the PCL and MFLs to resisting posterior drawer at displacement of 7 mm. The crossed hairlines mark the assumed AP neutral and zero load. (From Gupte CM, Bull AM, Thomas RD, Amis AA. The meniscofemoral ligaments: secondary restraints to the posterior drawer. Analysis of anteroposterior and rotatory laxity in the intact and posterior cruciate-deficient knee. *J Bone Joint Surg Br.* 2003;85:765-773.)

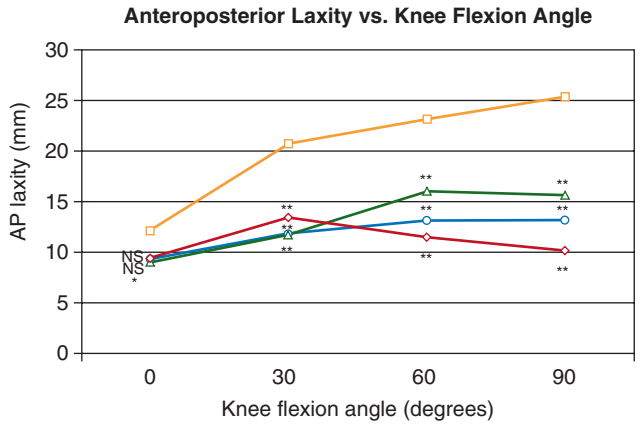


FIG 15-26 Anteroposterior (AP) laxity with the knee in 0, 30, 60, and 90 degrees of flexion. The test was performed under four conditions: with the posterior cruciate and meniscofemoral ligaments intact (diamonds), with the ligaments transected and the tibia in neutral rotation (squares), with the ligaments transected and the tibia in internal rotation (circles), and with the ligaments transected and the tibia in external rotation (triangles). **Significant difference at $P \leq .001$; *significant difference at $P \leq .05$; NS indicates no significant difference ($P > .05$) compared with the laxity measured with the ligaments transected and the tibia in neutral rotation. (From Bergfeld JA, McAllister DR, Parker RD, et al. The effects of tibial rotation on posterior translation in knees in which the posterior cruciate ligament has been cut. *J Bone Joint Surg Am.* 2001;83:1339-1343.)

TABLE 15-5 Anteroposterior Laxity for Each Condition at Each Knee Flexion Angle

	ANTEROPOSTERIOR LAXITY (mm)			
Condition	0 Degrees Flexion	30 Degrees Flexion	60 Degrees Flexion	90 Degrees Flexion
PCL and MFL intact	9.4	13.5	11.5	10.2
PCL and MFL transected				
Neutral tibial rotation	12.1*	20.8†	23.3†	25.5†
Internal tibial rotation	9.3*‡	11.8*‡	13.2*§	13.2§¶
External tibial rotation	9.0*	11.7*	16.1†	15.7†

*$P < .05$ compared with the intact condition.
†$P < .001$ compared with the intact condition.
‡$P > .05$ compared with the test performed with the ligaments transected and the tibia in external rotation.
§$P < .05$ compared with the test performed with the ligaments transected and the tibia in external rotation.
¶$P < .05$ compared with the intact condition.
MFL, Meniscofemoral ligament; *PCL,* posterior cruciate ligament.

suggests the potential benefit of preserving the function of the MFLs when possible at surgery, which is often difficult in double-bundle PCL reconstructions. This also provides the rationale for protecting knees with isolated PCL ruptures, using a postoperative brace at full extension with a calf pad for 4 weeks to allow initial healing. The secondary ligament restraints maintain a normal tibiofemoral joint position at full extension, keeping a normal PCL tibiofemoral attachment distance.

Bergfeld and associates[7] conducted a cadaveric study on 20 knees in which total AP translation was measured in four different flexion angles after cutting the PCL and MFLs. Testing was performed with the tibia in neutral, internal, and external rotation (5 N-m torque). Statistically significant decreases in posterior tibial translation occurred with internal and external tibial rotation (Fig. 15-26 and Table 15-5). The authors concluded that 90 degrees of knee flexion and neutral tibial rotation was the best position to test for maximum posterior translation and that the medial and lateral secondary restraints were tensioned to reduce the posterior limit with internal-external tibial rotation. Because the MFLs were cut, other structures limited posterior translation in internal tibial rotation and not the MFLs, as had been reported previously.[14] Note in Chapter 3, after sectioning the PCL, that the posterior tibial translation increased 12.1 ± 0.6 mm and that 15 of 22 specimens had increases greater than 10 mm. This indicates that the amount of posterior translation determined by secondary restraints will vary depending on their physiologic laxity. Therefore the frequently reported value of greater than 10-mm posterior translation, indicating injury to the secondary restraints cannot be used. The secondary restraints may be lax owing to either physiologic laxity or injury.

Gupte and colleagues[31] introduced the concept of a "meniscal tug test" at arthroscopy, which involves placing tension on the AMFL with a nerve hook and observing movement in the posterior horn of the lateral meniscus. The AMFL was confirmed in 88% of 68 knees, whereas the PMFCL was identified in only 9%. The authors concluded that this test could be used to distinguish between fibers of the PCL and MFLs, which is helpful in avoiding a misdiagnosis of a partial versus a complete PCL tear.

POPLITEOMENISCAL FASCICLE ATTACHMENTS

Staubli and Birrer[97] conducted anatomic dissections of the popliteus tendon and its fascicles and described the relationship of these to the lateral meniscus attachments in cadaveric knees. These authors also compared arthroscopic examinations of the popliteus-lateral meniscus attachments in a normal control group of 107 patients with those of 68 patients with acute and chronic ACL disruptions. Structural lesions of the popliteus meniscus attachments were observed in approximately 19% of control knees compared with 86% to 95% of ACL-deficient knees. The authors concluded that the surgeon should determine whether an anterior subluxation and disruption of lateral meniscus attachments is present, requiring operative repair at the time of ACL reconstruction.

Simonian and coworkers,[95] in a cadaveric study, transected the anteroinferior fascicle and then the posterosuperior fasciculi to determine the contribution of these structures to lateral meniscus stability. The mean lateral meniscal motion under a 10-N load was 3.6 mm. After the anteroinferior fascicle was cut, an increase in anterior displacement of the posterior horn of the lateral meniscus of 1.8 mm (50%) occurred, and when both fasciculi were cut, an increase of 2.8 mm (78%) was found. The authors concluded that the popliteomeniscal fasciculi contributed to lateral meniscus stability and acknowledged the difficulty in objectively determining abnormal meniscus displacements at the time of arthroscopic surgery. Tests for abnormal lateral meniscus displacement at the time of arthroscopic surgery and the repair of the popliteomeniscal fascicles are discussed in Chapter 23.

CRITICAL POINTS Popliteomeniscal Fascicle Attachments

- Structural lesions of the popliteus system observed in approximately 19% of control knees compared with 86% to 95% of ACL-deficient knees in one study.
- Popliteomeniscal fasciculi contribute to lateral meniscus stability, difficult to objectively determine abnormal meniscus displacements at arthroscopy.
- Surgeon determines whether an anterior subluxation of the posterior horn lateral meniscus is present with partial disruption of meniscus attachments, requiring operative repair. This is common with ACL ruptures.

PCL FIBER FUNCTION: SCIENTIFIC BASIS FOR PLACEMENT OF PCL GRAFTS AT TIBIOFEMORAL LOCATIONS

The anatomy of the cruciate ligaments has been described for over a century in qualitative terms as having two major bundles or bands. The Weber brothers in 1836[111] and Fick in 1911[23] published some of the first anatomic descriptions of the ACL and PCL; however, these authors did not conduct biomechanic studies to support their descriptions. The PCL has been classically described as a structure composed of an anterolateral bundle that is tense in flexion and a posteromedial bundle that is tense in extension. This nomenclature is still used today; however, we advance the concept that this classical description does not describe the function of the PCL fibers or provide the surgeon with adequate data for determining placement of PCL graft strands (see Chapter 16).

Inderster and associates[42] divided the PCL into three bundles: anterolateral, posteromedial, and posterior oblique. These authors reported that the femoral-to-tibial distances of the anterolateral and posteromedial bundles increased with knee flexion from 0 to 90 degrees, whereas the length of the posterior oblique bundle remained the same. Accordingly, they recommended a more posterior position of a PCL reconstruction at the femoral attachment of the posterior oblique bundle. The authors did not induce posterior loads on the tibia to determine femoral-tibial length changes under loading conditions, nor did they measure tibial displacements after PCL reconstruction.

Covey and colleagues[15,16] described a fiber continuum of the PCL consisting of four regions: anterior, central, posterior longitudinal, and posterior oblique. This four-fiber region classification was confirmed by Makris and coworkers[54] according to fiber orientation and osseous sites of attachment visualized in 24 cadaveric knees. The anterior fiber region attachment was located at the most anterior portion of the femoral attachment and inserted into the anterior portion of the tibial attachment. The central fiber region was the widest portion, representing the middle part of the femoral attachment, and inserted into the middle and slightly lateral aspect of the tibial attachment. The anterior and central fiber regions represented nearly 80% of the PCL, with the posterior fiber regions accounting for the remaining 15% to 20%. The posterior fiber region consisted of a posterior longitudinal attachment to the tibia medially and a posterior oblique region attachment to the tibia laterally.

In these investigations, the researchers reported that, under operative conditions, most of the PCL's attachment sites exhibit nonisometric behavior. Only the small posterior fiber attachment sites (which account for 15% of the PCL)[54] demonstrate near isometry. In addition, Covey and colleagues[15] reported marked loosening of most PCL fibers by an applied quadriceps force at knee flexion angles less than 75 degrees when compared with an unloaded state. Internal tibial rotation slackened certain fibers (anterior, central) near extension, but significantly tightened others (central, posterior) with flexion. The authors concluded that the joint angle and type of load applied to the knee joint produce different functional roles to the four fiber regions of the PCL.

CRITICAL POINTS Posterior Cruciate Ligament Fiber Function: Scientific Basis for Placement of Posterior Cruciate Ligament Grafts at Tibiofemoral Locations

- PCL classical description: anterolateral bundle tense in flexion, posteromedial bundle tense in extension. Does not describe function of PCL fibers, gives surgeon inadequate data for determining placement and tensioning PCL grafts.
- PCL ligament length pattern is highly dependent on a proximal-to-distal direction of the femoral attachment.
- Transitional zone in proximal one-third of PCL femoral attachment, approximately 11 mm from the articular cartilage distally, extending approximately 10 mm from the roof in a posterior direction.
- The bulk of the PCL lengthens with knee flexion, approximately one-third of the posterior fibers lengthen with knee extension.
- Graft placed within PCL attachment will have portions that undergo different elongations along every 2-3 mm in graft diameter, progressing in a proximal-to-distal direction.
- One- and two-strand reconstructions attached in three difference locations within PCL femoral footprint in a cadaveric investigation. Central tibial tunnel used.
  - One strand (distal and middle position) restored posterior translation limits to normal.
  - One strand (deep and proximal) abnormal increase in posterior translation.
  - Two strands (distal locations, tensioned at 90 degrees) shared applied load.
  - Two strands (one strand anterior, one proximal): reciprocal loading relationship.
  - Tension in single-strand PCL graft nearly doubles with knee flexion.
  - Placement of second graft strand in either distal or middle position most ideal.
- All graft constructs capable of restoring posterior translation limit to normal. However, the constructs do so by inducing high tensile forces in the graft that may be deleterious, producing eventual graft elongation.

Quantitative data have been reported by many investigators who have used a variety of techniques to determine the length-tension behavior of the PCL fibers under loaded conditions. These measurement conditions include the use of force measurement sensors,[4,58,63] wire cables,[21] mercury strain gauges,[22,44] and photogrammetric techniques.[18,101,106,107] Ahmad and associates[1] performed an analysis of PCL bundle length change and angle of orientation with knee flexion and extension. The anterolateral bundle was observed to become more vertical with increased knee flexion and the posteromedial bundle to become more horizontal. Therefore the posteromedial bundle has a better orientation to resist posterior tibial translation, owing to its horizontal position. The study data are in agreement with other studies showing the marked changes in the length of PCL fibers with knee flexion and extension based on their femoral attachment.

The use of an instrumented spatial linkage during application of joint loads (followed by digitization of the tibia and femoral surfaces and ligament attachment locations) allows the length of discrete fiber strands or regions within a ligament to be measured based on

tibiofemoral attachment sites and the change in distance (fiber length) with knee motion.[28,38,87] This information is required to determine locations of graft attachments whose tibiofemoral length changes the least with knee flexion or, alternatively, graft attachment locations at which the fiber length changes the most. The surgeon should select graft attachment locations that have the least amount of change in tibiofemoral length and tension the graft at the knee flexion position where the graft length is the longest (and therefore functional). For example, if a graft is tensioned at a knee flexion angle where the tibiofemoral fiber length is at its shortest, the graft will initially constrain knee flexion or extension and fail as the graft construct (tibiofemoral distance) lengthens with further knee flexion or extension.

The PCL ligament length pattern is highly dependent on a proximal-to-distal direction of the femoral attachment, and not on an anterior-to-posterior direction, as proposed by the anterolateral-posteromedial bundle concept previously discussed. In Figure 15-27, the tibiofemoral separation distances are shown for a number of proximal-to-distal locations that pass through the PCL femoral attachment. A transitional zone (<2-mm length change) adjacent to the center of rotation is shown. All attachment locations distal to line A-A lengthen with knee flexion, and all fibers proximal to this line shorten with knee flexion. In Figure 15-28, the average tibiofemoral separation length is shown along three femoral attachment site locations. Two sites are within the PCL femoral attachment, and one is outside the PCL attachment. These data demonstrate that the fiber length change is minimal in an anterior-to-posterior direction within the PCL attachment. These experimental findings were corroborated by Sidles and colleagues,[93] Ogata and McCarthy,[76] and Trus and coworkers.[102]

The changes in tibial attachment location show only a small effect on the tibiofemoral separation distance, as demonstrated in Figure 15-29. These experimental conditions are valid if one assumes a PCL fiber follows a straight path between attachment sites. Native PCL fibers do not follow straight paths but may have curvatures induced by other fibers. As yet, there is no description of fiber anatomy suggesting major PCL fiber curvature from one attachment site to another.

A simplified planar model may be used to explain the larger effect of the femoral attachment on PCL fiber length change in comparison with the tibial attachment. The model is shown in Figure 15-30, where the tibia is stationary and the femur rotates about a fixed center. The femur is positioned at 45 degrees, and the change in tibiofemoral distance is shown relative to the center of rotation with knee extension and flexion to 90 degrees. The planar model does not describe the true

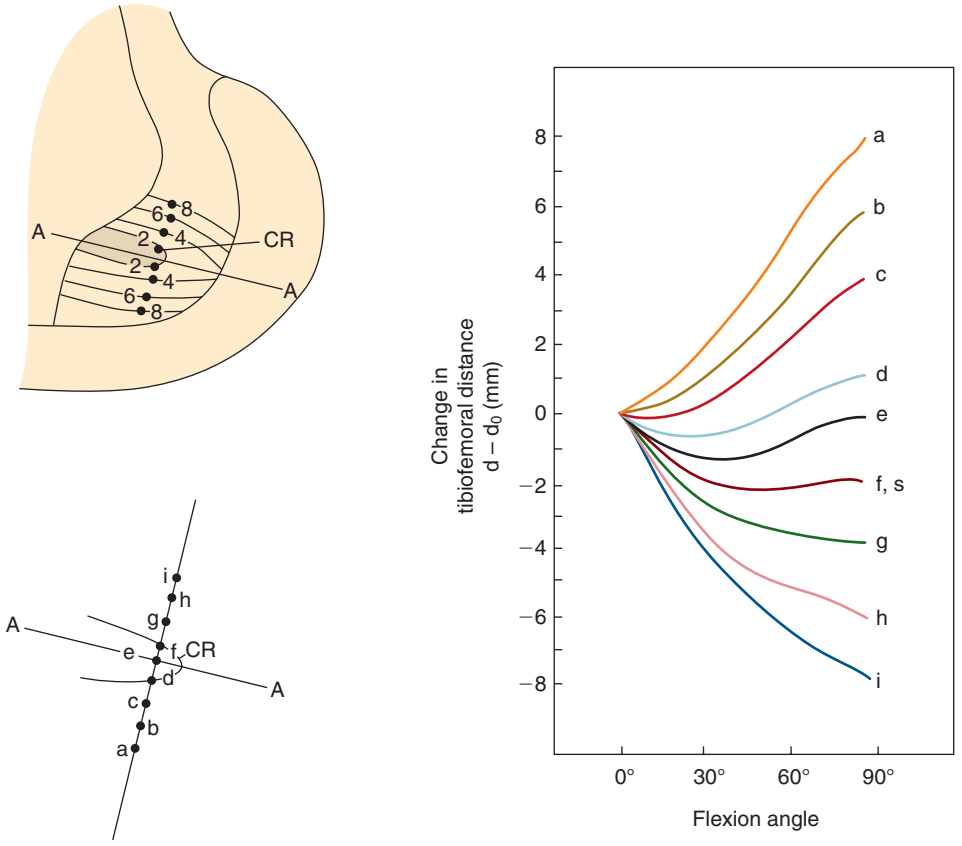


FIG 15-27 Contour map for one typical knee. The number on each contour line indicates the magnitude of the maximum length change. Line A-A represents the most isometric line and runs almost in the anteroposterior direction. Point CR indicates the intersection of the best-fit flexion axis with the lateral surface of the medial femoral condyle. Note that line A-A passes near point *CR*. The curves at the right show the changes in the tibiofemoral separation distances that occurred for selected femoral attachments. Attachments proximal to the isometric line were shorter at 90 degrees than at full extension. Attachments distal to the line were longer at 90 degrees. Attachments along line A-A had a length at 90 degrees that was nearly identical to its length at 0 degrees. (From Grood ES, Hefzy MS, Lindenfeld TN. Factors affecting the region of most isometric femoral attachments. Part I: the posterior cruciate ligament. *Am J Sports Med.* 1989;17: 197-207.)

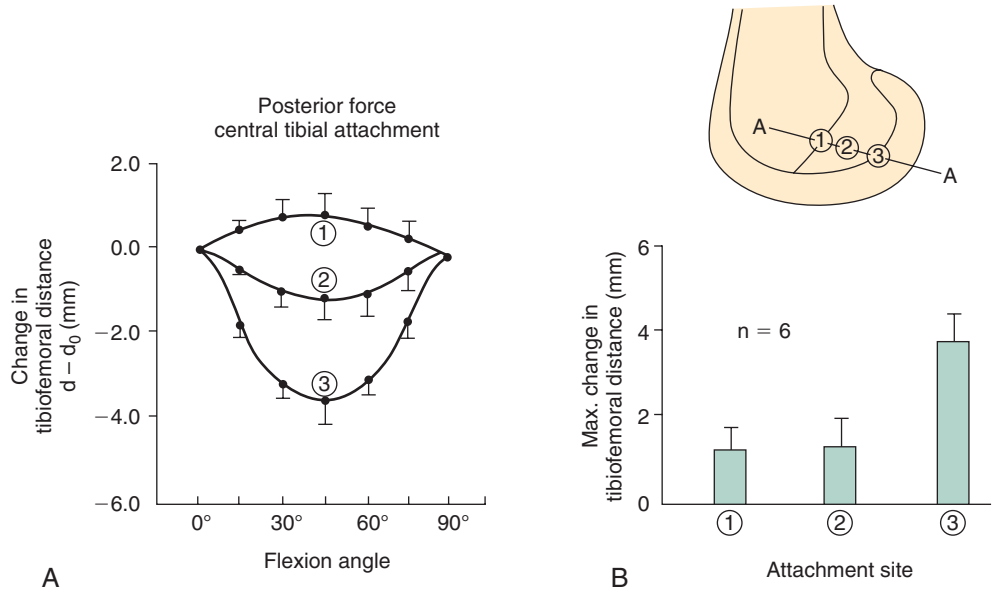


FIG 15-28 **A,** Average tibiofemoral separation distance vs. knee flexion for three femoral attachment sites located along the most isometric line. **B,** The average and standard deviation (shown by bars) of the difference between the maximum and minimum tibiofemoral separation distance for each of the three femoral attachment sites. (From Grood ES, Hefzy MS, Lindenfeld TN. Factors affecting the region of most isometric femoral attachments. Part I: the posterior cruciate ligament. *Am J Sports Med.* 1989;17:197-207.)

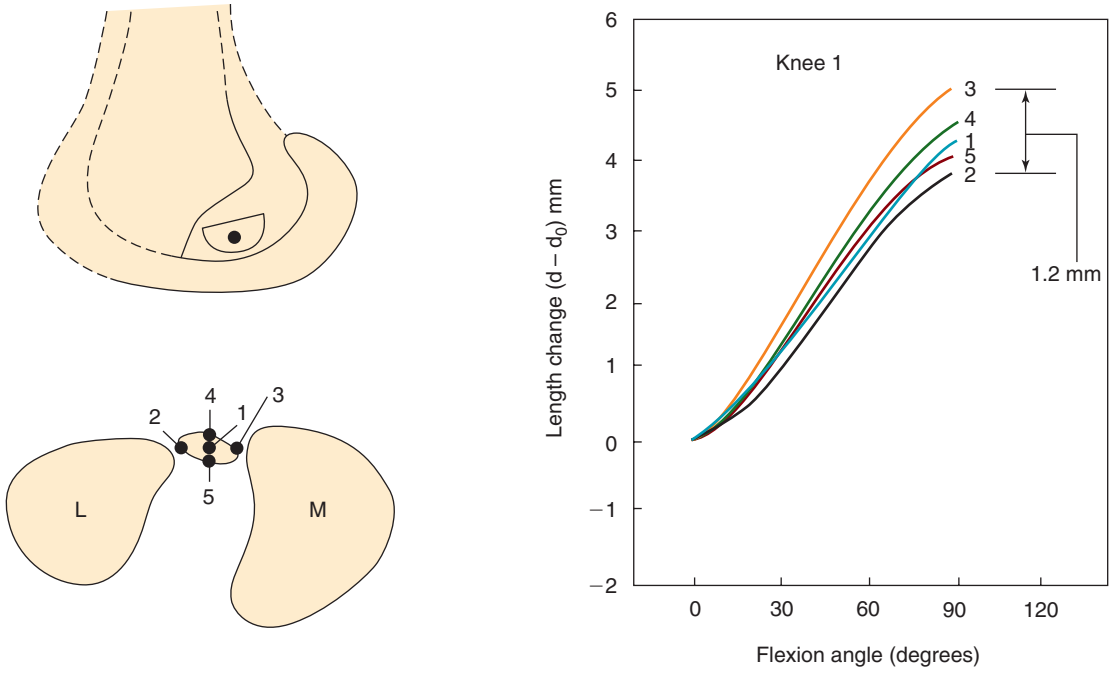


FIG 15-29 Relation between the change in the tibiofemoral separation distance and that at full extension and flexion angle for five tibial attachment sites in one typical knee. (From Grood ES, Hefzy MS, Lindenfeld TN. Factors affecting the region of most isometric femoral attachments. Part I: the posterior cruciate ligament. *Am J Sports Med.* 1989;17:197-207.)

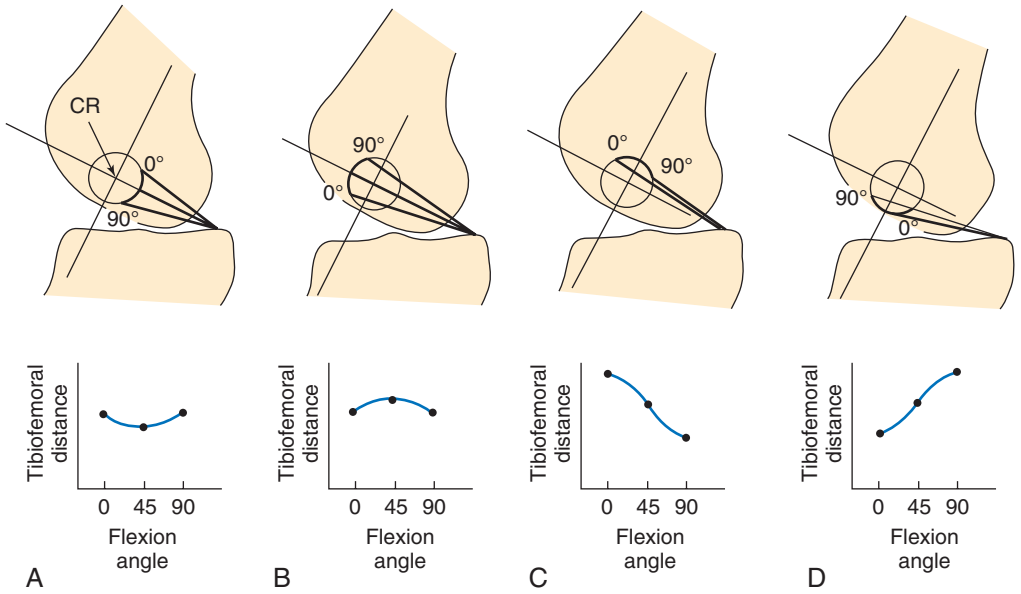


FIG 15-30 The mechanism governing the sensitivity of the length patterns of the fibers within the posterior cruciate ligament to their femoral attachments. **A,** Fiber is attached posterior to the center of rotation (CR) and has a concave length pattern. **B,** Fiber is attached anterior to the CR and has a convex length pattern. **C** and **D,** Length patterns of fibers with femoral attachments located proximal and distal to the CR. The fiber with proximal attachment (**C**) becomes longer with flexion, whereas the fiber with distal attachment (**D**) becomes shorter with flexion. (From Grood ES, Hefzy MS, Lindenfeld TN. Factors affecting the region of most isometric femoral attachments. Part I: the posterior cruciate ligament. *Am J Sports Med.* 1989;17: 197-207.)

3-dimensional behavior of the PCL fibers, which is more complex. However, the model does show how the fiber length change is dependent on its femoral attachment relative to the center of femoral rotation, which is simplified to a fixed point. Refer to Chapter 3 for further information on ACL and PCL fiber function.

The contour map showing the length change of PCL fibers based on their femoral attachment from 0 to 90 degrees is shown in a planar manner in Figure 15-31. A previous study showed that a graft placed into a nonisometric location, just distal to the transitional zone, demonstrated a few millimeters' increase in the tibiofemoral distance with knee flexion, providing greater control of posterior tibial displacement than a graft placed in a so-called isometric zone.[28] These data show that any graft placed within the PCL attachment will have portions that undergo different elongations along every 2 to 3 mm in a graft cross-sectional area, progressing in a proximal-to-distal direction.

In a second investigation at our laboratory,[87] several attachment sites at the proximal and distal origins located around the circumference of the PCL femoral attachment were studied. The peripheral attachment sites originated on the proximal border of the PCL (anterior, middle, posterior, and posterior oblique) and on the distal border (anterior, middle, and posterior). The limbs were loaded to 100 N, and the knees were flexed from 0 to 120 degrees. This was one of the first studies to examine PCL fiber length changes at knee flexion angles greater than 90 degrees. The changes in tibiofemoral length for the seven selected peripheral attachment points are shown in Figure 15-32. These data confirm that proximal PCL fibers lengthen with knee extension, whereas distal fibers lengthen with knee flexion. In Figure 15-33, the flexion angles in which the fiber length elongations were the least (within 5% of the maximum length and therefore the functional zone) are graphed for each attachment point. The data as a whole show a progressive loading of fibers from distal to proximal within the PCL

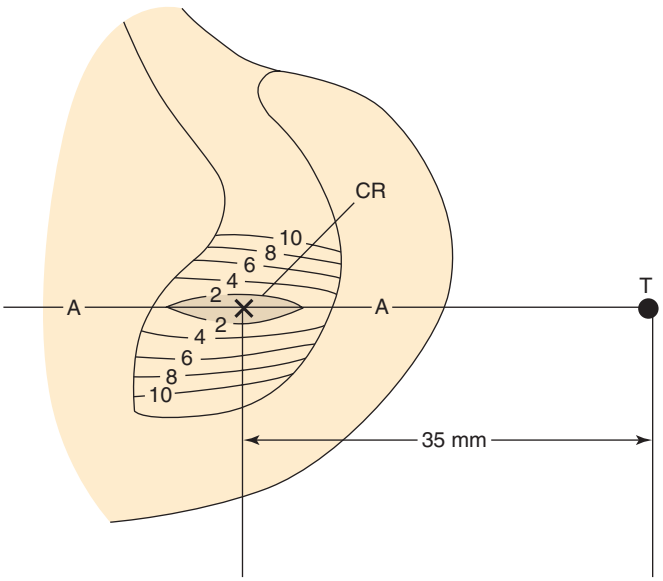


FIG 15-31 Contour map obtained from the single-hinge model in which the knee rotates around a single axis of rotation. A tibial attachment site (T) 35 mm away from this axis was used in the analysis. The number on each contour line indicates the magnitude of the maximum length change found as the knee was rotated from 0 degrees to 90 degrees. Line A-A represents the "most isometric" line. This line, besides being an axis of symmetry for the contour map, passes through the center of rotation (CR) and the tibial attachment site when the knee is positioned midway between the limits of flexion. Shading represents the region within which a maximum length change of less than 2 mm was found. (From Grood ES, Hefzy MS, Lindenfeld TN. Factors affecting the region of most isometric femoral attachments. Part I: the posterior cruciate ligament. *Am J Sports Med.* 1989;17:197-207.)

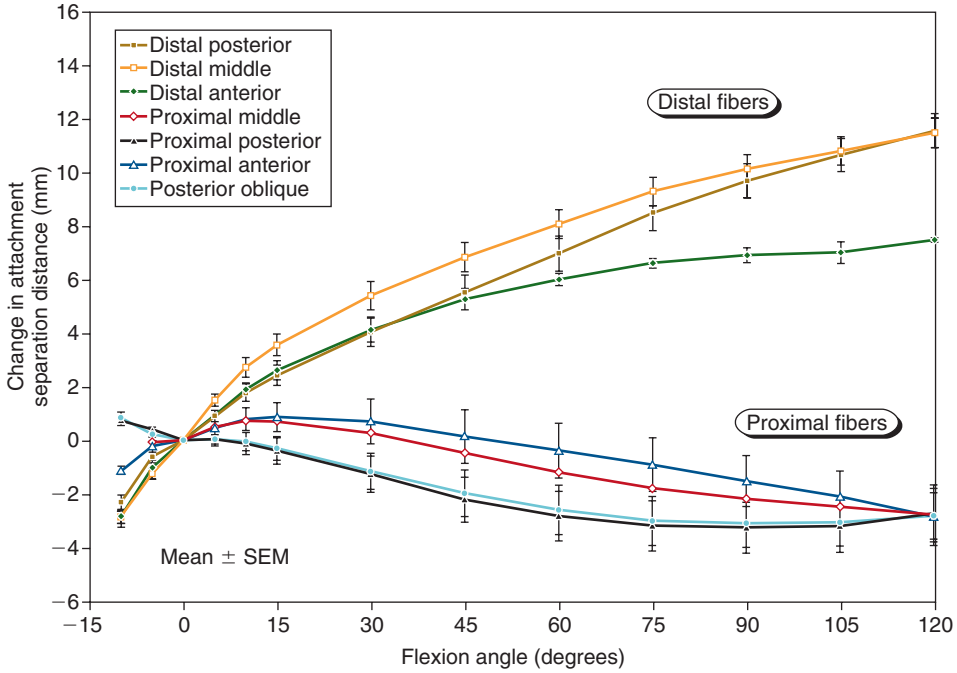


FIG 15-32 Changes in attachment separation distance in millimeters are measured with progressive knee flexion under a 100 N posterior load. Distal fibers lengthen with knee flexion, and proximal fibers shorten with knee flexion. (From Saddler SC, Noyes FR, Grood ES, et al. Posterior cruciate ligament anatomy and length-tension behavior of PCL surface fibers. *Am J Knee Surg*. 1996;9:194-199.)

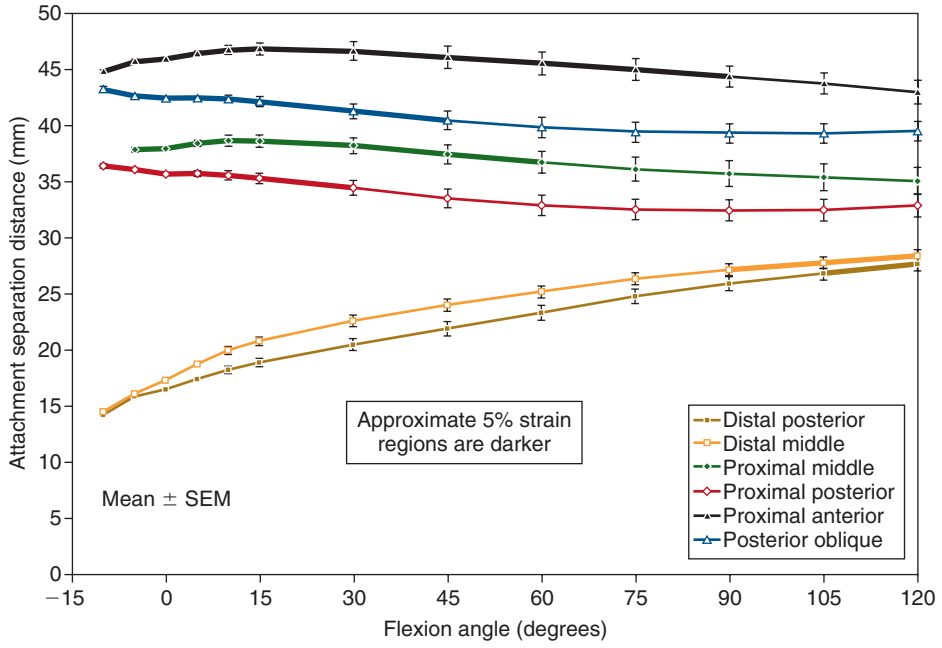


FIG 15-33 The change in attachment separation distance curves has been shifted to begin at the measured absolute length of each fiber. The darker area for each curve represents the 5% strain for each fiber. This, in theory, represents the functional range of knee flexion for each fiber. Note that this model predicts that the proximal anterior fiber will function over the longest functional range. (From Saddler SC, Noyes FR, Grood ES, et al. Posterior cruciate ligament anatomy and length-tension behavior of PCL surface fibers. *Am J Knee Surg*. 1996;9:194-199.)

Test Performed	Measurements
I. Intact knee (N = 12) a. 50-N posterior force b. 100-N posterior force	Six-degrees-of-freedom knee kinematics
II. PCL and MFL sectioned (N = 12) Same as in I	Same as in I
III. One-strand PCL reconstructions S_1 (N = 12), S_2 (N = 7), D (N = 5) 50 N posterior force	Six-degrees-of-freedom knee kinematics Strand tension
IV. Two-strand PCL reconstructions S_1–S_2 (N = 7), S_1–D (N = 5) 100 N posterior force	Six-degrees-of-freedom knee kinematics Tension in both strands

FIG 15-34 Tests performed and measurements made using six-degrees-of-freedom knee kinematics that include the three rotations (flexion/extension, adduction/abduction, and external/internal) and three translations (anterior/posterior, medial/lateral, and proximal/distal). (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000;28:833-845.)

attachment with progressive knee flexion. There is a smaller effect proceeding from anterior to posterior. These data contradict the description of PCL fiber function that divides the PCL into an anterolateral bundle (which is tight in flexion) and posteromedial bundle (which is tight in flexion).

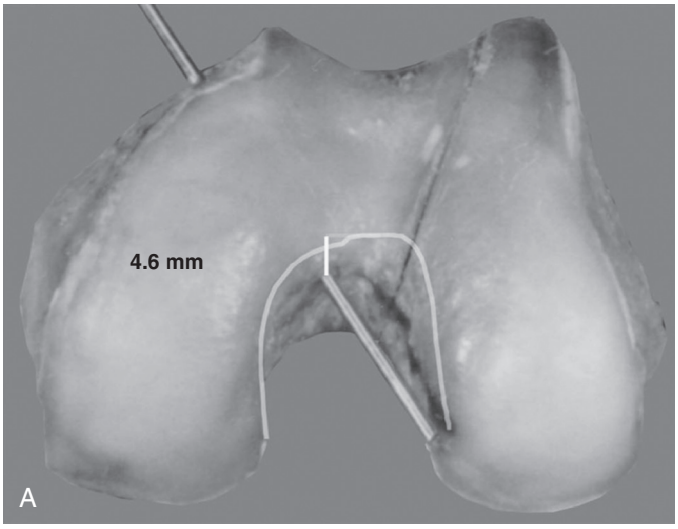
The surgeon has the option of placing a PCL graft strand in different regions of the PCL femoral attachment site that determines the functional range of the graft with knee flexion and the knee flexion position to tension the graft. This was investigated in a third cadaveric study in our laboratory in 12 cadaveric knees (Fig. 15-34).[55] The one-strand and two-strand reconstructions were attached in three different locations within the PCL femoral footprint (Figs. 15-35 to 15-37). A bone-patellar tendon-bone (B-PT-B) graft was used to provide secure fixation and prevent slippage in the fixture apparatus. The shallow edge of the graft was placed 2 mm from the articular cartilage margin. The center of the deep proximal strand was within 1 to 2 mm of the proximal edge of the PCL attachment. Within the femoral tunnels, the graft orientation was chosen to place the fibers on either the shallow or distal side of the tunnel, with the bone placed along the deep side. A central tibial tunnel was chosen. A 50-N posterior force was applied to the tibia for the single-strand constructions, and a 100-N force was applied to the two-strand PCL reconstructions. The tension in the graft strand was adjusted to restore posterior translation to within ±1 mm of the intact knee. The graft tensioning was performed at 90-degree flexion for all grafts except the proximal (deep) graft, which was tensioned at 30-degree knee flexion. This was done to remain consistent with prior data on the increased tibiofemoral separation distance of a graft placed at this location.

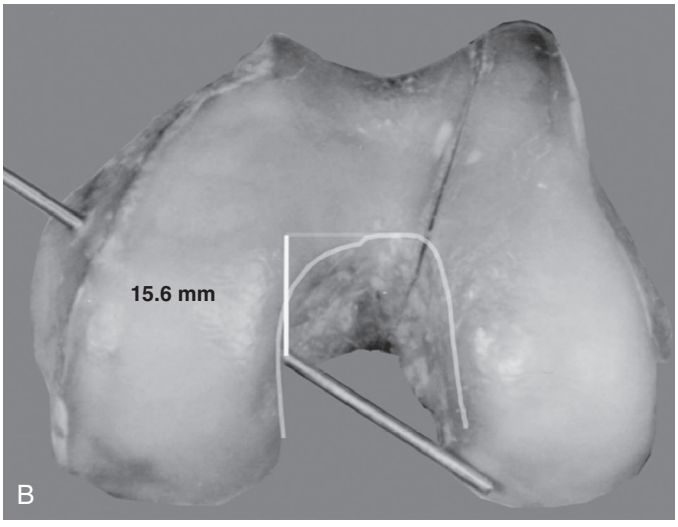
In Figure 15-38, the increase in graft tension with knee flexion is shown along with the posterior translation limit. The one-strand graft restored the knee joint to a normal posterior translation limit, with a more than doubling of graft tension with knee flexion (maximum, 118 ± 15 N; $P < .001$). In Figure 15-39, the one-strand reconstruction placed at the distal and middle (S_2) position shows a similar tension relationship with knee flexion and also restored knee posterior translation limits to normal. In contrast, the single-graft strand placed into a deep and more proximal position (Fig. 15-40) showed less overall graft tensile loading and an abnormal increase in posterior translation with knee flexion. The difference in the behavior from the two shallow grafts was significant ($P < .001$). The more proximal graft position and graft tensioning did not restore normal posterior translation limits and therefore is not a position recommended for PCL reconstruction.

The more complex behavior of a two-strand PCL reconstruction is shown in Figure 15-41, where the two strands were both placed into the more distal locations and tensioned at 90 degrees. Both strands shared the applied load, as shown. In contrast, a two-strand construct in which one strand was placed anterior and a second was placed more proximal resulted in a marked difference in load-sharing, with a reciprocal loading relationship found between strands (Fig. 15-42). In both situations, posterior translation limits were restored to normal. Similar results were reported by Carson and associates,[11] who conducted an in vitro study of cadaveric knees using a two-bundle (two femoral tunnels) and tibial inlay graft and measured forces in the anterolateral and posteromedial bundles. A reciprocal loading pattern was reported when the anterolateral bundle was placed anterior and the posteromedial bundle posterior to the center of femoral rotation. These authors recommended that tensioning and fixation of the anterolateral and posteromedial bundles be performed at 90 and 0 degrees, respectively.

To further investigate these findings, a fourth cadaveric study was conducted on 19 lower limbs to determine the tension that develops in various two-strand PCL graft constructs.[91] The test conditions are shown in Figure 15-43 for the graft strand configurations. A one-strand PCL reconstruction was performed, and the measured graft tension compared with three different two-strand reconstructions. The location of the single- and two-strand graft configurations are shown in Figure 15-44. The one-strand graft was placed in the anterior one-third and middle of the PCL femoral attachment. In the two-strand PCL graft reconstructions, one strand was placed in the anterior femoral region (AD_2) and the second in either the distal, middle, or proximal one-third of the PCL attachment. The reconstructions were tensioned (with a custom-designed instrumented spatial linkage) to restore posterior translation to ±1 mm of the intact knee (90 degrees flexion, 100-N posterior load). The two-strand graft configurations were all tensioned to share load, with the exception that the proximal strand (MP) was tensioned to carry 20%

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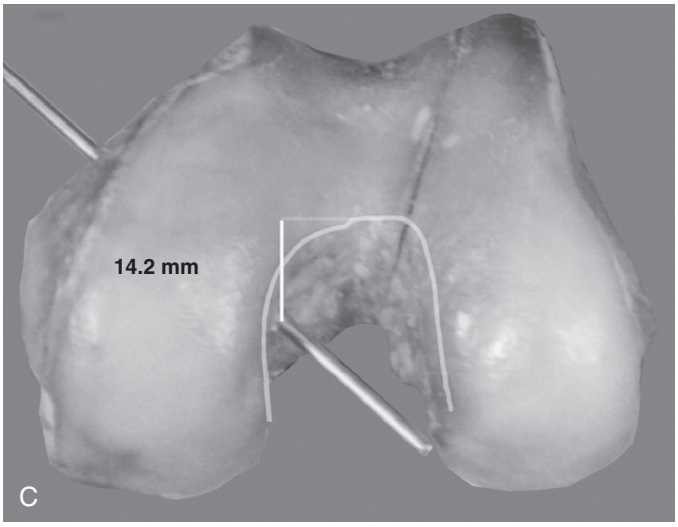
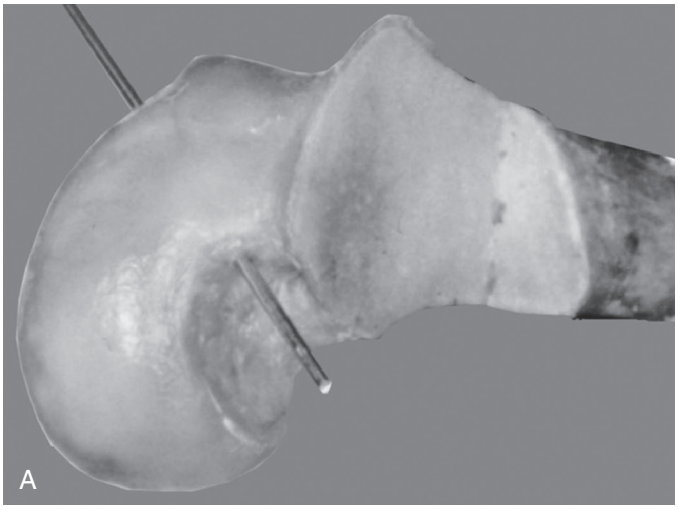
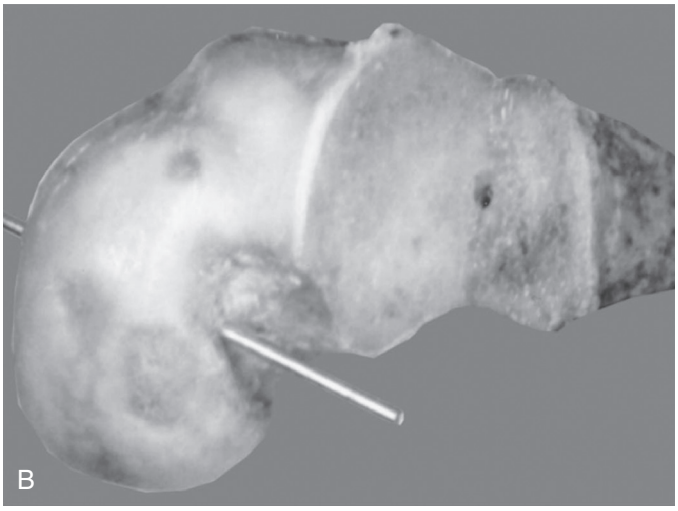


FIG 15-35 The transverse view of the three femoral tunnel positions. The measurements are taken posteriorly from the point at which the trochlear groove meets the intercondylar notch. (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000;28:833-45.)





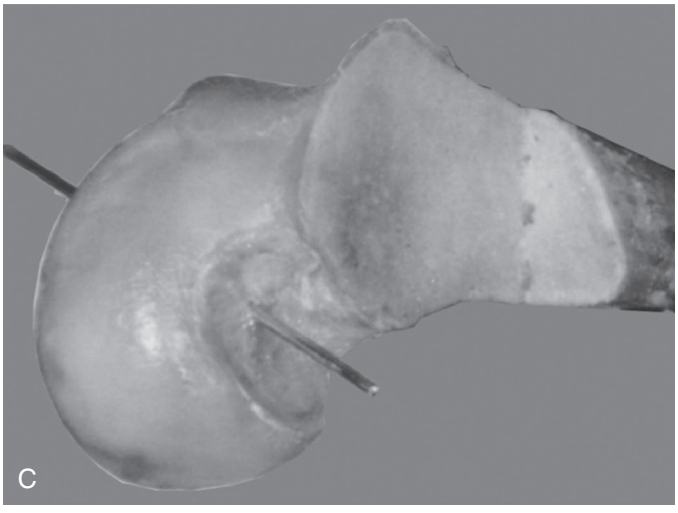


FIG 15-36 The oblique view of the three femoral tunnel positions. (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000;28:833-845.)

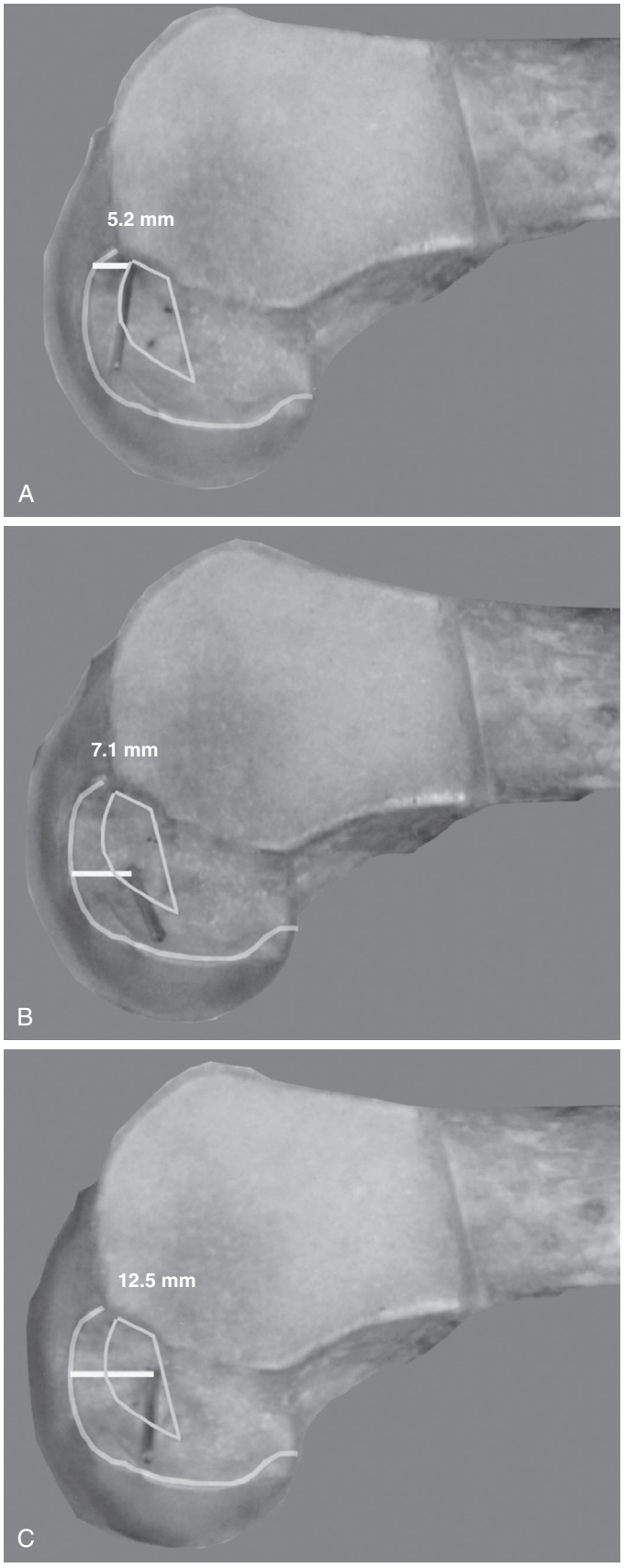


FIG 15-37 The sagittal view of the three femoral tunnel positions. (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000;28:833-845.)

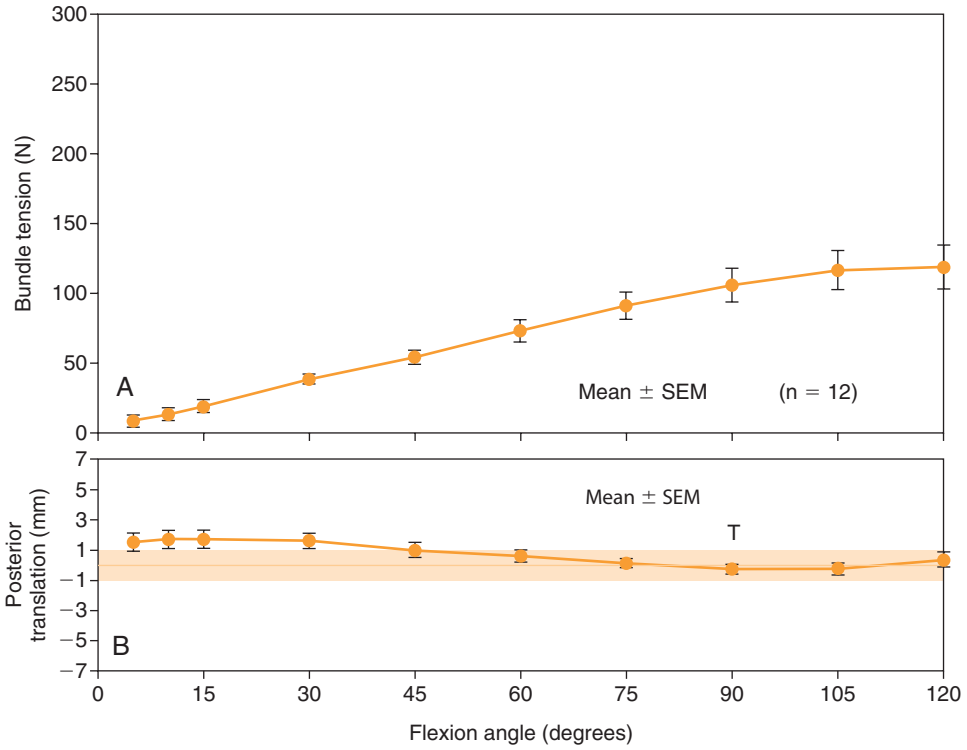


FIG 15-38 Strand tension (**A**) and change in posterior translation from intact (**B**) for the S_1 one-strand reconstruction with a 50-N posterior force. The *T* indicates the flexion angle where the strand was tensioned. The shaded area for posterior translation represents the translation for the intact knee ±1 mm. *SEM,* Standard error of the mean. (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000;28:833-845.)

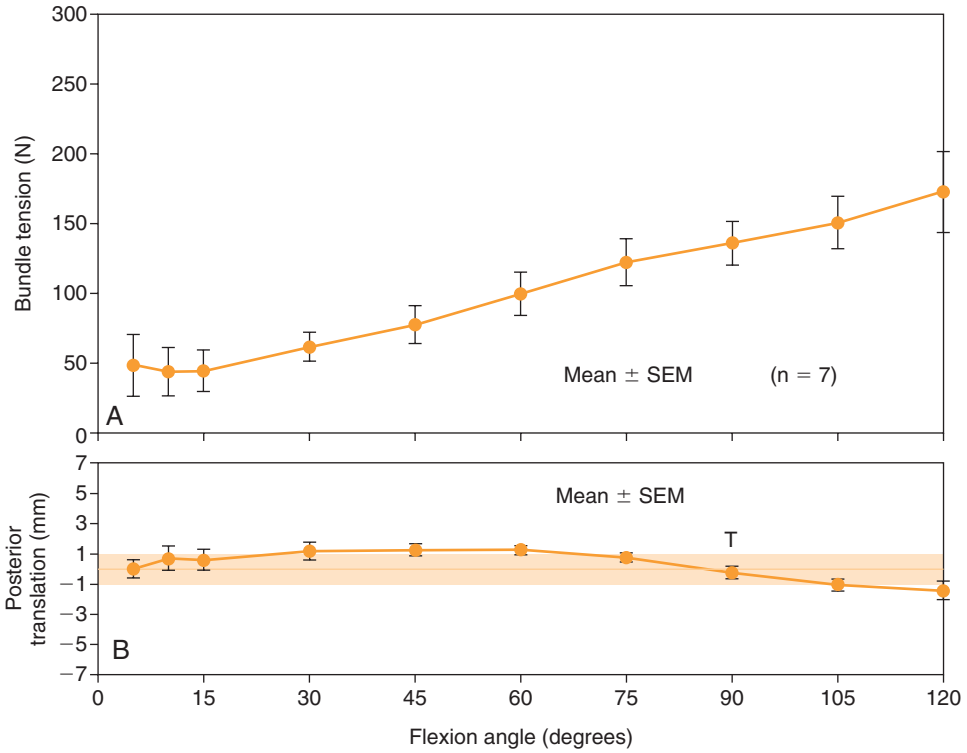


FIG 15-39 Strand tension (**A**) and change in posterior translation from intact (**B**) for the S_2 one-strand reconstruction with a 50-N posterior force. The *T* indicates the flexion angle where the strand was tensioned. The shaded area for posterior translation represents the translation for the intact knee ±1 mm. *SEM,* Standard error of the mean. (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000;28:833-845.)

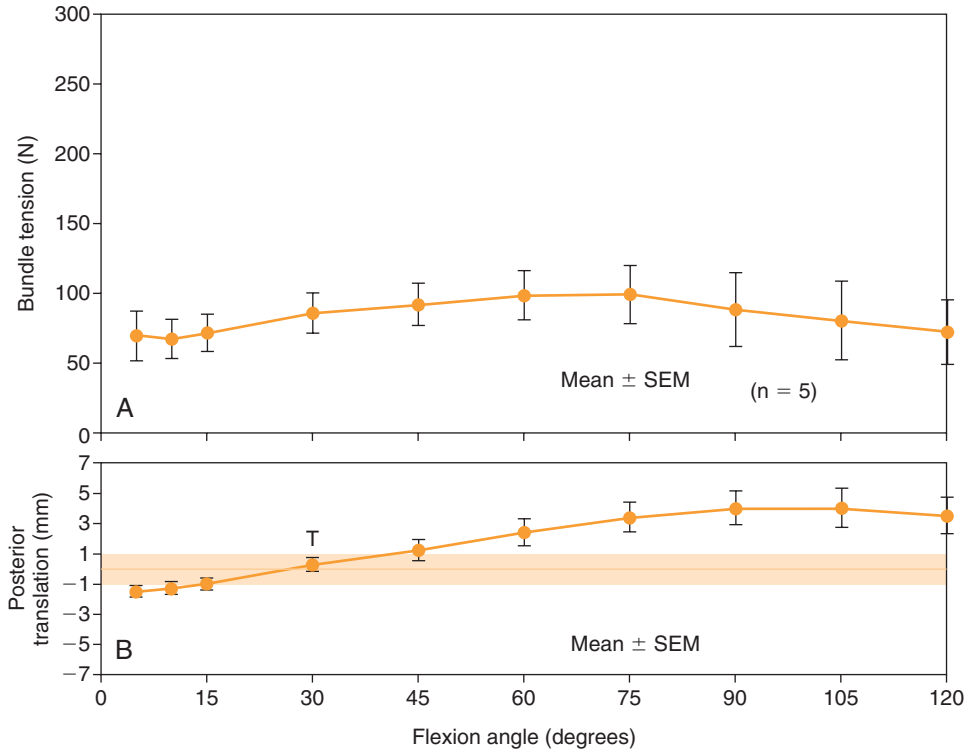


FIG 15-40 Strand tension (**A**) and change in posterior translation from intact (**B**) for the distal one-bundle reconstruction with a 50-N posterior force. The *T* indicates the flexion angle where the strand was tensioned. The shaded area for posterior translation represents the translation for the intact knee ±1 mm. *SEM,* Standard error of the mean. (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000;28:833-845.)

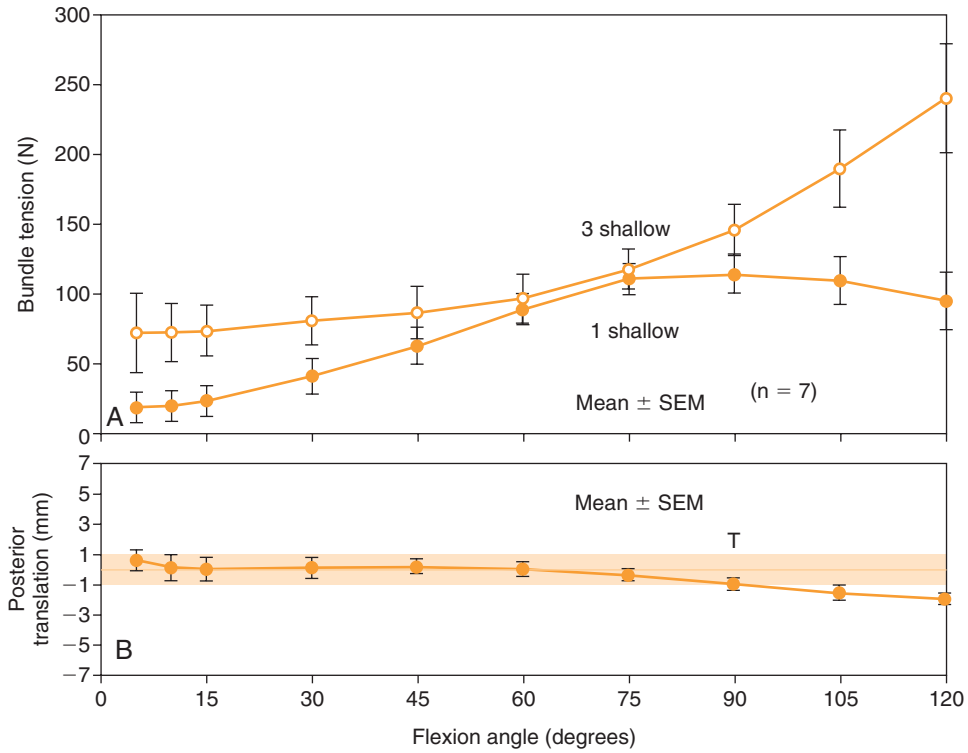


FIG 15-41 Strand tension (**A**) and change in posterior translation from intact (**B**) for the $S_1 - S_2$ two-strand reconstruction with a 100-N posterior force. The *T* indicates the flexion angle where the strands were tensioned. The shaded area for posterior translation represents the translation for the intact knee ±1 mm. *SEM,* Standard error of the mean. (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000;28: 833-845.)

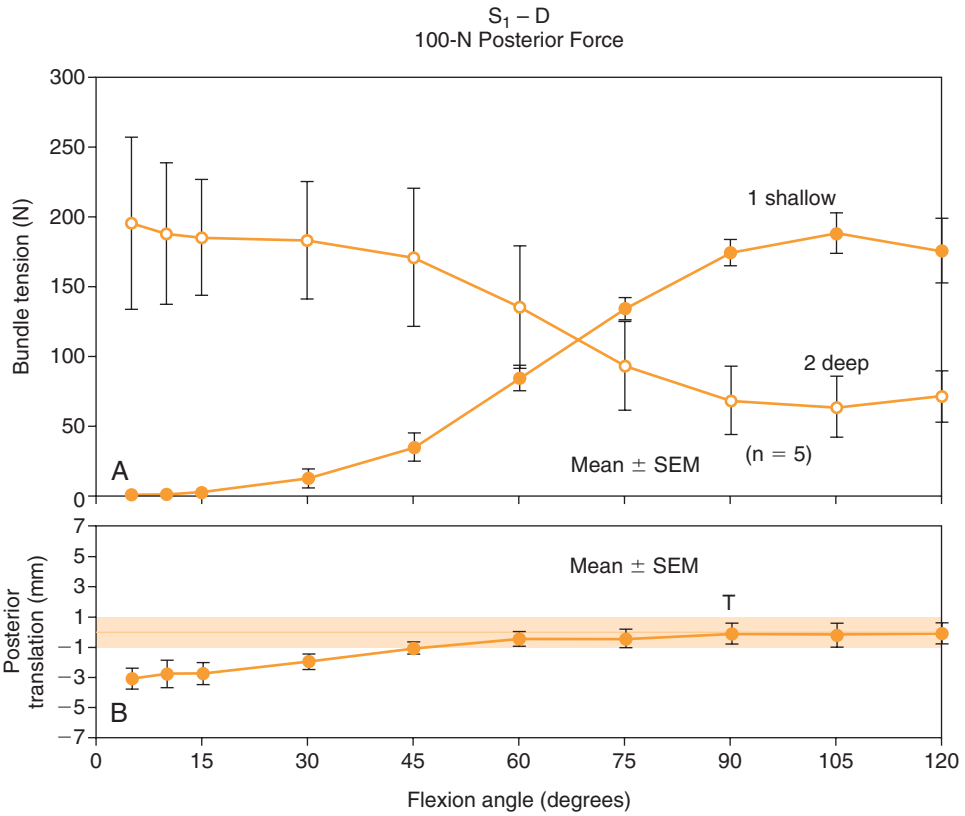


FIG 15-42 Strand tension (**A**) and change in posterior translation from intact (**B**) for the S_1 – D two-strand reconstruction with a 100-N posterior force. The *T* indicates the flexion angle where the strands were tensioned. The shaded area for posterior translation represents the translation for the intact knee ±1 mm. *SEM,* Standard error of the mean. (From Mannor DA, Shearn JT, Grood ES, et al. Two-bundle posterior cruciate ligament reconstruction. An in vitro analysis of graft placement and tension. *Am J Sports Med.* 2000; 28:833-845.)

Configurations Tested	Measurements
I. Intact knee (N = 14)	Flexion angle, AP translation
II. PCL and MFL sectioned (N = 14)	Same as I
III. One-strand PCL reconstruction AD_1 (N = 5)	Flexon angle, AP translation, strand tension
IV. Two-strand PCL reconstruction AD_2 – MD (N = 5) AD_2 – MM (N = 5) AD_2 – MP (N = 4)	Same as III

FIG 15-43 Knee configurations tested and measurements made. *AD_1,* One-strand anterior-distal reconstruction; *AD_2 – MD,* two-strand anterior-distal, middle-distal reconstruction; *AD_2 – MM,* two-strand anterior-distal, middle-middle reconstruction; *AD_2 – MP,* two-strand anterior-distal, middle-proximal reconstruction. (From Shearn JT, Grood ES, Noyes FR, Levy MS. Two-bundle posterior cruciate ligament reconstruction: How bundle tension depends on femoral placement. *J Bone Joint Surg Am.* 2004;86:1262-1270.)

of the load and the anterior strand was tensioned to carry 80%. The tension in each graft strand was directly measured during knee motion using strain-gauge load cells following a methodology previously described.[91]

The relationship between graft strand placement within the PCL femoral attachment and the tension and function of the graft strand is shown in Table 15-6. In Figure 15-45, the tension in the single-strand PCL graft is shown to nearly double with knee flexion. Under a 100-N posterior load, the graft tension reached over 200 N. This doubling of the tensile load as a multiple of the applied posterior load has been shown in numerous experiments conducted in laboratory studies. With the knee at 90 degrees of flexion, the PCL is elevated approximately 60 degrees from the sagittal AP plane. At this flexion position, the PCL resists nearly all (95%) of the applied posterior force. In this study, the graft tensions required to restore normal posterior translation limits ranged from 230 to 300 N.

TABLE 15-6 Posterior Translation With Graft Tensioning

Reconstruction	No. Knees	Change in Posterior Translation (mm)*	Anterior-Distal Strand Tension (N)	Second Strand Tension (N)	Total Strand Tension (N)
One-strand (anterior-distal)	5	–0.7 ± 0.3	230.3 ± 23	NA	230.3 ± 23
Two-strand (anterior-distal, middle-distal)	5	–0.1 ± 0.3	123.3 ± 6	152.3 ± 14	275.6 ± 19
Two-strand (anterior-distal, middle-middle)	5	–0.1 ± 0.4	148.0 ± 12	155.1 ± 15	303.1 ± 22
Two-strand (anterior-distal, middle-proximal)	4	0.6 ± 0.5	246.9 ± 20	40.8 ± 16	287.7 ± 25

Data are for 90 degrees of flexion with a 100-N posterior force applied to the proximal part of the tibia. The values are given as the mean ± standard error of the mean.
*Compared with the intact knee.
NA, Not available.

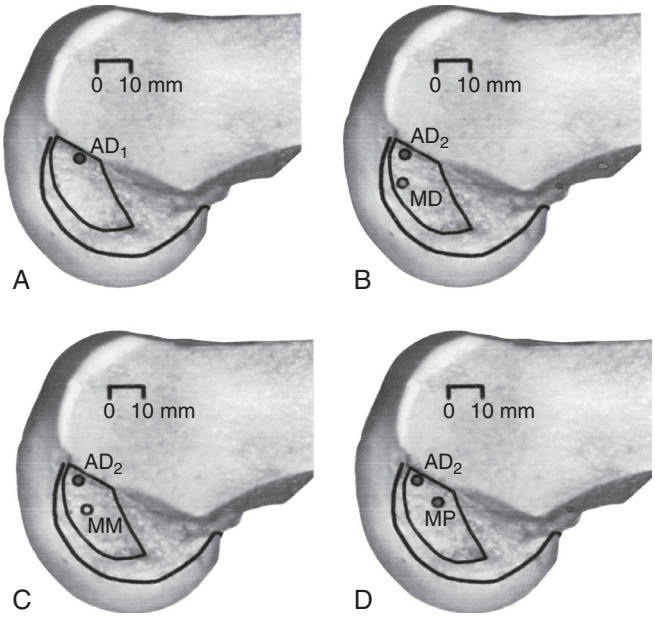


FIG 15-44 Sagittal views of the femur in 90 degrees of flexion. **A,** One-strand anterior-distal (AD) reconstruction. The AD_1 attachment is 6.7 mm from the trochlear groove and 10.6 mm from the cartilage edge. **B,** Two-strand AD, middle-distal reconstruction. The AD_2 attachment is 5.2 mm from the trochlear groove and 6.3 mm from the cartilage edge. **C,** Two-strand AD, middle-middle reconstruction. The middle-middle attachment (MM) is 14.8 mm from the trochlear groove and 9.5 mm from the cartilage edge. **D,** Two-strand AD, middle-proximal reconstruction. The middle-proximal attachment (MP) is 12.1 mm from the trochlear groove and 13.3 mm from the cartilage edge. (From Shearn JT, Grood ES, Noyes FR, Levy MS. Two-bundle posterior cruciate ligament reconstruction: how bundle tension depends on femoral placement. *J Bone Joint Surg Am.* 2004;86:1262-1270.)

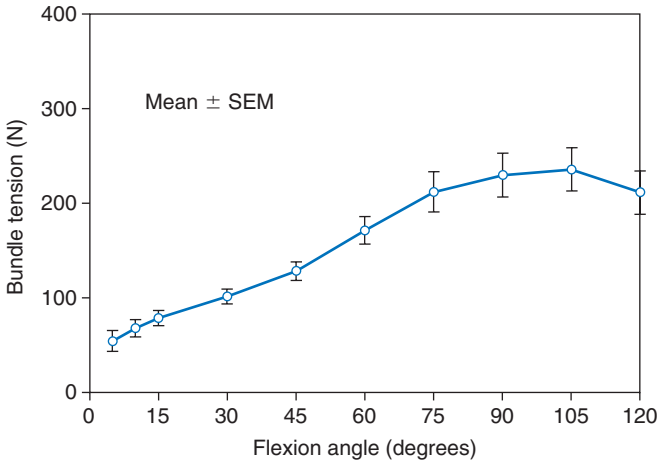


FIG 15-45 Strand tension for the one-strand reconstruction. *SEM,* Standard error of the mean. (From Shearn JT, Grood ES, Noyes FR, Levy MS. Two-bundle posterior cruciate ligament reconstruction: how bundle tension depends on femoral placement. *J Bone Joint Surg Am.* 2004;86:1262-1270.)

The graft strand tensions for the two-strand PCL reconstructions are shown in Figures 15-46 to 15-48. The average tension and the peak tension decreased for the two-strand reconstructions in which the second graft strand was placed in either a distal or a middle position and was able to share the posterior resisting load (Table 15-7). This represented the most ideal arrangement for the two graft strands, particularly when the second graft strand was placed in the middle third of the PCL attachment. In contrast, placement of the second graft strand in a more proximal location resulted in a reciprocal loading behavior between both graft strands, with higher loads placed on the anterior graft strand in comparison with those in the other two-strand configurations.

The data in this experiment support the conclusions of prior studies previously described that small changes in graft position in a proximal-to-distal direction within the PCL attachment have a pronounced effect on graft tension behavior. The hypothesis of this study is that load-sharing between two-strand PCL reconstructions is more ideal in terms of graft function in the long term in preventing posterior tibial subluxation with increasing knee flexion. In addition, the lower graft strand loads in a load-sharing configuration would be more protective against deleterious graft elongation that would be expected to occur under higher loads. It should be noted that, under the conditions of the experiment, all of the two-strand reconstructions restored the posterior translation limit to within ±1 mm of the intact knee, whereas the single-strand reconstruction resulted in a slight overconstraint of 2 mm (which occurred at the 30-degree flexion position; Fig. 15-49).

Petersen and associates,[79] in a cadaveric study, examined the effect of the femoral tunnel position of a two-bundle PCL reconstruction using a robotic testing system. These authors reported a significant effect of the femoral tunnel position in fiber tension behaviors. An

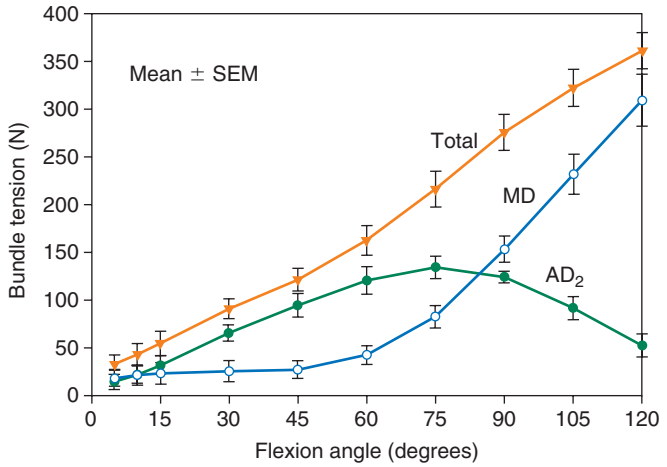


FIG 15-46 Strand tension for the anterior-distal, middle-distal reconstruction. *AD_2,* Anterior strand; *MD,* middle-distal strand; *SEM,* standard error of the mean. (From Shearn JT, Grood ES, Noyes FR, Levy MS. Two-bundle posterior cruciate ligament reconstruction: how bundle tension depends on femoral placement. *J Bone Joint Surg Am.* 2004;86:1262-1270.)

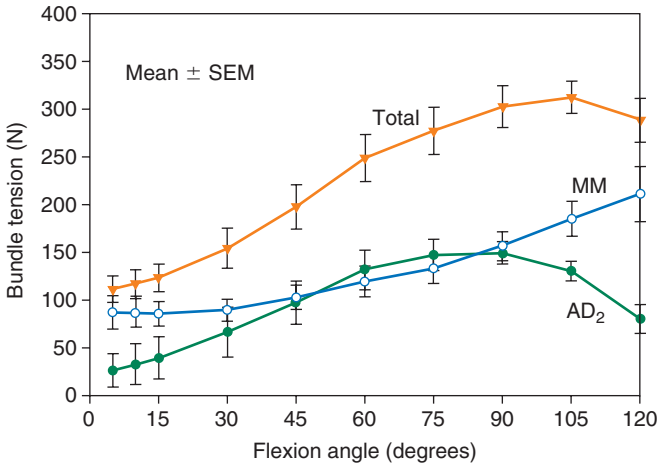


FIG 15-47 Strand tension for the anterior-distal, middle-middle reconstruction. *AD_2,* Anterior strand; *MM,* middle-middle strand; *SEM,* standard error of the mean. (From Shearn JT, Grood ES, Noyes FR, Levy MS. Two-bundle posterior cruciate ligament reconstruction: how bundle tension depends on femoral placement. *J Bone Joint Surg Am.* 2004; 86:1262-1270.)

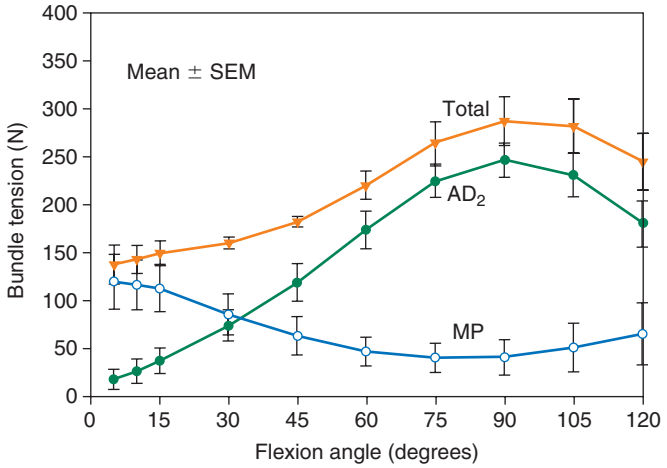


FIG 15-48 Strand tension for the anterior-distal, middle-proximal reconstruction. *AD_2,* Anterior strand; *MP,* middle-proximal strand; *SEM,* standard error of the mean. (From Shearn JT, Grood ES, Noyes FR, Levy MS. Two-bundle posterior cruciate ligament reconstruction: how bundle tension depends on femoral placement. *J Bone Joint Surg Am.* 2004; 86:1262-1270.)

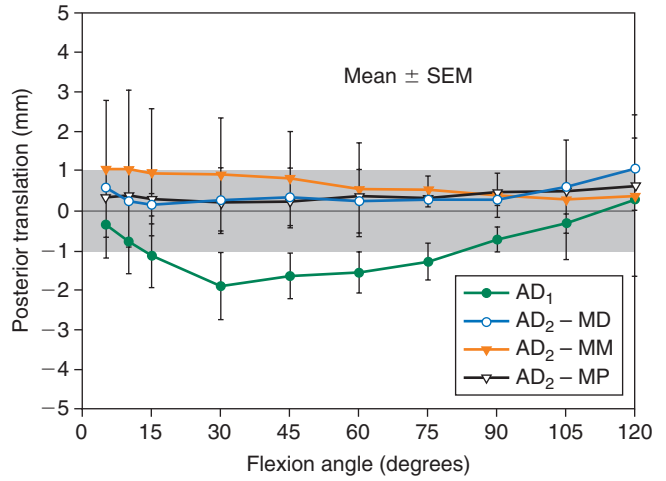


FIG 15-49 Change in posterior translation compared with the intact knee. The gray-shaded area represents translation within ±1 mm of that in the intact knee. *AD_1,* Single-strand anterior-distal reconstruction; *AD_2–MD,* two-strand anterior-distal, middle-distal reconstruction; *AD_2 – MM,* two-strand anterior-distal, middle-middle reconstruction; *AD_2 – MP,* two-strand anterior-distal, middle-proximal reconstruction. (From Shearn JT, Grood ES, Noyes FR, Levy MS. Two-bundle posterior cruciate ligament reconstruction: how bundle tension depends on femoral placement. *J Bone Joint Surg Am.* 2004;86:1262-1270.)

TABLE 15-7 Anterior Strand Tension

Reconstruction	Average Tension (N)	Peak Tension (N)	Angle at Peak Tension	Slope* (N/30-Degree Flexion)
One strand (AD)	149.3 ± 11	236.2 ± 23	105 degrees	49.9 ± 4
Two-strand (AD-MD)	74.7 ± 7	133.9 ± 12	75 degrees	18.9 ± 4
Two-strand (AD-MM) 88.6 ± 9	148.0 ± 12	90 degrees	25.7 ± 5	
Two-strand (AD-MP)	133.2 ± 14	246.9 ± 20	90 degrees	60.0 ± 6

*Values are the mean ± standard error of the mean.
AD, Anterior-distal; *AD-MD,* anterior-distal, middle-distal; *AD-MM,* anterior-distal, middle-middle; *AD-MP,* anterior-distal, middle-proximal.

anterior position of the two tunnels (anterolateral 7 mm, posteromedial 4 mm from femoral articular cartilage) was recommended. A more posterior (deep) placement of the tunnels was not recommended. One problem should be noted in that the PCL reconstructions (80-N tension at 90 degrees of knee flexion) resulted in a residual posterior tibial translation (7-10 mm at 90 degrees of knee flexion). It is preferred that biomechanic experiments tension grafts until the abnormal posterior translation is eliminated and not to an arbitrary graft tension, as in this study.

Markolf and colleagues[56] conducted a cadaveric study in which one- and two-strand PCL reconstructions were performed to determine whether the second graft strand placed in a posterior position (two placements, center and proximal PCL footprint) provided an advantage in terms of tensile load-sharing between graft fibers. The posteriorly placed grafts provided a resistance to posterior tibial translation, developed tension in the low knee flexion range, and developed greater than the normal PCL forces measured before PCL reconstructions. One problem not explained in the study is that, under 100-N posterior tibial load, the PCL would be expected (as the primary restraint in an oblique position) to develop close to or greater than the 100-N applied posterior forces. In the experimental results, the PCL developed forces of only approximately 30 to 50 N in the 20- to 40-degree flexion range, which is considerably lower than would be expected. Therefore it is difficult to interpret the data because the PCL and graft forces were less than expected.

Race and Amis[82] examined the separate functions of the anterolateral PCL (APCL) and posteromedial PCL (PPCL) bundles under loaded conditions in cadaveric knees. The results showed that approaching knee extension, ligamentous restraints other than the PCL contribute significantly to resisting posterior tibial translation (Fig. 15-50). With increasing knee flexion, the APCL and the PPCL provide a posterior resisting force. These results question the traditional concept that the PPCL provides a posterior resistance close to knee extensions, because the PPCL is aligned nearly perpendicular to a posterior loading direction. Further, with knee flexion, the PPCL is oriented in a more advantageous position because it is less vertical in terms of resisting posterior tibial displacement. These data support those of the senior author,[55] as already discussed. In addition, surgical reconstruction of the knee with significant posterior instability at low flexion angles implies damaged medial structures and PLSs described in the bumper model analogy in Chapter 3.

Race and Amis[81] demonstrated, in a cadaveric study, that a single anterolateral bundle reconstruction alone would not prevent abnormal posterior tibial translation at high flexion angles. Markolf and coworkers,[57] in a cadaveric study, evaluated the effect of a single PCL graft placed in three tunnels (anterior, central and posterior) within the PCL femoral footprint. They reported that if a single graft is used, a central location provides the best match for the PCL. The anterolateral and posterolateral tunnel positions did not control posterior tibial translation and underwent potentially deleterious high forces. A problem in the experimental design was that the posteromedial graft was tensioned at 90 degrees of knee flexion (its shortest position) and therefore underwent very high tensile loads as the knee approached full extension. It is important at surgery to determine the length change of the graft construct (tibiofemoral separation distance during knee flexion-extension), as will be discussed.

In a cadaveric study, Wiley and associates[114] examined the effect of single- and double-bundle PCL grafts and reported that the double-bundle reconstruction had statistically lower posterior tibial translation. Both graft constructs were placed into the distal two-thirds or shallower. PCL femoral attachment (avoiding a posterior or deep graft placement) and both grafts were tensioned at 90 degrees of knee flexion. The single-bundle PCL reconstruction was placed more proximal in the PCL attachment.

The primary conclusion of these studies is that most of the graft constructs are capable of restoring the posterior translation limit to normal after PCL sectioning. However, the constructs do so by inducing high tensile forces in the graft that may be deleterious and result in graft elongation and failure. To the extent that the in vitro data apply to in vivo graft function, the surgeon may select a position of the second graft strand that induces either load-sharing or reciprocal loading. Placement of the two graft strands in the middle region avoids the large tibiofemoral separations and resultant graft tensions that affect grafts placed closer to the periphery of the PCL attachment. These findings contradict those of other studies that recommend that the second graft strand be placed distal or proximal to the PCL attachment.[82,83] Even though the surgeon may select a more ideal graft placement in regard to load-sharing between graft strands, or the more ideal placement of a single graft strand, the data show that, owing to the diameter of the graft, there will be asymmetrical graft loading with portions of the graft at the outside diameter undergoing different elongation and tension than other portions. This makes it difficult for

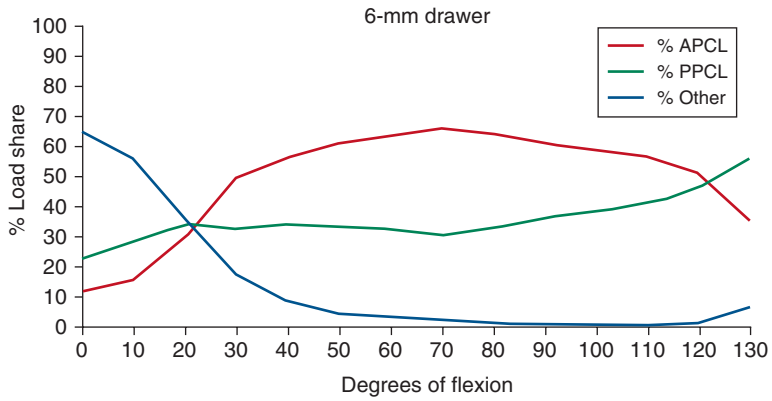


FIG 15-50 Graph of average percentage contribution to resisting posterior displacement against flexion angles for the anterolateral posterior cruciate ligament (APCL), the posteromedial posterior cruciate ligament (PPCL), and combined other structures ($n = 9$). (From Race A, Amis AA. Loading of the two bundles of the posterior cruciate ligament: an analysis of bundle function an A-P drawer. *J Biomech.* 1996;28:873-879.)

any graft strand to reproduce the complex microgeometry of the PCL in which different lengths of collagen fibers are brought into the loading sequence as knee flexion occurs.

Data are not currently available from clinical studies to determine whether two-strand PCL grafts are more successful in restoring posterior tibial translation than single-strand PCL grafts. There are no clinical data comparisons of two-strand PCL grafts implanted in an equal load-sharing configuration versus a reciprocal load-sharing (proximal-distal grafts) configuration. These are important areas for future study to improve the success rate of PCL reconstructions.

CYCLIC FATIGUE TESTING OF ONE- AND TWO-STRAND PCL GRAFT CONSTRUCTS

Several potential mechanisms exist for failure of a PCL graft after implantation, and it is important to design operative techniques and a postoperative rehabilitation program that diminish high tensile forces when possible. Because the PCL is the primary restraint to posterior tibial subluxation, any activities that involve high knee flexion or hamstring activation (descending stairs, walking down a ramp, squatting) may induce deleterious graft tensile forces.[6,12,62,77] In the early postoperative period, before graft maturation occurs and an adequate quadriceps muscle force production is able to counteract these forces, graft elongation or failure may occur. All of the muscles that cross the knee joint are involved in increasing joint contact forces by allowing normal knee joint geometry to decrease high tibial shear forces (see Chapter 18).[12,59,68] Improper graft tensioning (at the knee position of the shortest length) will produce high tensile forces as the graft elongates with knee flexion or extension. Abrasion of collagen strands against bone tunnels is a known cause of graft thinning and rupture.[8,64,92]

The cyclic fatigue of a PCL graft after implantation has been reported in only a few studies.[8,64,92] The failure mechanism of cyclic fatigue involves the nonuniform distribution of loads. For example, a single graft strand placed into the PCL femoral attachment with knee flexion-extension would subject the individual graft fibers to different tensions and lengths. The native PCL has different fiber lengths that are brought into the loading profile; however, a single-diameter graft of a fixed length does not function as a native PCL fiber. This means that individual fibers would, at certain periods, be carrying the majority of the applied load, potentially resulting in an overload and graft fiber elongation. The biomechanic studies already presented show that a proximal-to-distal change in graft position of 2 to 3 mm results in significant changes in graft tension-length relationships. As well, a PCL graft strand may be subjected to angulation (bending) or torsional forces at the bone insertion site. A native ligament has two fibrocartilaginous zones[74] owing to diffuse insertional forces over a wide area and decreased stiffness that prevents stress concentration effects. It is theorized that collagen graft fibers placed into a bone tunnel do not undergo remodeling to restore a normal attachment site[9,112] and that stress concentration effects are therefore always present, particularly at higher in vivo loads when activity is resumed. There is evidence that the bone-tendon junction does remodel to a normal attachment site with a B-PT-B graft.[86]

In studies of cyclic fatigue testing of PCL grafts after implantation, researchers have reported a marked effect of this loading that produced premature graft failure. In three studies, the flexion angle of the graft construct was fixed and a load applied in a cyclic manner to test a one-strand B-PT-B graft.[8,64,66] This type of loading is less ideal in terms of understanding graft cyclic fatigues properties, because single tensile loading does not reproduce the loading profile that a graft would be subjected to with knee flexion-extension motion. Mehalik[67] studied the cyclic behavior of a one-strand Achilles tendon graft in knees cycled to 90 degrees of flexion and reported an increase in posterior translation of approximately 1.7 mm after 1000 cycles (posterior load 50 N; flexion limit, 105 degrees).

Markolf and colleagues[64] performed a cyclic loading study of a B-PT-B allograft using a tibial tunnel and a tibial inlay technique. After 2000 cycles, the graft length of the inlay and tunnel methods increased by 5.9 and 9.8 mm, respectively (load level, 50-300 N). The authors concluded that grafts undergo thinning and increase in length with both fixation techniques. There was greater thinning and degradative effects of the angulated grafts in tibial tunnels compared with the tibial inlay grafts. For example, 10 (32%) of 31 grafts failed at the acute angle of tibial attachment before 2000 cycles, whereas all of the 31 tibial inlay graft constructs survived the testing procedure. The data suggest that a 10-mm-wide B-PT-B graft replacement for PCL reconstruction, with either a tunnel or inlay technique, may result in unacceptable graft elongation under the loading profile. However, the relationship of the cyclic loading behavior to the other mechanic properties of the graft was not studied, and it is possible that significant disuse and age effects resulted in increased elongation or premature failure.

Bergfeld and coworkers[8] compared a tibial tunnel graft technique with a tibial inlay technique using a 10-mm central third B-PT-B graft in cadavers. Both reconstructions restored posterior translation limits to within 2 mm (150-N loading). A tensile load of 89 N on the PCL graft at the femoral site was used. After 72 cycles (from 0 to 90 degrees), the "laxity" of both reconstructions increased as a result of graft stretching, with thinning of the graft found at the tibial tunnel exit but not in the tibial inlay group. The authors acknowledged that the conditions of tensioning may have overconstrained knees in the inlay group.

In a study done at our laboratory,[92] the cyclic behavior of a PCL B-PT-B graft was reported using cadaveric knee joints cycled from 5 degrees to 120 degrees under 100-N posterior loading. The conditions of the experiment were already described, and four graft constructs used are shown in Figure 15-43. The behavior of a normal PCL under cyclic loading is shown in Figure 15-51 where, at 2048 cycles, the increase in posterior translation under loading was less than 1 mm.

CRITICAL POINTS Cyclical Fatigue Testing of One- and Two-Strand Posterior Cruciate Ligament Graft Constructs

- Design operative techniques and postoperative rehabilitation program that diminish high tensile forces.
- High knee flexion activities, hamstring activation (descending stairs, walking down a ramp, squatting) produce deleterious graft tensile forces.
- In the early postoperative period, before adequate quadriceps muscle force able to counteract forces, graft elongation or failure may occur.
- A single-diameter graft of a fixed length does not function as a native PCL.
- A proximal-to-distal change in graft position of only a few millimeters results in significant changes in graft tension-length relationships.
- Cyclic fatigue testing of PCL grafts shows a marked effect, producing premature graft failure after a few hundred knee flexion cycles.
- All graft configurations show marked sensitivity to cyclic loading.
- Only the two-strand construct (one anterior strand, one central strand) showed a two- to threefold increase in number of cycles to graft failure.
- Number of cycles to failure would be reached in the first 2 weeks of rehabilitation unless appropriate measures were taken to limit posterior translation loads and number of flexion-extension cycles.
- In vitro data indicate need to build into protocols measures to protect PCL grafts early postoperatively.

TABLE 15-8 Cyclical Data for the Reconstructed Knees

Reconstruction	Number	Cycle Number to 2.5 mm	Rate of Posterior Translation Return for 2.5 mm*	Cycle Number to 7.5 mm	Rate of Posterior Translation Return for 7.5 mm*
AD_1	4†	137 ± 44	2.3 ± 0.7	267 ± 52	2.5 ± 0.4
AD_2 – MD	4	171 ± 15	1.5 ± 0.2	347 ± 63	2.1 ± 0.5
AD_2 – MM	4†	158 ± 21	1.5 ± 0.1	694 ± 188	1.2 ± 0.3
AD_2 – MP	4‡	80 ± 10	3.1 ± 0.5	176 ± 14	4.0 ± 0.4

*Mean ± standard error of the mean in millimeters/100 cycles.
†Specimen excluded from 7.5-mm group.
‡Specimen excluded from 2.5-mm group.
AD_1, One-strand anterior-distal; *AD_2 – MD,* two-strand anterior-distal, middle-distal; *AD_2 – MM,* two-strand anterior-distal, middle-middle; *AD_2 – MP,* two-strand anterior-distal, middle-proximal.

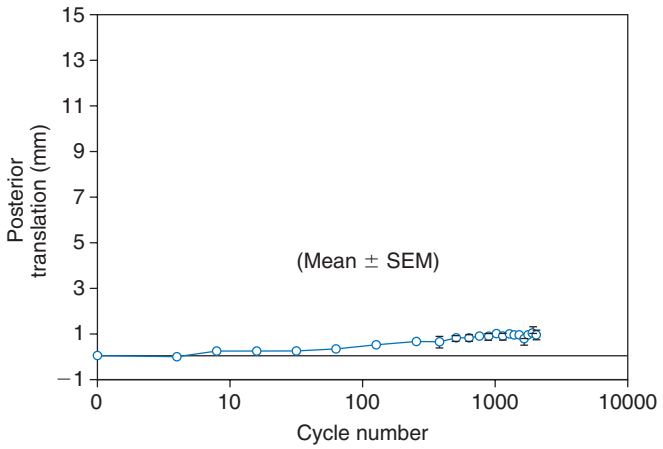


FIG 15-51 For an intact knee, the posterior translation increased during a cyclic fatigue test at 90-degree flexion ($n = 8$ for cycle numbers 384, 640, 896, 1152, 1408, 1664, 1920; $n = 12$ for the other cycle numbers). *SEM,* Standard error of the mean. (From Shearn JT, Grood ES, Noyes FR, Levy MS. One and two-strand posterior cruciate ligament reconstructions: cyclic fatigue testing. *J Orthop Research*. 2005;23:958-963.)

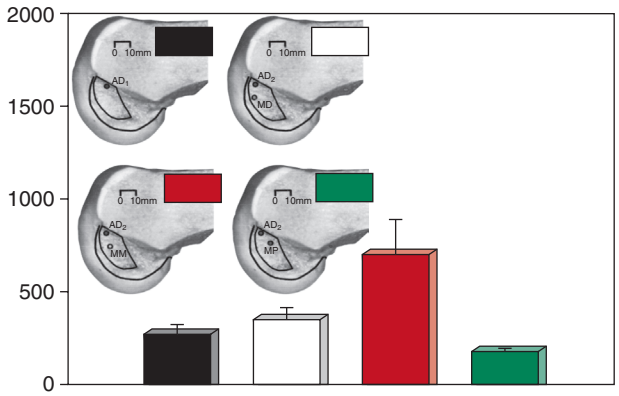


FIG 15-52 Cycle number corresponding to a 7.5-mm posterior translation increase. (From Shearn JT, Grood ES, Noyes FR, Levy MS. One and two-strand posterior cruciate ligament reconstructions: cyclic fatigue testing. *J Orthop Research*. 2005;23:958-963.)

The return of 2.5 mm of posterior translation for the four PCL reconstruction techniques is shown in Table 15-8. All of the graft configurations showed a marked sensitivity to cyclic loading. The return of 7.5 mm of posterior translation was also low in terms of the numbers of cycles. Only the two-strand construct with one anterior graft strand and a second strand placed in the middle configuration showed a two- to threefold increase in the number of cycles to graft failure (Fig. 15-52). Even so, this number of cycles to failure would be reached within the first 2 weeks of rehabilitation unless appropriate measures were taken to limit flexion-extension cycles or the maximum of 120 degrees. The results further showed that 76% of the grafts failed at or adjacent to the femoral attachment region (19 of 25 grafts), with 20% (5 of 25 grafts) in the mid susbstance and 4% (1 of 25 grafts) at the tibial attachment ($P < .001$).

Hiraga and colleagues[40] reported the results of cyclic loading tests on four types of PCL reconstructions in cadaveric knees. The knee joints were cycled between 0 and 100 N for 1000 cycles. Increases in posterior tibial translation were attributed to slippage of the graft and/or permanent elongation of the graft construct. The knees were positioned at 90 degrees of flexion, and the cyclic loading involved repetitive AP displacements. This is in contrast to the study by Shearn and coworkers,[92] where the knees were cycled between 0 and 120 degrees of knee flexion. It is important that differences in cyclic loading techniques be understood because the cyclic loading under both posterior load and knee flexion-extension is more detrimental in terms of inducing graft elongation or failure than unidirectional loading. Hiraga and colleagues[40] reported that no grafts failed under the reduced loading of 100 N; however, there were increases in posterior tibial translation after only 100 cycles in all reconstruction groups. The greatest increase was found in semitendinosus-gracilis (STG) grafts fixated with an EndoButton (Smith & Nephew), which was less than an STG graft fixed with an interference screw and an EndoPearl device (ConMed Linvatec). There was no difference between B-PT-B tibial tunnel and B-PT-B tibial inlay reconstructions, with increases in residual posterior translation of approximately 3 mm reported for both tunnel and inlay grafts.

To the extent that these in vitro results apply to in vivo PCL graft constructs, the data indicate the potential need to protect PCL grafts in the initial postoperative period. The in vitro data represent the worst-case scenario for a PCL graft in that the PCL construct was loaded to 100 N and up to 120 degrees of knee flexion, which would be expected to induce graft tensile loads already reported of 200 to 300 N. In addition, a 5-mm B-PT-B graft was used, in contrast to larger-diameter grafts used in vivo, which would undoubtedly require greater number of cycles to ultimate failure. There are insufficient in vitro and in vivo biomechanic and clinical data on the effects of these variables to scientifically construct a rational treatment program. We stress that the surgeon needs to select empiric rules in terms of the postoperative treatment rehabilitation protocol.

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16

Posterior Cruciate Ligament Injuries: Diagnosis, Operative Techniques, and Clinical Outcomes

Frank R. Noyes, Sue D. Barber-Westin

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VIDEO CONTENT

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FIG 16-1 Severe posterior tibial subluxation is shown in a chronic posterior cruciate ligament–deficient knee. There is loss of the normal anterior tibiofemoral step-off.

CRITICAL POINTS Indications

- Mechanism of injury, low versus high velocity.
- Complete PCL rupture usually associated with other ligament injuries.
- Isolated PCL rupture represents serious injury, chance of functional deterioration, arthritis over time.
- Indications for chronic isolated complete PCL rupture: pain and instability with athletics or other activities, swelling, ≥10 mm of increased posterior tibial translation (90 degrees of flexion).
- Results of PCL reconstruction in chronic knees less favorable as arthritic symptoms persist.

INDICATIONS

Complete ruptures to the posterior cruciate ligament (PCL) account for approximately 2% to 3% of all knee ligament injuries in the general population.[131,213] However, the reported incidence of PCL ruptures ranges between 1% and 44% of all acute knee ligament injuries.[192] These injuries are classified as either low-velocity, such as those that occur from contact with another player in sports, or high-velocity, such as a dashboard injury in a motor vehicle accident. The mechanism of PCL rupture in athletes is usually a fall on the flexed knee with a plantar-flexed foot or hyperflexion of the knee.[192,235] High-velocity injuries frequently involve dislocations with multiple ligament ruptures that require immediate medical attention. Traffic-related injuries appear to produce greater posterior tibial displacement values on stress radiography than sports-related injuries.[193] In this chapter, the different types of PCL reconstructive techniques are described in detail to allow the surgeon to select the procedure most suited for the specific knee injury. In addition, the initial diagnosis and management of acute PCL ruptures is addressed in the "Preoperative Planning" section.

The proper management of complete ruptures to the PCL requires thorough knowledge of anatomy, diagnosis, surgical reconstruction, and rehabilitation concepts. Some aspects of the treatment of complete isolated PCL ruptures are controversial owing to the surgical limitations in completely restoring knee stability and the unclear natural history regarding long-term symptoms, functional limitations, and risk of joint arthritis. Although some studies (that included large percentages of patients with partial PCL deficiency) reported that patients did well when treated conservatively,[177,199,200] other investigations described noteworthy symptoms and functional limitations after the injury.[11,19,41,43,97] Many knees with complete PCL ruptures develop articular cartilage deterioration over time that usually occurs on the medial femoral condyle and patellofemoral surfaces owing to increased joint pressures and altered tibiofemoral and patellofemoral kinematics.* Posterior tibial subluxation with activities after PCL rupture has a deleterious effect to the knee similar to that of a medial meniscectomy[57] because there is loss of medial meniscus function and increased joint contact stress. There is less of a deleterious effect on the lateral tibiofemoral compartment because the lateral meniscus retains load-bearing function. Posterior tibial subluxation with weight-bearing activities results in a loss of normal joint kinematics[64,218] and in coupled external tibial rotation with joint loading. Accordingly, a PCL rupture would be expected to have a more deleterious effect in a varus-angulated knee with associated loss of the medial meniscus and, in particular, larger-sized athletes who desire to return to strenuous athletics. All of these factors alone or together result in substantial medial tibiofemoral loads and risk of joint deterioration.

The indications for surgical reconstruction in knees with a chronic isolated complete PCL rupture are pain and instability with athletics or other activities, swelling, and 10 mm or more of increased posterior tibial translation at 90 degrees of flexion (Fig. 16-1). PCL reconstruction is most frequently performed in dislocated knees with gross instability owing to other ligament injuries to the anterior cruciate ligament (ACL), medial collateral ligament (MCL, see Chapter 19), or posterolateral structures (see Chapter 17). Indications for surgery in acute isolated PCL ruptures are discussed later in this chapter.

If symptomatic meniscal tears or early patellofemoral or tibiofemoral articular cartilage damage are present, early PCL reconstruction is recommended with the goal of decreasing joint deterioration over

*References 32, 60, 61, 64, 65, 73, 79, 106, 121, 172, 212, 217, 218, 222.

time. The results of PCL reconstruction in knees with chronic ruptures are not as favorable as those that undergo reconstruction for acute injuries. This is because patients with chronic ruptures frequently present with pain and swelling from joint deterioration that will often persist even though some benefit may be gained from improved knee stability from a reconstruction.[154]

CONTRAINDICATIONS

Contraindications to PCL reconstruction include acute partial and complete isolated tears that will heal and provide partial function with conservative treatment. Advanced symptomatic patellofemoral or tibiofemoral arthritis is a frequent contraindication. Unfortunately, many patients with chronic PCL deficiency present with severe associated joint arthritis. It is important to distinguish joint instability symptoms from symptomatic arthritis, in which case a ligament reconstruction would provide little to no benefit.

Patients with chronic PCL ruptures, varus angulation, and early medial tibiofemoral arthritis, or with increased lateral joint opening and associated posterolateral insufficiency, require high tibial osteotomy (HTO) before PCL reconstruction.

Dislocated knees require initial observation, vascular evaluation (ankle-brachial index), possible arteriography, early protected range of motion, and rehabilitation to restore muscle function before PCL reconstruction. We discourage the use of external fixators to initially stabilize the knee joint, because the use of these devices frequently results in arthrofibrosis and pin track infection and limits the ability to perform a ligament reconstruction. It is important to document with lateral radiographs that tibiofemoral reduction has been maintained and a residual posterior subluxation is not present.

In addition, patients with chronic PCL deficiency who have severe muscle atrophy, loss of knee motion, or hyperextension gait abnormalities require extensive rehabilitation and gait retraining before reconstruction (see Chapter 29).[165]

A select group of morbidly obese patients sustain serious knee dislocations with minimal trauma. The lack of protective muscle function and the abnormal body weight places excessive tensile loads on ligament reconstructions, and a high rate of failure of a PCL reconstruction is expected. The preferred treatment for these patients is short-term plaster immobilization (and occasionally external fixation) to allow healing of soft tissues, followed by rehabilitation to return muscle function and knee motion. In only exceptional circumstances would operative repair (acute or chronic) be warranted in these patients, although consideration for surgical reconstruction is warranted after appropriate weight reduction.

CRITICAL POINTS Contraindications

- Acute partial and complete isolated PCL tears that will heal and provide partial function.
- Advanced symptomatic patellofemoral or tibiofemoral arthrosis.
- Varus-angulated knees with early medial tibiofemoral arthrosis; osteotomy required before PCL reconstruction.
- Dislocated knee: vascular evaluation, protected range of knee motion, and return of muscle function before PCL reconstruction.
- Loss of knee motion, quadriceps weakness, and hyperextension gait abnormalities require extensive rehabilitation and gait retraining before PCL reconstruction.

POSTERIOR CRUCIATE LIGAMENT ANATOMY

The PCL attaches in a depression posterior to the intraarticular upper surface of the tibia and courses anteromedially behind the ACL to the lateral surface of the medial femoral condyle (see Chapter 2; Fig. 16-2). Illustrations by Anderson and colleagues[9]

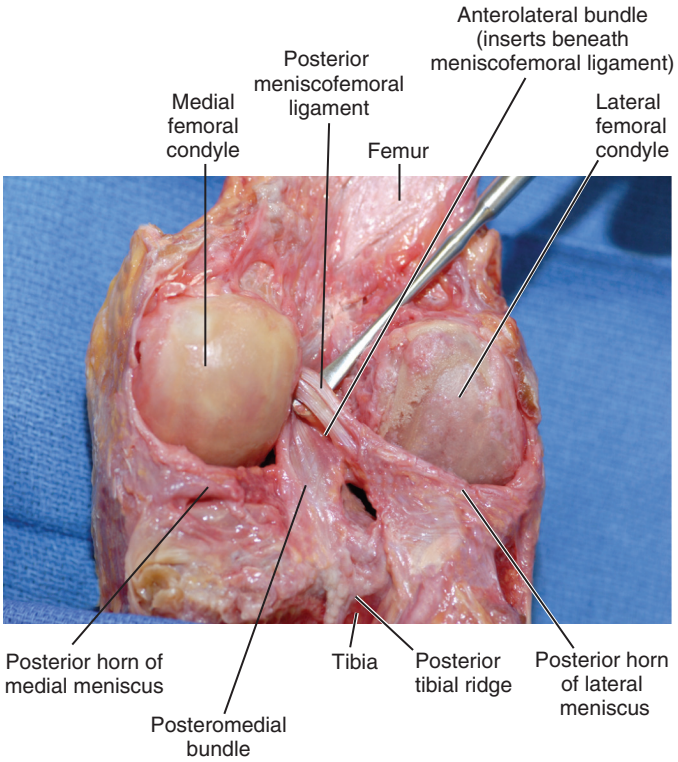


FIG 16-2 Posterior cruciate ligament femoral and tibial attachments. Note the prominent posterior meniscofemoral ligament and broad posterior tibial attachment.

CRITICAL POINTS PCL Anatomy

- PCL arises from a depression posterior to the intraarticular upper surface of the tibia, courses anteromedially behind ACL to lateral surface of medial femoral condyle.
- Contains type I, type II, type IV mechanoreceptors.
- 91% of knees have at least one meniscofemoral ligament.
- PCL complex anatomic structure composed of a continuum of fibers of different lengths and attachment characteristics.
- PCL attachment extends from high in the notch (11:30 to 5 o'clock, right knee).
- Anterior portion of PCL attachment follows articular cartilage within 2 to 3 mm of its edge.
- Posterior third of PCL is 5 mm from the articular margin.
- Proximal edge of PCL is straight or oval, with the attachment tapered in width along its posterior portion.
- PCL femoral attachment described using rule of thirds to define the proximal-middle-distal thirds (deep to shallow in the femoral notch) and anterior-middle-posterior thirds.
- Femoral attachment location strongly influences graft tension, ability of reconstruction to restore posterior stability.
- PCL fibers function from proximal-to-distal in length changes with knee flexion.

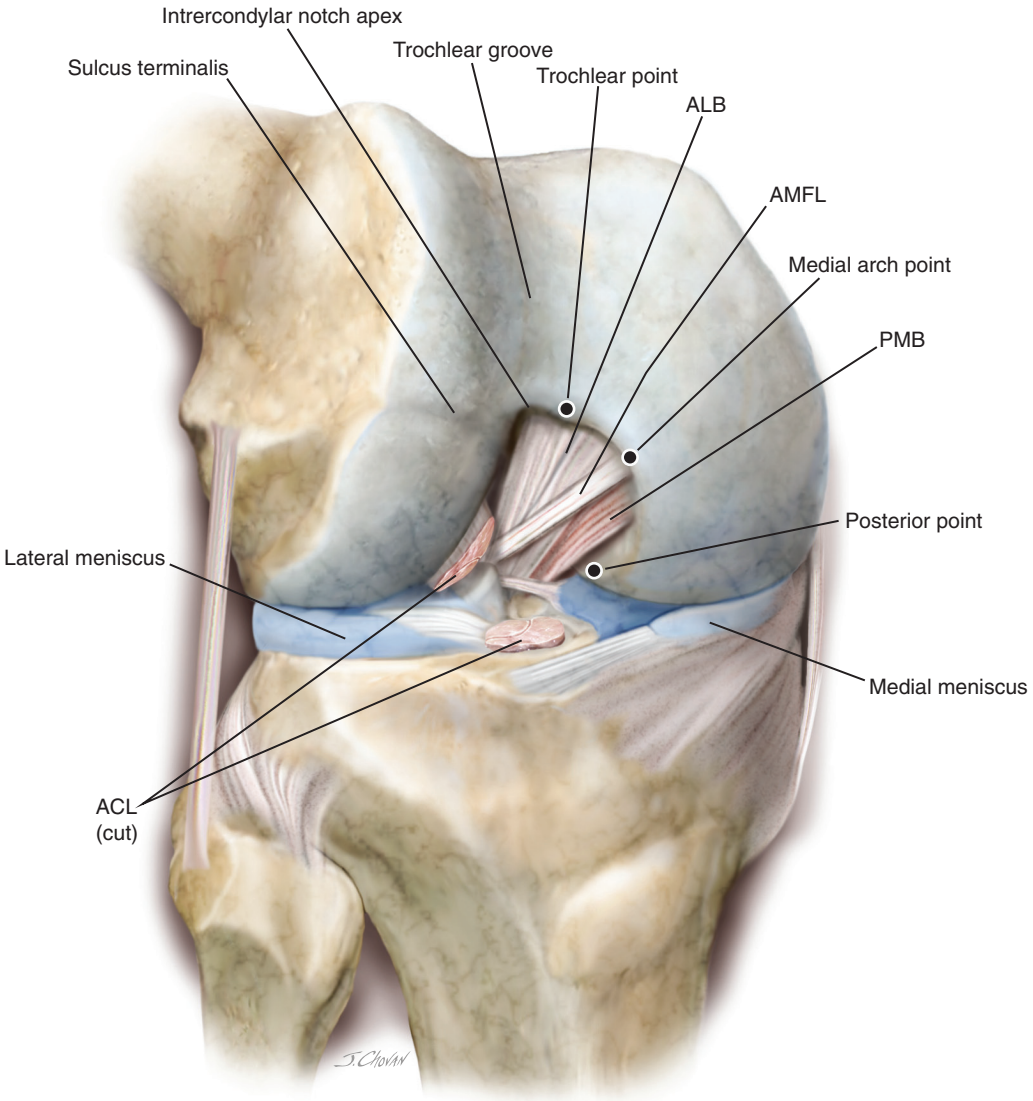


FIG 16-3 Anterior view of a right knee flexed to 90 degrees with the posterior cruciate ligament intact, demonstrating the characteristic morphology of the cartilage margin of the femoral intercondylar notch. The illustration also shows the trochlear, medial arch, and posterior points as well as the intercondylar notch apex and trochlear groove. *ACL*, Anterior cruciate ligament; *ALB*, anterolateral bundle; *aMFL*, anterior meniscofemoral ligament; *PMB*, posteromedial bundle. (Modified from Anderson CJ, Ziegler CG, Wijdicks CA, Engebretsen L, LaPrade RF. Arthroscopically pertinent anatomy of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *J Bone Joint Surg Am.* 2012;94:1936-1945.)

show the anterior (Fig. 16-3) and posterior (Fig. 16-4) aspects of the PCL and its insertion characteristics. The PCL has an average length of 38 mm and an average width of 13 mm (Table 16-1).[63,220] The cross-sectional area of the PCL is variable and increases from its tibial to femoral insertions.[76] It is approximately 50% larger than the ACL at its femoral origin and 20% larger than the ACL at its tibial insertion.

Free nerve endings and mechanoreceptors have been identified in the femoral and tibial attachment sites and on the surface of the PCL.[96,191] The mechanoreceptors resemble Golgi tendon organs and are believed to have a proprioceptive function in the knee.[98]

In a histologic study of the PCL in cadaveric knees, Katonis and coworkers[96] reported a neural innervation similar to that of the ACL. Specifically, the PCL contains type I or Ruffini's corpuscles that have a slow threshold to pressure changes, type II (Vater-Pacini) corpuscles that are more rapid acting, and type IV (free nerve endings) corpuscles for pain reception. The mechanoreceptors are located at each ligament bony attachment and on the surface of the PCL.

The meniscofemoral ligaments are in close proximity to the PCL. They arise from the posterior horn of the lateral meniscus and insert near the PCL insertion site on the lateral aspect of the medial femoral condyle.[76] The anterior meniscofemoral ligament (ligament of Humphrey) courses anterior to the PCL, and the posterior meniscofemoral ligament (ligament of Wrisberg) runs obliquely behind the PCL. Frequently, the anterior meniscofemoral ligament interdigitates with the PCL fiber attachments on the medial femoral condyle

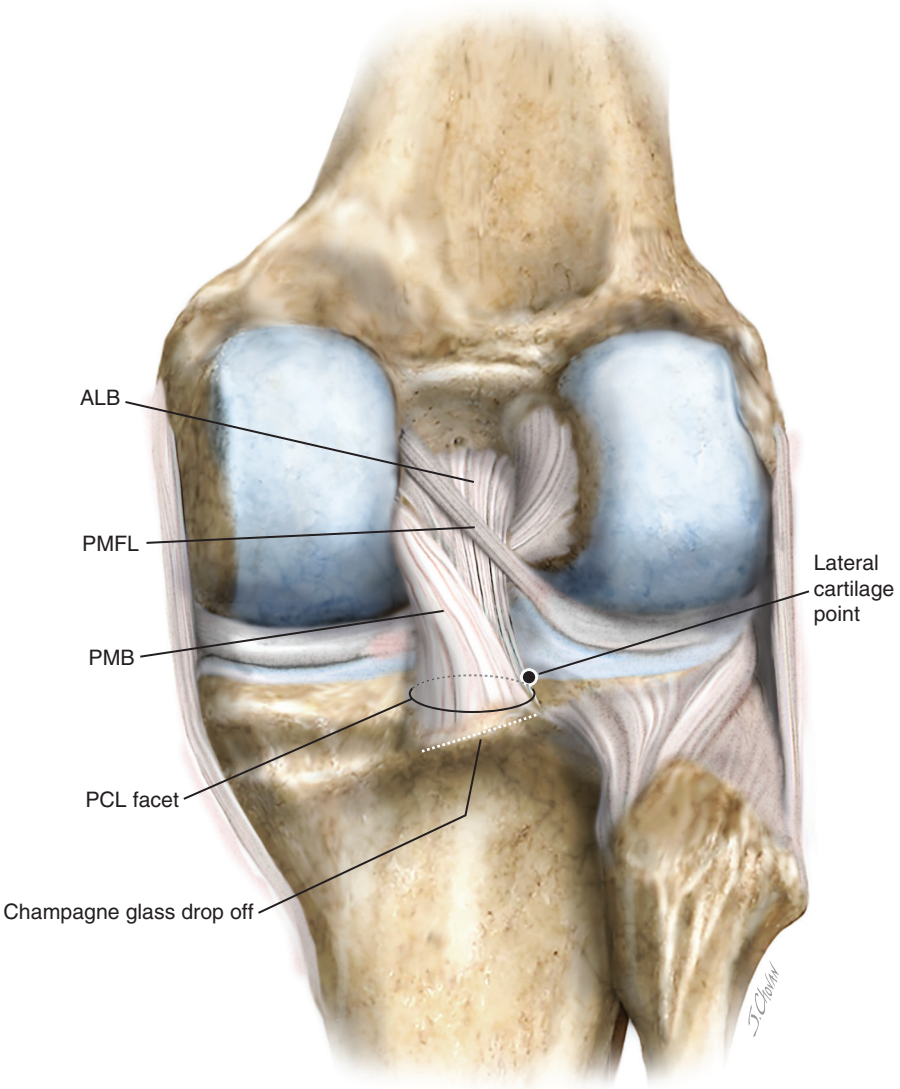


FIG 16-4 Illustration of the posterior aspect of a right knee with the posterior cruciate ligament (PCL) intact, demonstrating the fiber orientation. *ALB*, Anterolateral bundle; *PMB*, posteromedial bundle; *PMFL*, posterior meniscofemoral ligament. (Modified from Anderson CJ, Ziegler CG, Wijdicks CA, Engebretsen L, LaPrade RF. Arthroscopically pertinent anatomy of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *J Bone Joint Surg Am.* 2012;94:1936-1945.)

(Fig. 16-5).[144] At least one of the meniscofemoral ligaments is present in 91% of knees, and both ligaments may be found in 50% of knees in young individuals.[72,76,144] The biomechanical function of the meniscofemoral ligaments is discussed in detail in Chapter 23.

The traditional division of the PCL into a separate anterolateral bundle (ALB) and posteromedial bundle (PMB) oversimplifies PCL fiber function. The PCL is a complex anatomic structure composed of a continuum of fibers of different lengths and attachment characteristics. The length-tension behaviors of the fibers that resist posterior tibial translation (with knee flexion) are controlled primarily by femoral attachment regions.[40,55,69,132,133,189,197,203] The distal fibers lengthen with increasing knee flexion and the proximal fibers shorten with knee flexion.[144,189] A detailed description of the length-tension behavior of the PCL appears in Chapter 15.

The anatomy of the PCL femoral attachment site has been studied extensively (see Table 16-1).[144,189] Variation exists between knees in the shape of this attachment, from the common elliptical shape to a more rounded and thicker shape (Fig. 16-6).[144] Different measurement systems have been proposed to describe the femoral attachment site. The most common method uses a clock reference position (Fig. 16-7), with measurement lines perpendicular to the articular cartilage edge and measurement lines parallel to the femoral shaft (Fig. 16-8). The clock method is a general guide and not highly accurate; therefore the entire PCL footprint and relationships to other structures described should be viewed.

In general, the PCL attachment extends from high in the notch (11:30 to 5 o'clock position on a right knee) along the medial femoral

Text continued on p. 456

TABLE 16-1 Posterior Cruciate Ligament Anatomy Studies

Study	Methods	Specimens	PCL Footprint, Attachment/Insertion Sites	Anatomic Landmarks	Conclusions
Narvy et al[149] (2014)	Systematic review of cadaveric and radiographic studies; 10 yr		*Radiographic parameters:* ALB center 40% and PLB 56% distance anterior surface femur. *Cadaveric data*: center of ALB 8 mm (27.5%) from cartilage edge, PLB 11.9 mm (42.5%) from anterior articular surface.	Blumensaat line, articular cartilage surface, medial intercondylar ridge	Review of 38 studies on PCL femoral footprint anatomy
Hatsushika et al[77] (2013)	ALB and PMB separated into ~20 small bundles (1 mm in diameter), attachment sites preserved; photographs, illustrations	$n = 12$, age unknown	Femoral attachment patterns similar; each small bundle ran in parallel towards tibial attachment in extension, crossed over each other in flexion. Tibial attachments showed two patterns: parabolic and transverse.	NA	First study to describe two patterns of ALB and PMB attachments in the tibia
Van Hoof et al[221] (2013)	3-D model from CT images. Concepts of best-fit cylinder and central axis given; illustrations	$n = 9$, 66-97 years	Mean footprint surface area: tibia 189.1 mm^2, femoral 293.3 mm^2. Mean diameter of best-fit cylinder, 10.5 mm. Mean coverage best-fit cylinder on tibial footprint 76.5%, femoral footprint 46.5%.	NA	Study confirmed large difference between tibial and femoral footprints. Best-fit 10-mm tunnel covers only 50% of femoral footprint; single-bundle PCL not able to be considered anatomic on femoral side.
Westermann et al[231] (2013)	3-D model from CT images; photographs, illustrations	$n = 7$, age unknown	Femoral footprint: center is 38% of the entire medial femoral condyle from anterior to posterior, parallel to Blumensaat's line on perfect lateral view and 25% of the condyle height from the notch roof on a perfect notch view.	NA	Provides standards of measurement for future studies that use advanced imaging for entire PCL insertion. Not applicable for location ALB or PMB.
Johannsen et al[89] (2013)	AP and lateral x-rays, attachment centers labeled with radiopaque spheres, attachment areas labeled with barium sulfate; illustrations	$n = 20$, 21-59 years	Lateral view: ALB center located 17.4 mm posteroproximal, PMB center located 23.9 mm posteroproximal to anterior cortex line of femoral condyles. ALB tibial center located 8.4 mm, PMB center located 2.5 mm superior, PCL center 5.5 mm superior to "champagne glass drop-off" of posteroproximal tibia.	Lateral view: Blumensaat line and anterior cortex line, champagne glass drop-off of posteroproximal tibia	Most important findings on lateral views. Femur: measurements to Blumensaat line and anterior cortex line. Tibia: PCL attachment center measurement to champagne glass drop-off. Size scaling percentages not incorporated in measurements. Radiographic landmarks differ from cartilage-based arthroscopic landmarks.

TABLE 16-1 Posterior Cruciate Ligament Anatomy Studies—cont'd

Study	Methods	Specimens	PCL Footprint, Attachment/Insertion Sites	Anatomic Landmarks	Conclusions
Anderson et al[9] (2012)	Electromagnetic tracking system used to outline structures, distances measured between center of fiber bundles and anatomic landmarks; photographs, illustrations, arthroscopic views	$n = 20$, 21-49 years	Femoral attachment: mean area PCL 192 mm^2, ALB 112 mm^2, PMB 60 mm^2, anterior MFL 35 mm^2, posterior MFL 31 mm^2. Tibial attachment: mean area PCL, 219 mm^2, PCL facet 291 mm^2, ALB 88 mm^2, PMB 105 mm^2.	Tibia: lateral plateau articular cartilage, medial meniscus attachment, osseous ridge separating anterolateral and posteromedial bundles.	Used two femoral tunnels, one tibial tunnel. Center of femoral AL tunnel should be triangulated on basis of the trochlear point, the medial arch point, and the medial bifurcate prominence. Distal edge should be placed adjacent to articular cartilage. Femoral PM tunnel should be placed equal distance from the posterior point and medial arch point and just distal to the medial intercondylar ridge (center a mean 8.6 mm proximal to articular cartilage margin). Center of tibial tunnel should be just anterosuperior to bundle ridge, on the medial side of the PCL facet, 9.8 mm from lateral cartilage point and 5 mm from medial groove.
Osti et al[173] (2012)	High-resolution digital images, two grid systems (16 rectangular zones), AP and lateral x-rays; photographs	$n = 15$, 82 ± 8 years	PCL tibial footprint mediolateral 10.37 mm, superoinferior 9.58 mm. ALB length 31.79 mm, femoral footprint mediolateral 7.85 mm, anteroposterior 8.51 mm, superoinferior 8.56 mm. PMB length 32.42 mm, femoral footprint mediolateral 6.84 mm, anteroposterior 8.82 mm, superoinferior 8.83 mm.	Cartilage borders, intercondylar roof, medial femoral condyle used in two measurement grid systems.	Provides femoral measurement grid system for arthroscopic views and x-ray images.
Greiner et al[66] (2011)	CT, insertions marked with plastic markers; photographs, CT images, illustrations	$n = 10$, 60-85 years	Femoral insertion mean surface area 232 mm^2. Tibial insertion trapezoidal shape, mean surface area 154.8 mm^2.	Mean distance center of femoral insertion to roof of notch 8.9 mm; to anterior articular cartilage surface 18.7 mm. Tibial insertion centered 9.1 mm from posterior border of tibia on retrospinal surface, 1.6 mm inferior to plane of articular cartilage.	Study documented native femoral and tibial attachments relative to CT-specific landmarks.

Continued

TABLE 16-1 Posterior Cruciate Ligament Anatomy Studies—cont'd

Study	Methods	Specimens	PCL Footprint, Attachment/Insertion Sites	Anatomic Landmarks	Conclusions
Lee et al[117] (2010)	Four corners of tibial footprint marked with drill tip, screws inserted at each corner and at 1-cm intervals in posterior cortex aligned with the tibial tunnel. AP and lateral x-rays, CT; photographs, x-ray, and CT images	$n = 10$, 34-61 years	Mean tibial insertion from joint line on AP x-ray 5.9 ± 1.1 mm to proximal aspect of PCL, 17.4 ± 2.4 mm to the distal aspect of PCL. Mean tibial insertion from joint line on lateral x-ray, 2.2 ± 1.2 mm to proximal aspect of PCL and 12.3 ± 1.5 mm to distal aspect of PCL.	PCL facet (fossa) consistent radiographic landmark for pin placement. PCL insertion was in posterior 48% of the area of the posterior intercondylar fossa, to the posterior cortex.	Mean tibial insertion of PCL from joint line was located higher on lateral x-ray than on AP x-ray. Identified posterior intercondylar fossa and posterior cortex that align with the tibial tunnel.
Jeong et al[88] (2010)	3-D CT-based knee joint model. Femoral attachment divided into four sectors, tibial attachment divided into six sections; 24 virtual PCL bundles; illustrations	$n = 10$ living subjects, healthy knees, scanned 0, 90, 135 degrees	At 0 and 90 degrees, bundle with least amount of length change was PMB inserting into most posterior femoral sector and most distal tibial sector. Change was not different compared with other bundles with tibial points attached to same femoral sector.		No isometric points in any virtual PCL bundle. Avoid high flexion during postoperative rehabilitation.
Tajima et al[214] (2009)	Macroscopic observation, 3-D laser photography; photographs, illustrations	$n = 21$, 42-93 years	Mean area PCL tibial attachment 243.9 mm^2, AL insertion 93 mm^2, PM insertion 150.8 mm^2.	Posterior intercondylar fossa: ALB attached to superolateral aspect (slope), PMB attached to inferomedial aspect (slope). Change of >10 degrees observed between AL and PM slopes.	Tibial insertion complex, shapes, and positions of insertion sites of AL and PM consistently located in different planes on fossa.
Lopes et al[127] (2008)	Macroscopic observation, 3-D laser photographs; photographs, illustrations	$n = 20$, 57-93 years	Mean area PCL femoral footprint 209 mm^2, mean ALB 118 mm^2, PMB 90 mm^2. AL center 7 ± 2 mm (10:20 o'clock), PM center 10 ± 3 mm (8:30 o'clock) from the articular cartilage.	Femoral footprint: osseous prominence proximal frequently seen (medial intercondylar ridge). Small osseous prominence between ALB and PMB in some knees.	Femoral footprint has medial intercondylar ridge usually present.
Moorman et al[147] (2008)	Observation, histology, lateral x-rays; photographs, x-rays	$n = 14$, age unknown	Mean PCL tibial insertion AP dimension 15.6 ± 1.1 mm. Center tibial insertion mean 7 mm anterior to the posterior cortex. Majority of fibers insert on posterior half of PCL facet.	PCL facet	Tunnel placement at the center of the PCL can be measured along the PCL facet as seen in a true lateral x-ray.
Edwards et al[47] (2007)	Observation, high-resolution digital photos; photographs, illustrations	$n = 39$, 60-80 years	Tibial attachment occupied posterior intercondylar fossa. Parallel femoral long axis: AL 9 to 12 o'clock (center, 10:20); 7 ± 2 mm (range, 4-12 mm) from cartilage edge. PMB 7:30 to 10:30 o'clock (center, 8:30), 10 ± 3 mm (range, 6-19 mm) from cartilage edge.	Posterior intercondylar fossa, Blumensaat's line, articular cartilage outlines	Tibial attachments consistent pattern in posterior intercondylar fossa. Femoral attachment required more than one measuring system.

ALB, anterolateral bundle; *AP*, anteroposterior; *CT*, computed tomography; *MFL*, meniscofemoral ligament; *NA*, not available; *PCL*, posterior cruciate ligament; *PMB*, posteromedial bundle.

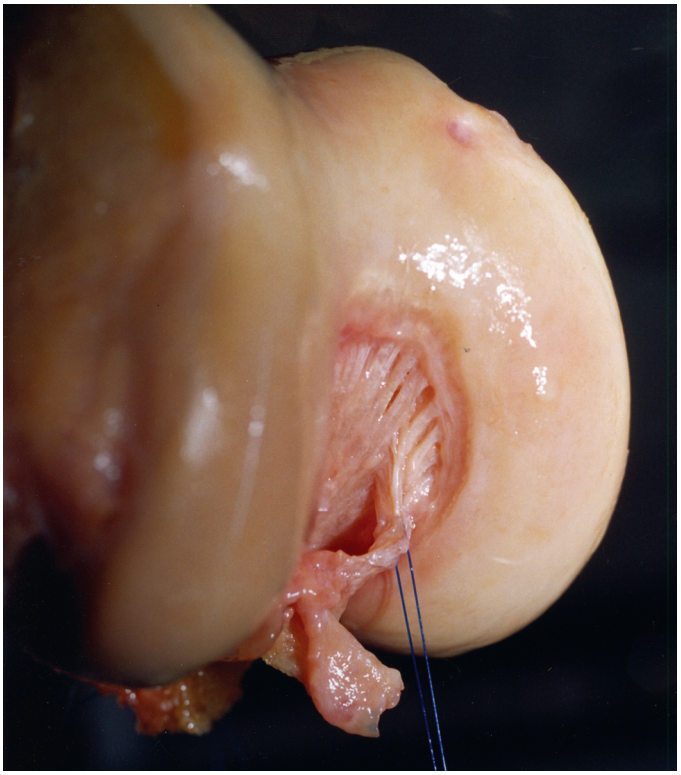


FIG 16-5 Anterior meniscofemoral ligament (ligament of Humphrey) attachment on the femur interdigitates with the posterior cruciate ligament distal fibers. (From Mejia EA, Noyes FR, Grood ES. Posterior cruciate ligament femoral insertion site characteristics. Importance for reconstructive procedures. *Am J Sports Med*. 2002;30:643-651.)

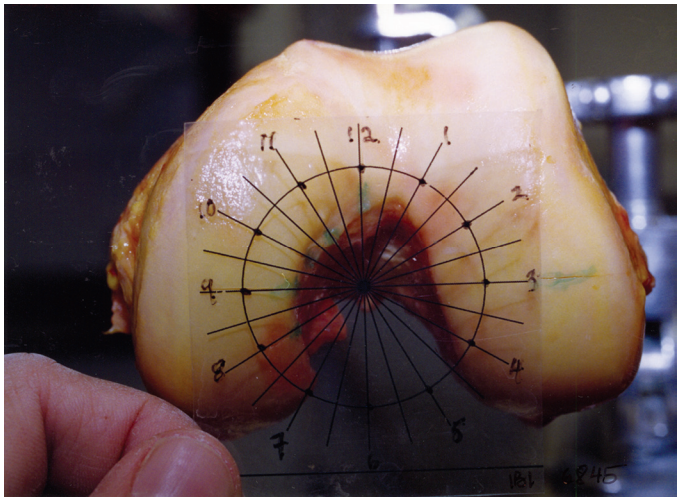


FIG 16-7 Clock-face markings on the medial femoral condyle as projected from a transparent sheet of acetate onto the notch viewed axially from a knee at 90 degrees of flexion. (From Mejia EA, Noyes FR, Grood ES. Posterior cruciate ligament femoral insertion site characteristics. Importance for reconstructive procedures. *Am J Sports Med*. 2002; 30:643-651.)

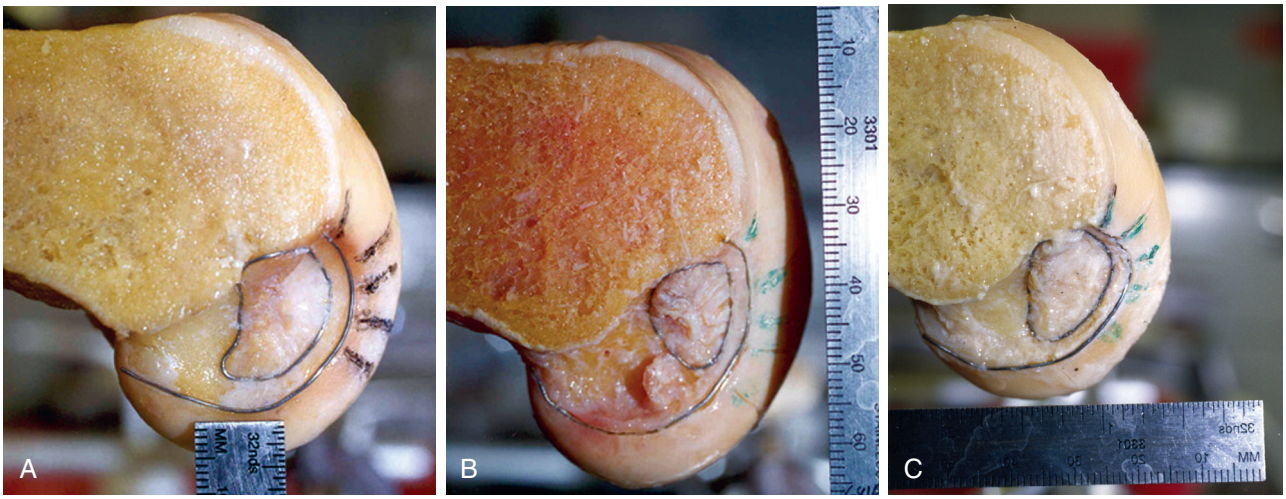


FIG 16-6 Composite of the shapes of different posterior cruciate ligament (PCL) insertion sites as seen on lateral views. Variability is noted among specimens from an oval to an elliptical PCL footprint configuration. Note the differences in anterior-to-posterior and proximal-to-distal dimensions in the PCL footprint. The most common shape of the PCL footprint is elliptical. **A,** Note that the fibers insert proximally to the intercondylar roof. The PCL footprint is smaller in its anteroposterior dimension. **B,** Note the prominent posterior meniscofemoral ligaments. **C,** A more oval PCL attachment with greater proximal-to-distal width. (From Mejia EA, Noyes FR, Grood ES. Posterior cruciate ligament femoral insertion site characteristics. Importance for reconstructive procedures. *Am J Sports Med*. 2002;30:643-651.)

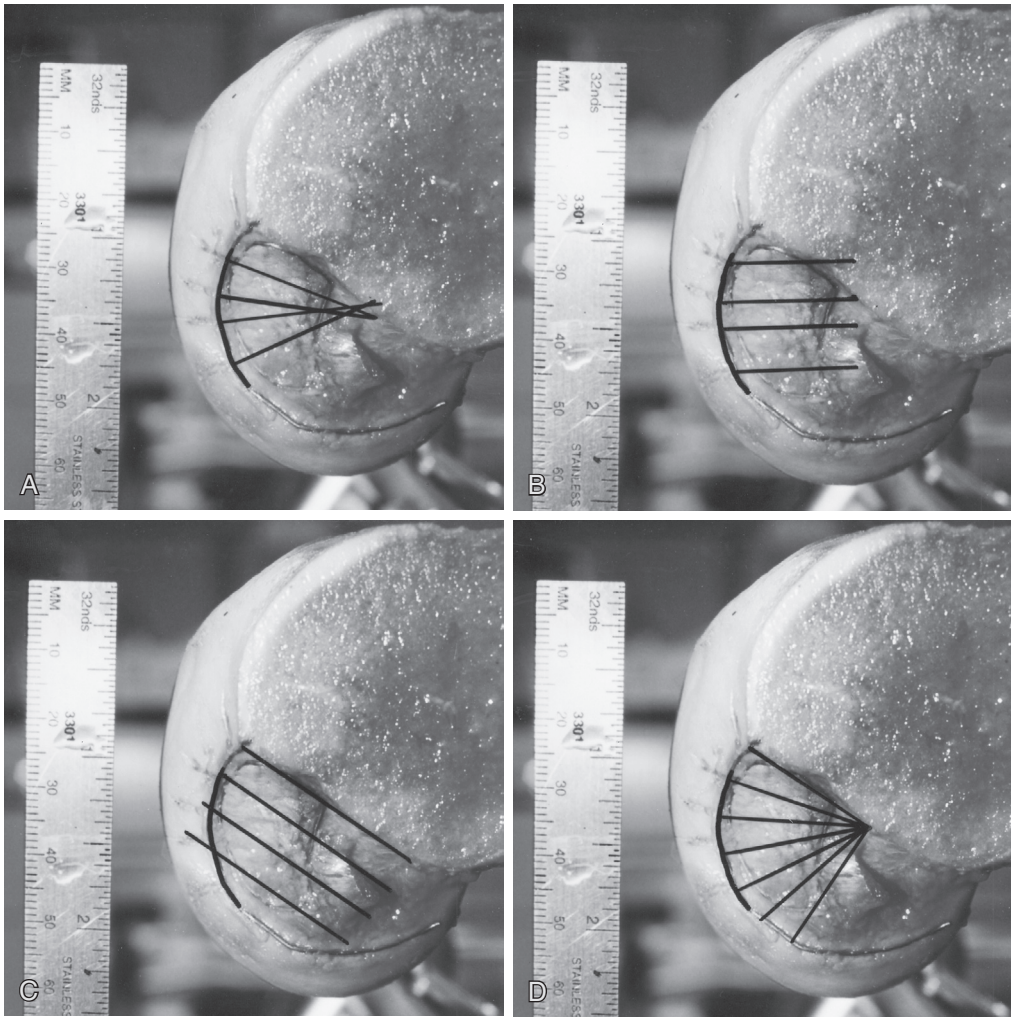


FIG 16-8 **A,** Measurement lines referenced from clock-face positions perpendicular to the cartilage edge. These reference lines represent the shortest distance to the distal margin of the posterior cruciate ligament (PCL) attachment. **B,** Measurement lines referenced from a clock-face position parallel to the femoral shaft. **C,** Measurement lines referenced from a clock-face position parallel to the intercondylar roof (5-mm increments). **D,** Measurement lines referenced radially from the intercondylar roof. These lines are directed from a center located at the most proximal extent of the PCL attachment onto the roof of the intercondylar notch. This point is, on average, located at approximately 60% of the roof depth. The line progresses from the 12 o'clock position (*top line*) to the 6 o'clock position (*bottom line*). (From Mejia EA, Noyes FR, Grood ES. Posterior cruciate ligament femoral insertion site characteristics. Importance for reconstructive procedures. *Am J Sports Med.* 2002;30:643-651.)

condyle notch. The anterior portion of the PCL attachment follows the articular cartilage within 2 to 3 mm of its edge and gradually recedes deeper within the notch until, at the 5 o'clock position, the posterior third is 5 mm from the articular margin. Therefore the distal boundary of the PCL femoral attachment does not parallel the articular margin as reported by others[63,219] but is farthest away from the cartilage margin posteriorly.

The distal and proximal measurements for the PCL femoral attachment are shown in Table 16-2 and measurements vary from one study to another depending on the method selected. The proximal edge of the PCL is usually straight or partially oval, with the attachment tapered in width along its posterior portion.

The PCL attachment measurements parallel to the intercondylar roof are shown in Table 16-3. The length of the radial measurement lines extending from the intercondylar roof are shown in Table 16-4. This method provides a means to measure the middle and lower portions of the PCL and provides information on the distance from the lowest cartilage margin to the most posterior portion of the PCL attachment.

The use of measurement lines perpendicular to the cartilage edge is preferred for describing the distal attachments of the PCL (see Fig. 16-8, *A*). The disadvantage of this system is that the 12 o'clock and usually the 1 o'clock measurements cannot be made parallel to the femoral shaft but must be done perpendicular to the cartilage (Fig. 16-9).

Therefore more than one measurement system is required to describe the anterior, middle, and posterior portions of the PCL femoral origin. Location of the center of the clock face midway in the

TABLE 16-2 Posterior Cruciate Ligament Femoral Attachment Measurements Made With the Femoral Condyle Articular Cartilage Clock System

Measurement	Distal (mm)	Proximal (mm)	Thickness (mm)
Perpendicular to the Cartilage			
12 o'clock	2.54 ± 1.0	12.92 ± 2.8	10.38 ± 2.8
1 o'clock	2.38 ± 0.7	14.33 ± 2.2	11.96 ± 2.0
2 o'clock	2.38 ± 0.5	14.79 ± 1.8	12.42 ± 1.7
3 o'clock	2.54 ± 0.5	14.83 ± 2.0	12.50 ± 1.7
4 o'clock	2.71 ± 0.7	13.92 ± 2.4	11.21 ± 2.2
Parallel to the Femoral Shaft			
12 o'clock	2.54 ± 1.0	12.75 ± 2.8	10.25 ± 2.8
1 o'clock	2.38 ± 0.7	13.75 ± 2.8	11.38 ± 2.8
2 o'clock	2.46 ± 0.7	14.63 ± 2.0	12.17 ± 1.9
3 o'clock	2.63 ± 0.8	13.42 ± 2.2	10.83 ± 2.2
4 o'clock	3.78 ± 1.0	11.06 ± 2.6	7.39 ± 2.9

From Mejia EA, Noyes FR, Grood ES. Posterior cruciate ligament femoral insertion site characteristics. Importance for reconstructive procedures. *Am J Sports Med.* 2002;30:643-651.

TABLE 16-3 Length of Measurement Lines Parallel to the Intercondylar Roof

Line Location (mm)	Distal (mm)	Proximal (mm)	Thickness (mm)
0	3.50 ± 1.7	13.82 ± 2.8	10.36 ± 3.3
5	2.50 ± 0.7	16.96 ± 2.5	14.54 ± 2.0
10	3.67 ± 1.3	15.21 ± 3.7	11.46 ± 3.7
15	4.25 ± 1.1	13.25 ± 3.9	9.00 ± 4.9

From Mejia EA, Noyes FR, Grood ES. Posterior cruciate ligament femoral insertion site characteristics. Importance for reconstructive procedures. *Am J Sports Med.* 2002;30:643-651.

TABLE 16-4 Length of Measurement Lines Radial to the Intercondylar Roof

	Distal (mm)	Proximal (mm)	Thickness (mm)
0	3.17 ± 1.9	12.92 ± 4.7	9.75 ± 4.2
1	2.33 ± 0.7	15.00 ± 2.5	12.67 ± 2.0
2	2.63 ± 0.7	14.96 ± 2.0	12.33 ± 1.8
3	2.54 ± 0.5	14.04 ± 1.7	11.50 ± 1.9
4	2.75 ± 0.9	12.88 ± 1.8	10.13 ± 1.9
5	3.08 ± 0.9	1.46 ± 2.1	8.38 ± 2.1
6	3.21 ± 1.1		

From Mejia EA, Noyes FR, Grood ES. Posterior cruciate ligament femoral insertion site characteristics. Importance for reconstructive procedures. *Am J Sports Med.* 2002;30:643-651.

notch is difficult but critical for identification of the landmarks required to map the PCL femoral attachment. This location should be identified with the knee at 90 degrees of flexion. Ideally, sagittal, anteroposterior (AP), and notch descriptions are required to anatomically represent the entire PCL attachment.

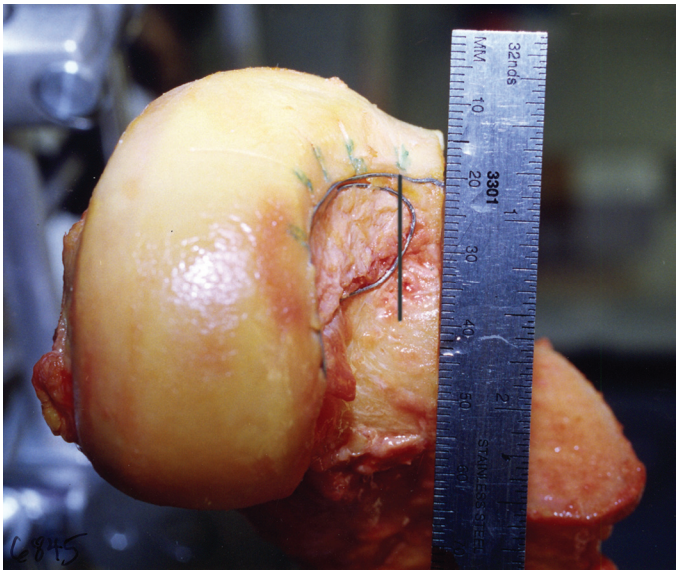


FIG 16-9 Reference line at the 12 o'clock position. The curved posterior cruciate ligament attachment is shown extending to the intercondylar roof. (From Mejia EA, Noyes FR, Grood ES. Posterior cruciate ligament femoral insertion site characteristics. Importance for reconstructive procedures. *Am J Sports Med.* 2002;30:643-651.)

A clear understanding of the anatomy of the native PCL is critical to determine what portion of the ligament will be reconstructed. The terms "high," "low," "shallow," and "deep" are only general descriptors. Because there may be considerable confusion regarding femoral graft tunnel placement during PCL reconstruction, the PCL femoral attachment is described using the rule of thirds (Fig. 16-10) to define the proximal-middle-distal thirds (deep to shallow in the femoral notch), and anterior-middle-posterior thirds (high to low), with a small posterior oblique portion in the sagittal plane.[144,151] This provides a grid for the identification of the tunnel locations for the graft strands and is preferred by the senior author (F.R.N.).

It is well appreciated that the PCL graft femoral attachment location strongly influences graft tension and the ability of the reconstruction to restore posterior stability.[12,56,189,197] Investigations by Grood and associates[68] and Sidles and colleagues[203] demonstrated that the femoral attachment location determines the graft tibiofemoral separation distance with knee flexion-extension, much more so than the tibial attachment location. The proximal-distal femoral location of a graft has a greater effect on the attachment separation distance than the AP femoral location, which is the basis for the rule of thirds (see Fig. 16-10, *B*). A graft placed in the distal and middle thirds elongates with knee flexion, whereas a graft placed in the proximal third elongates with knee extension. These concepts are used to select PCL graft attachment locations and tensioning described in the "Operative Techniques" section.

Anderson and colleagues[9] described, in 20 unpaired cadaveric knees, the PCL femoral and tibial attachments of the ALB and PMB to provide the surgeon with landmarks for the placement of PCL grafts. The femoral PCL attachment is illustrated in Figure 16-3 and the arthroscopic viewpoint is illustrated in Figure 16-11. The centers of the ALB and the PMB were a mean of 7.9 mm and 8.6 mm, respectively, from the articular cartilage edge, which is in close agreement with the data previously presented (see Table 16-1). It is understood that the variability among studies of a few millimeters reflect differences in both measurement techniques and cadaveric specimens. Even

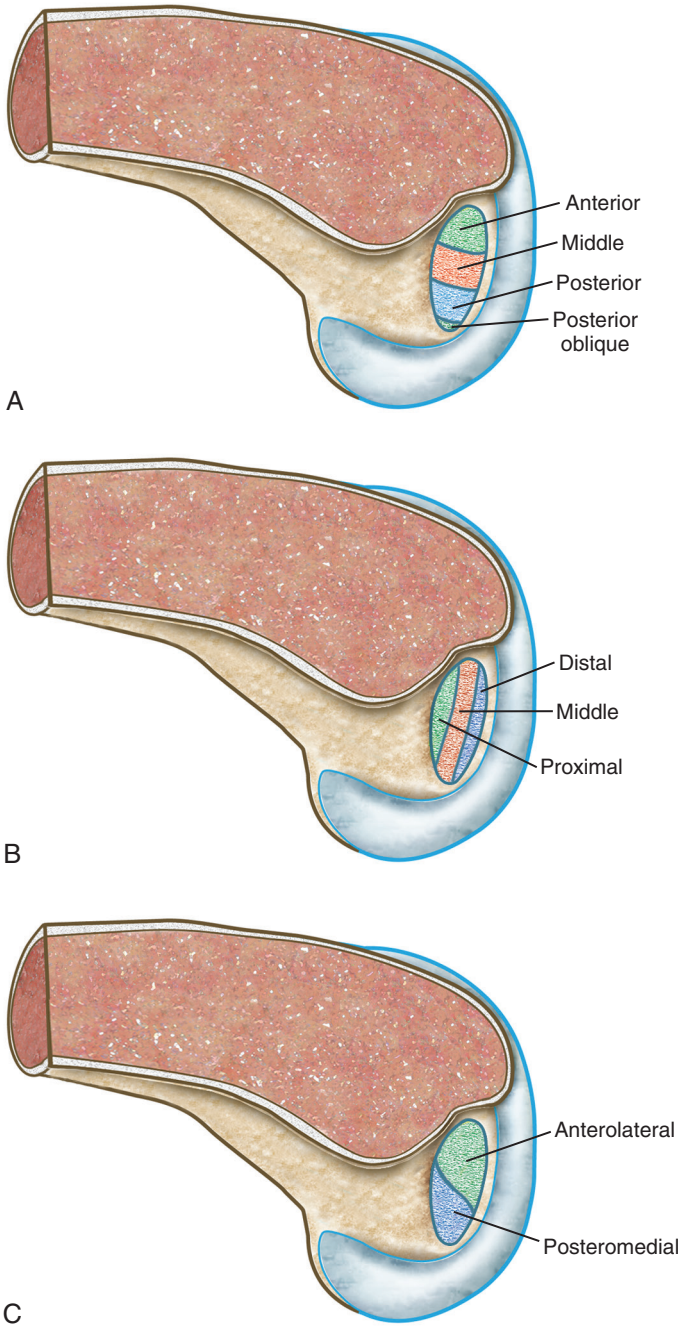


FIG 16-10 A, Rule of thirds: The posterior cruciate ligament (PCL) footprint is divided into anterior, middle, and posterior thirds. The anterior third extends past the midline (12:30, left knee) and the posterior region extends to 5 o'clock. The smaller posterior oblique portion of the PCL footprint is also represented. The PCL footprint is elliptical in most knees, but variations exist. **B,** Rule of thirds: The PCL footprint is further divided into the distal, middle, and proximal thirds. This allows for more exact referencing of graft strand placement during PCL reconstruction. The PCL fibers in the distal two-thirds lengthen with knee flexion while the proximal fibers shorten. The reverse occurs with knee extension. **C,** Classical division of anterolateral and posteromedial bundles provides a general description of PCL fiber length change of anterolateral fibers that lengthen and posteromedial fibers that shorten with knee flexion.

so, the data of these collective studies allow a reasonable definition of the PCL attachment sites at surgery. The AL portion extends distally to within approximately 2 mm of the femoral articular cartilage edge or margin, and the PM portion extends distally 4 to 6 mm from the femoral articular cartilage edge. This analysis allows for a more distal femoral placement of PCL grafts than has been historically recommended, as will be discussed.

An illustration of the posterior PCL tibial attachment is shown in Figure 16-4. The landmarks for the tibial attachment of the PCL are illustrated in Figure 16-12. The *shiny fibers* of the medial meniscus attachment are easily viewed at surgery. The posterior capsule attachment at the posterior tibial ridge is illustrated as an opening to show the proximity of the popliteus muscle. This posterior capsular attachment is always preserved and not violated at surgery.

VASCULAR ANATOMY AND VARIATIONS

The vascular supply to the cruciate ligaments is provided mostly by the middle genicular artery, which is a branch of the popliteal artery that penetrates the posterior capsule of the knee.[10,190] The PCL is covered with a well-vascularized synovial sleeve that contributes to its blood supply. The distal portion of the PCL also receives some vascular supply from capsular vessels originating from the inferior genicular arteries and the popliteal artery.

Detailed knowledge of posteromedial knee anatomy, especially the vascular structures, is required to avoid complications when using a posteromedial approach to a tibial inlay PCL reconstruction (see Chapter 2). The popliteal artery originates at the adductor hiatus and passes through the popliteal fossa. Before passing deep to the fibrous arch over the soleus muscle, it divides into the anterior and posterior tibial arteries at the distal aspect of the popliteus muscle.

Proximal to the knee joint, several muscular branches arise and supply the adductor magnus and hamstring muscles. At the level of the supracondylar ridge, the superomedial and superolateral genicular arteries are present.

At the level of the knee joint, four major arteries are distributed: the medial and lateral sural arteries, a cutaneous branch that travels with the small saphenous vein to supply superficial tissues, and the middle genicular artery. Finally, the medial and lateral inferior genicular arteries are present just distal to the knee joint.

Two branches deserve particular attention. The medial inferior genicular artery arises from the medial aspect of the distal portion of the popliteal artery and runs medially, deep to the medial head of the

CRITICAL POINTS Vascular Anatomy and Variations

- Vascular supply mostly provided by middle genicular artery.
- Popliteal artery originates at adductor hiatus, passes through popliteal fossa, and divides into anterior and posterior tibial arteries at the distal aspect of the popliteus muscle.
- Four major arteries at level of knee joint: medial and lateral sural arteries, a cutaneous branch that travels with the small saphenous vein to supply superficial tissues, middle genicular artery.
- Medial and lateral inferior genicular arteries given off just distal to knee joint.
- Normal vascular pattern 88% of knees, 5%-7% anatomic variation, anterior tibial artery passes anterior and proximal to popliteus muscle.
- Popliteal artery: anatomic variability possible, manifests as popliteal artery entrapment syndrome.
- Embryologic development explains abnormal vascular patterns.

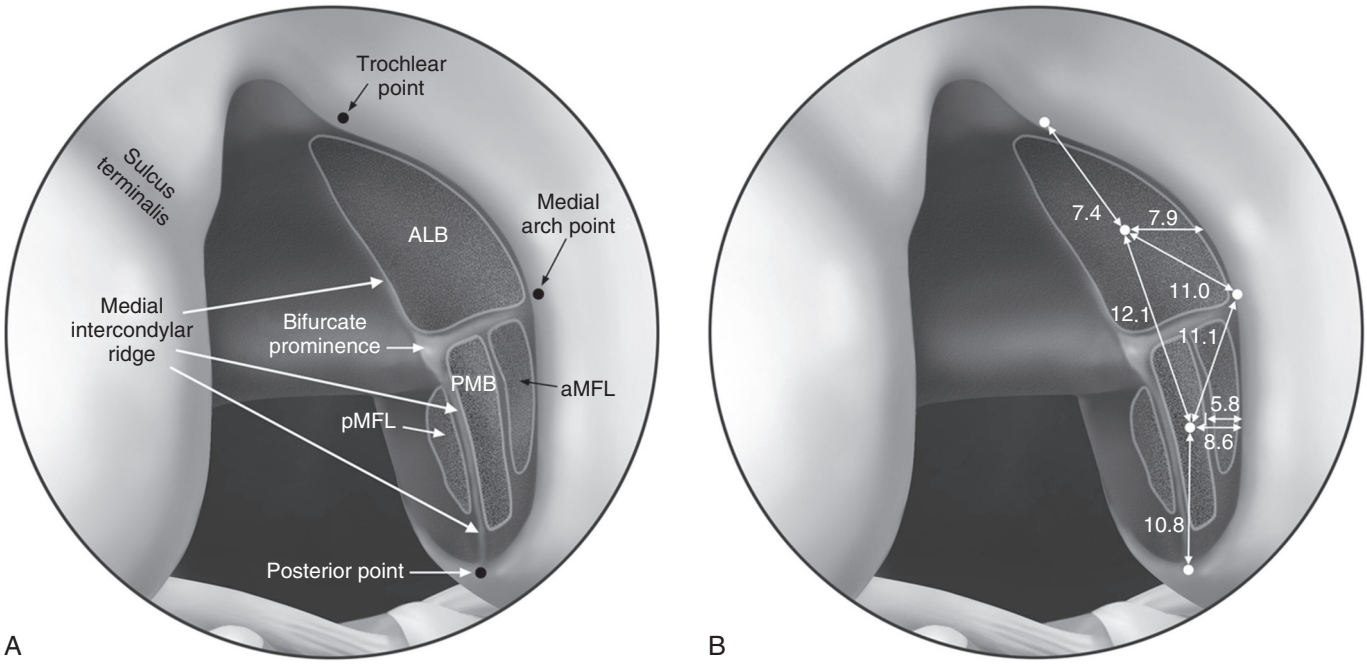


FIG 16-11 **A,** The arthroscopic view of the femoral attachment of the posterior cruciate ligament (PCL) in a right knee, demonstrating pertinent landmarks. **B,** Illustration showing the quantitative measurements for the femoral attachment of the PCL. The values are reported in millimeters. *ALB*, Anterolateral bundle; *aMFL*, anterior meniscofemoral ligament; *PMB*, posteromedial bundle; *pMFL*, posterior meniscofemoral ligament. (From Anderson CJ, Ziegler CG, Wijdicks CA, Engebretsen L, LaPrade RF. Arthroscopically pertinent anatomy of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *J Bone Joint Surg Am*. 2012;94:1936-1945.)

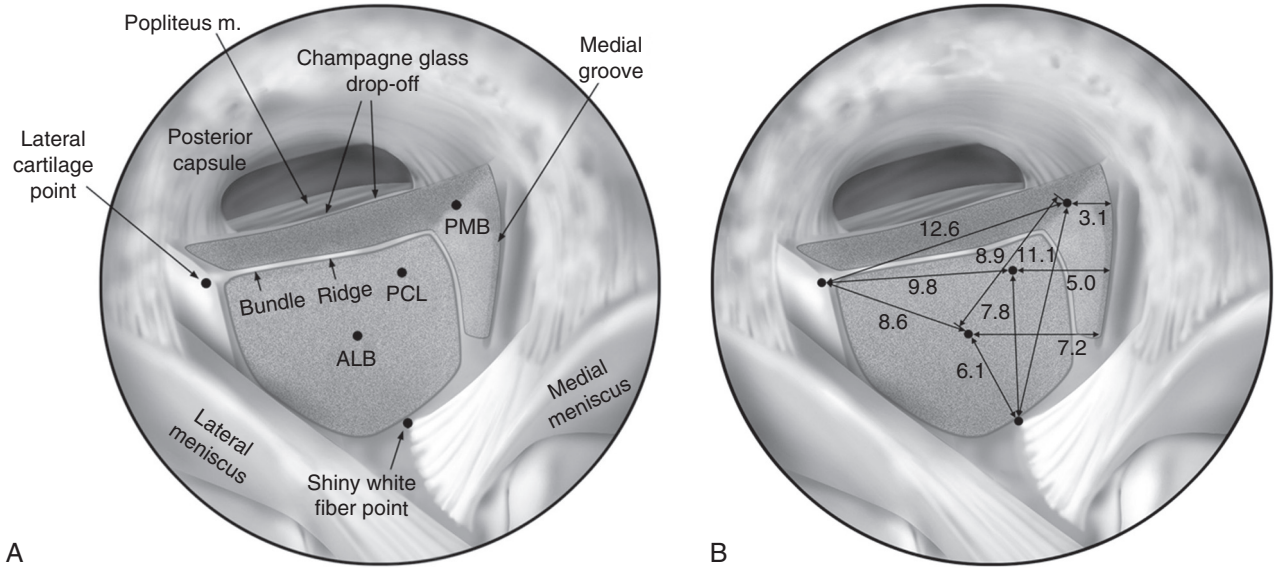


FIG 16-12 **A,** The arthroscopic view of the tibial attachment of the posterior cruciate ligament (PCL) in a right knee, demonstrating pertinent landmarks. **B,** Illustration showing the quantitative measurements for the tibial attachment of the PCL. The values are reported in millimeters. *ALB*, Anterolateral bundle; *PMB*, posteromedial bundle; *m*, muscle. (From Anderson CJ, Ziegler CG, Wijdicks CA, Engebretsen L, LaPrade RF. Arthroscopically pertinent anatomy of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *J Bone Joint Surg Am*. 2012;94:1936-1945.)

gastrocnemius, and approximately 2 to 3 mm from the superior surface of the popliteus muscle. It continues around the medial aspect of the proximal tibia, deep to the superficial medial collateral ligament (SMCL). The middle genicular artery arises at the level of the femoral condyles proximal to the joint line and passes anteriorly to pierce the oblique popliteal ligament (OPL) and posterior joint capsule and supply the cruciate ligaments.

This "normal" vascular pattern has been reported to occur in approximately 88% of cases.[42,140] In approximately 5% to 7% of cases, the popliteal artery will divide at least 2 cm or more proximal to the popliteus muscle.[38,42,140] In slightly less than half of these cases, with a high division of the popliteal artery, the anterior tibial artery passes anterior, not posterior, to the popliteus muscle belly.[216] The number of variations of the anterior tibial artery according to Mauro and coworkers[140] is illustrated in Figure 16-13. Therefore with a tibial inlay approach, the dissection is always proximal to the popliteus muscle with a meticulous technique, because the anterior tibial artery is at risk for transection in approximately 3% to 4% of knees.

An unusual variation in the vascular pattern involves the popliteal artery passing medial and then beneath the medial head of the gastrocnemius. Various subtypes of this abnormal pattern have been described. An abnormal vascular pattern may manifest clinically as the popliteal artery entrapment syndrome, which is characterized by vascular claudication symptoms.[112,185,207] Arterial insufficiency occurs most commonly with entrapment of the artery deep to the medial gastrocnemius muscle, but can also occur when the artery is entrapped deep to the popliteus muscle (persistence of ventral component of artery) or deep to an abnormal accessory head of the gastrocnemius. A history of pain in the lower extremity with activity and disappearance with rest, particularly in a young patient, should alert the surgeon to the possibility that an abnormal vascular pattern may exist. Further evaluation with angiography may be warranted.[54,128]

Embryologic development helps to explain these abnormal vascular patterns. In the embryo, the lower extremity blood supply is derived from the sciatic or axial artery (a branch of the internal iliac artery) as well as the femoral artery (a branch of the external iliac artery). The proximal sciatic artery regresses, whereas the middle and distal sciatic artery persist to form the definitive popliteal and peroneal arteries.

The anterior tibial artery arises as a branch of the popliteal artery and initially courses anterior to the popliteus muscle. In humans, the early anterior tibial artery is replaced with the superficial popliteal artery and passes posterior to the popliteus muscle, which then gives rise to the anterior tibial artery. Furthermore, during embryonic life, the medial head of the gastrocnemius migrates medially and cranially. It is with this migration that the popliteal artery can be caught and swept medially with the muscle.[140,185]

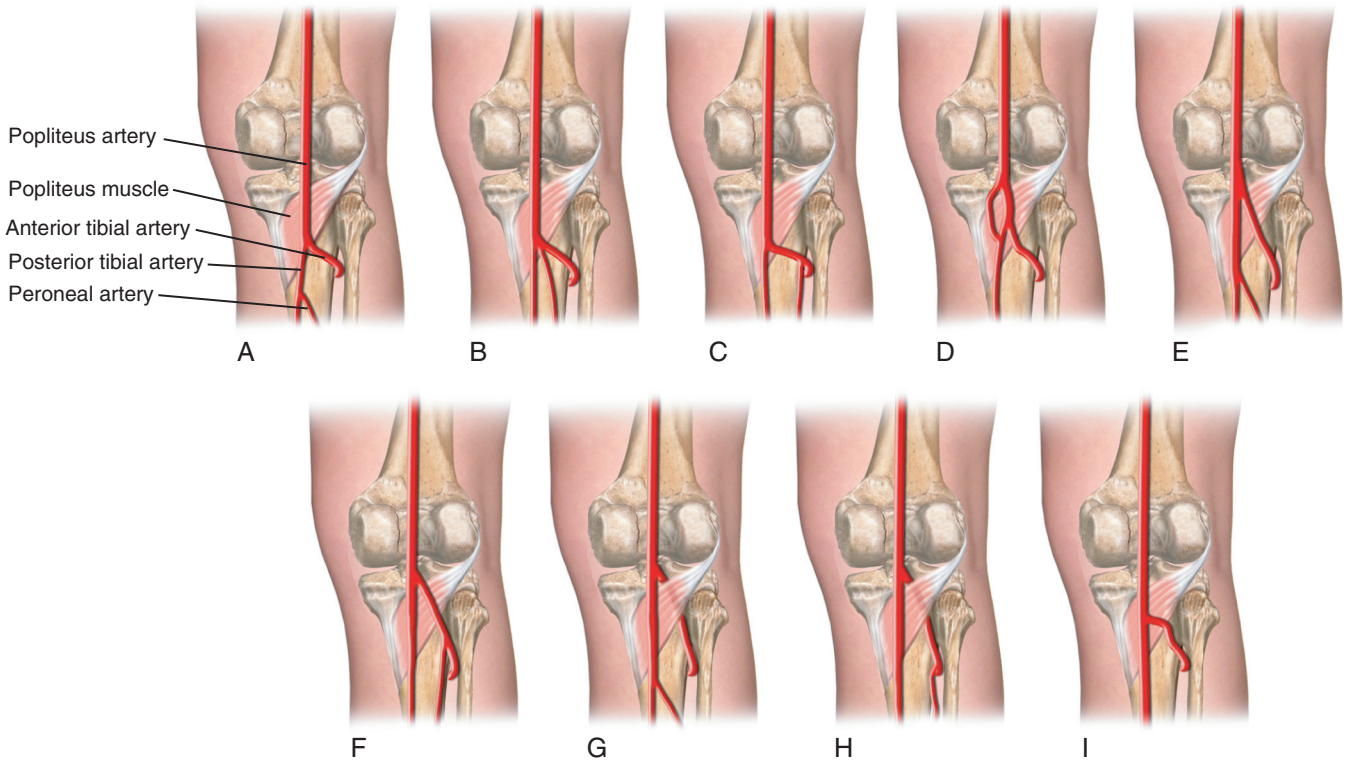


FIG 16-13 Anatomic variations of the popliteal artery and its branches. Diagrams represent posterior views of popliteal fossa and popliteus muscle. **A,** Normal. **B,** Trifurcating popliteal artery. **C,** Peroneal artery arising from low anterior tibial artery. **D,** "Island" popliteal artery (very rare). **E,** High anterior tibial origin passing superficial to popliteus muscle. **F,** Same as E with peroneal artery arising from anterior tibial artery. **G,** Same as E with anterior tibial artery passing deep to popliteus muscle. **H,** Same as F except anterior tibial artery passes deep to popliteus muscle. **I,** Absent posterior tibial artery. Note that the anterior tibial artery is at risk in the initial dissection proximal to the popliteus muscle in **D** through **H**. (From Mauro MA, Jacques PF, Moore M. The popliteal artery and its branches: embryologic basis of normal and variant anatomy. *AJR Am J Roentgenol.* 1988;150:435-437.)

CLINICAL EVALUATION

Physical Examination

A comprehensive examination of the knee joint is required to detect all abnormalities. This includes assessment of, first, the patellofemoral joint and patellar tendon-tibial tubercle alignment (Q angle), which may be increased owing to increased external tibial rotation when a posterolateral ligament injury accompanies the PCL rupture. Second, patellofemoral and tibiofemoral crepitus, is indicative of articular cartilage damage. Third, gait abnormalities (excessive hyperextension or varus thrust) are assessed during walking and jogging.[165] Finally, abnormal knee motion limits and subluxations are compared with those of the contralateral knee[167].

Experienced clinicians are aware that patients with chronic deficiency of the PCL and posterolateral structures may develop an abnormal gait pattern that is characterized by excessive knee hyperextension during the stance phase.[165] Subjective complaints of knee instability and giving-way during routine daily activities, along with severe quadriceps atrophy, often accompany this gait abnormality. Gait analysis and retraining are required in patients who demonstrate abnormal knee hyperextension patterns before proceeding with any ligament reconstruction (see Chapter 29).[165] The failure to do so may lead to failure of reconstructed ligaments if the abnormal gait pattern is resumed postoperatively.

Diagnostic Clinical Tests

The medial posterior tibiofemoral step-off on the posterior drawer test is performed at 90 degrees of flexion. The amount of posterior tibial translation will vary between knees with isolated PCL ruptures because of physiologic laxity or injury to the secondary posterolateral or medial soft tissue restraints. Posterior tibial translation progressively increases with injury to the secondary restraints. The importance of determining abnormal medial or lateral joint opening and increases in external-internal tibial rotation cannot be overemphasized, because the failure to correct these associated subluxations places PCL graft reconstructions under high in vivo forces postoperatively and risk of graft failure.[157] The diagnostic tests and their interpretation are discussed in Chapter 15.

The exact determination of the extent of a PCL tear (partial versus complete) can be difficult but is essential from a therapeutic standpoint. The clinical posterior drawer test can be highly subjective, with the forces applied too variable to allow accurate determination of the status of the PCL. Magnetic resonance imaging (MRI) is not always accurate in diagnosing partial PCL tears (Fig. 16-14). Frequently, this test may indicate that the ligament is completely ruptured; however, ligament continuity may still exist with some portions functioning to limit posterior tibial subluxation to only a few millimeters. Patten and associates[178] reported only a 67% sensitivity rate of the ability of MRI to distinguish complete from partial PCL tears by identifying focal areas of ligamentous discontinuity.

The quantitative measurement of posterior tibial subluxation in knees with PCL ruptures or reconstruction is therefore important.[80] The knee arthrometer is the most frequently used device to measure posterior tibial translation after PCL injury and reconstruction. However, the knee arthrometer underestimates the true amount of posterior translation in PCL-deficient and reconstructed knees, often by several millimeters.[80,134,208] Stress radiography is the most accurate and reproducible technique currently available.[46,80,134,181,193] We recommend that PCL clinical investigations incorporate stress radiography to provide a more valid measure of posterior tibial translation (Fig. 16-15). To correct for tibial rotation, which can produce errors in

CRITICAL POINTS Clinical Evaluation

Physical Examination
- Patellofemoral joint, extensor mechanism malalignment
- Patellofemoral and tibiofemoral crepitus
- Gait abnormalities
- Abnormal knee motion limits, subluxations

Diagnostic Clinical Tests
- Posterior drawer, 90 degrees of knee flexion
- Pivot shift, Lachman
- KT-2000, 20 degrees of knee flexion, 189 N of force (optional)
- Reverse pivot shift
- Medial tibiofemoral joint opening 0, 30 degrees of knee flexion
- Lateral tibiofemoral joint opening 0, 30 degrees of knee flexion
- Tibiofemoral rotation dial test, 30 and 90 degrees of knee flexion

Radiographic Assessment
- Anteroposterior
- Lateral, 30 degrees of knee flexion
- Posteroanterior, weight bearing, 45 degrees of knee flexion
- Patellofemoral axial
- Posterior stress, 90 degrees of flexion, 89 N posterior force on tibia
- Medial or lateral stress, neutral tibial rotation, tibia unconstrained, 89 N varus force
- Double-stance to measure mechanical axis and weight bearing line

Assessment of Symptoms and Functional Limitations With Activity: Use Cincinnati Knee Rating System
- Sports Activity and Function Form
- Occupational Rating Form
- Symptom Rating Form

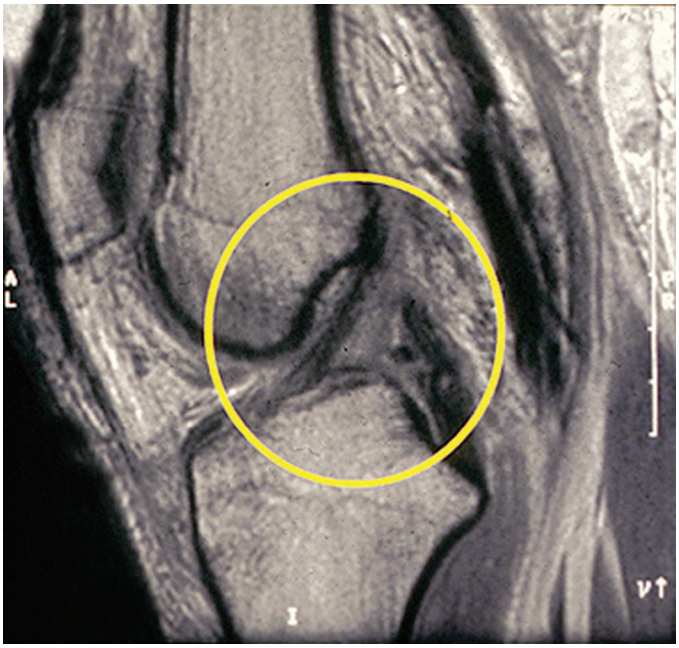


FIG 16-14 A partial posterior cruciate ligament (PCL) rupture is shown. Even though the magnetic resonance imaging suggests a complete rupture, there were remaining PCL fibers resisting posterior tibial subluxation.

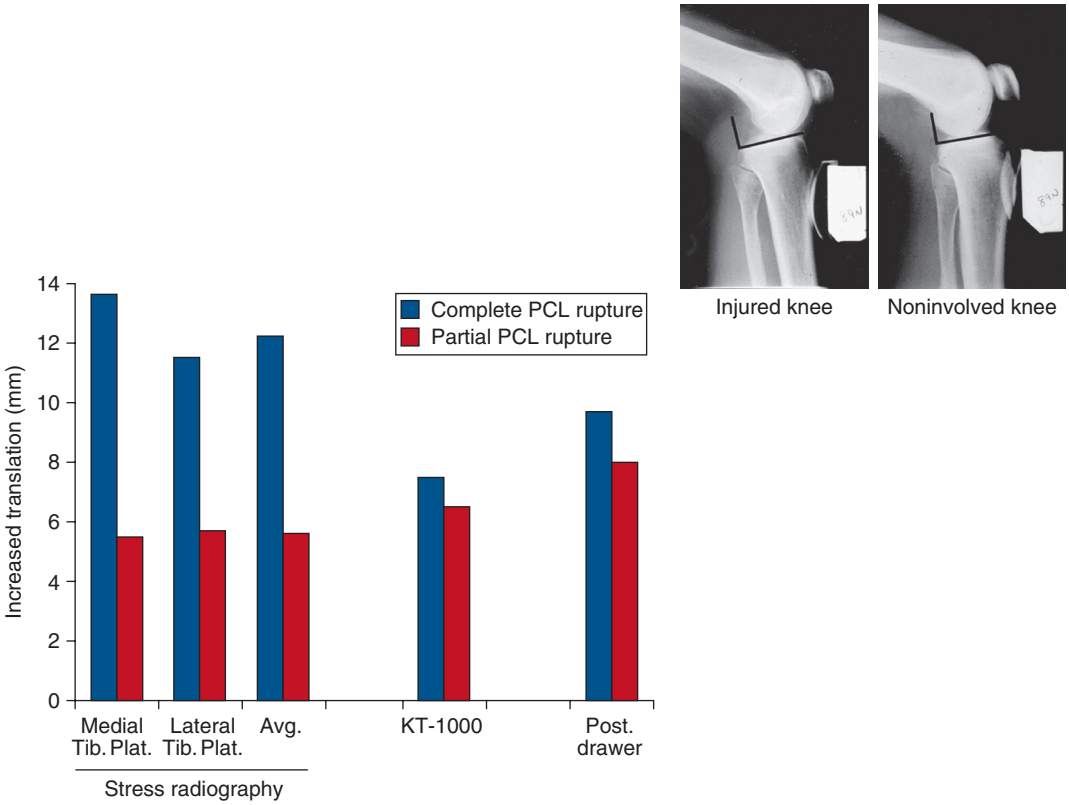


FIG 16-15 The results of lateral stress radiography on 20 patients with posterior cruciate ligament (PCL) deficiency (9 complete ruptures and 11 partial ruptures). The differences in the measurements between complete and partial PCL ruptures for the medial tibial plateau (Tib. Plat.), the lateral tibial plateau, and the average of both plateaus were statistically significant ($P < .01$). Differences in the KT-1000 and posterior (Post.) drawer measurements between complete and partial PCL ruptures were not significant. The KT-measurements at 70 degrees of flexion underestimated the magnitude of posterior tibial subluxation for complete PCL ruptures. (From Hewett TE, Noyes FR, Lee MD. Diagnosis of complete and partial posterior cruciate ligament ruptures. Stress radiography compared with KT-1000 arthrometer and posterior drawer testing. *Am J Sports Med.* 1997;25:648-655.)

measurement, the radiograph should be as close to a pure lateral as possible, with the two femoral condyles superimposed on themselves. A horizontal line is placed across the medial tibial plateau and a perpendicular line determines the posterior position of each femoral condyle. A similar measurement is made for the most posterior position of the medial and lateral tibial plateau. The amount of tibial translation is the average of both of these measurements. An alternative technique is to measure the posterior extent of the Blumensaat line and the proximal aspect of the PCL tibial fossa, which avoids the error of tibial rotation.[85]

The integrity of the ACL is determined by Lachman and pivot shift testing. The result of the pivot shift test is recorded on a scale of 0 to III, with a grade of 0 indicating no pivot shift; grade I, a slip or glide; grade II, a jerk with gross subluxation or clunk; and grade III, gross subluxation with impingement of the posterior aspect of the lateral side of the tibial plateau against the femoral condyle. A KT-2000 arthrometer test may be done at 20 degrees of flexion (134-N force) to quantify total AP displacement.

Medial and lateral ligament insufficiency are determined by varus and valgus stress testing at 0 and 30 degrees of knee flexion. The surgeon estimates the amount of joint opening (in millimeters) between the initial closed contact position of each tibiofemoral compartment, performed in a constrained manner avoiding internal or external tibial rotation, and the maximal opened position. The result is recorded according to the increase in the tibiofemoral compartment of the affected knee compared with that of the opposite normal knee.

The tibiofemoral rotation dial test at 30 and 90 degrees is done to determine whether increases in external tibial rotation exist with posterior subluxation of the lateral tibial plateau (see Chapter 17).[167]

The presence of a varus recurvatum in both the supine and standing positions is carefully assessed. The difference in results of these tests must be done between the injured and contralateral normal knee because of inherent physiologic looseness present in some individuals.

Radiographic Assessment

Radiographs taken during the initial examination include AP, lateral at 30 degrees of knee flexion, weight-bearing posteroanterior (PA) at 45 degrees of knee flexion, and patellofemoral axial views.

Posterior stress radiographs are done with an 89-N force applied to the proximal tibia.[80] A lateral radiograph is taken of each knee at 90 degrees of flexion. The limb is placed in neutral rotation with the tibia unconstrained and the quadriceps relaxed. The difference in posterior tibial displacement between the reconstructed knee and the contralateral knee is recorded. More than 8 mm of increase in posterior tibial translation on stress testing indicates a complete PCL rupture and

more than 12 mm of increase is indicative of probable injury to the posterolateral structures.[193]

Medial or lateral stress radiographs may be required of both knees. The patient is seated (20 degrees of knee flexion) in neutral tibial rotation with the tibia unconstrained. Approximately 89 N of varus or valgus force is applied and a comparison is made of the millimeters of medial or lateral tibiofemoral compartment opening between knees.

Full standing radiographs of both lower extremities, from the femoral heads to the ankle joints, are done in knees in which varus lower extremity alignment is detected on clinical examination. The mechanical axis and weight-bearing line are measured to determine whether HTO is indicated before PCL reconstruction (see Chapter 26).[45,163] If the varus malalignment is not corrected, there is a risk that either a PCL or ACL graft may fail owing to the varus thrusting forces and concurrent increased lateral joint opening producing high graft tension loads.[157]

Patients complete questionnaires and are interviewed for the assessment of symptoms, functional limitations, sports and occupational activity levels, and patient perception of the overall knee condition according to the Cincinnati Knee Rating System (CKRS).[13]

PREOPERATIVE PLANNING

Acute Ruptures of the Posterior Cruciate Ligament

Controversy exists in the treatment of isolated midsubstance complete PCL ruptures, primarily owing to the lack of a scientifically proven operative procedure that can predictably restore posterior stability and PCL function. In comparison, surgical procedures to reattach the native PCL in cases of bony avulsion injuries or peel-off injuries directly at the PCL attachment site have more predictable healing rates.[36,67,232,245] In cases of PCL rupture directly at the attachment site, there is usually sufficient ligament substance for a direct repair. In select situations, an augmentation using the semitendinosus tendon may facilitate PCL repair. Augmentation of partial PCL tears is controversial[6,44,92,93,103,114,115,239,241,248] and only indicated in high-grade tears. Posterior stress radiography plays an important role in determining whether an abnormal increase of 10 mm or more of posterior tibial translation exists, indicating loss of PCL function. Partial ligament tears are treated conservatively with an extension brace and posterior calf pad or bivalved cast to allow for potential PCL healing.

The treatment rationale for patients with acute PCL ruptures is shown in Figure 16-16. The algorithm is divided into three major sections based on the PCL tear (partial, complete, or combined with other ligament ruptures). The 10-mm division is somewhat arbitrary. As discussed, stress radiography is helpful in determining the exact increase in posterior tibial translation. The rules to treat partial or acute isolated PCL tears are used when the injury is seen within the first two weeks; after this time, the program is not instituted. The program rules are as follows:

1. Immobilize for 4 weeks in a full knee extension brace or bivalved cylinder cast to maintain tibiofemoral reduction.[4,87,95] Use quadriceps isometrics, electrical muscle stimulation, leg raises, and 25% weight bearing.
2. Obtain an AP and lateral radiograph to verify that no posterior tibial or lateral subluxation exists, which can occur in up to 50% of knees.
3. At 2 weeks, the therapist initiates 0 to 90 degrees of motion, maintaining an anterior tibial translation load. The patient must sleep in the brace and is not allowed unsupervised knee motion to prevent posterior tibial subluxation.
4. At 4 weeks, the patient is allowed to perform active quadriceps extension out of the brace, 50% weight bearing with crutch support, and maintains brace protection.
5. At 5 to 6 weeks, the patient is weaned from the brace and crutch support, full knee flexion is allowed, and the rehabilitation protocol (described in Chapter 18) is followed to protect the healing PCL fibers.

In our experience, 4 weeks of protection to allow initial healing of a complete PCL rupture will frequently restore partial PCL function, with less than 5 to 7 mm of posterior tibial subluxation remaining on examination. The initial PCL healing process involves a low tensile strength and an additional 4 to 6 weeks of protection is recommended, including avoiding athletics, running, walking on downhill grades,

CRITICAL POINTS Preoperative Planning

Acute Ruptures

- Reattach native PCL bony avulsion injuries, peel-off injuries directly at PCL attachment, predictable healing rates.
- Select knees, augmentation with semitendinosus tendon may facilitate PCL repair, add postoperative protection.
- Partial or acute isolated PCL tears
  - Immobilize 4 weeks in full knee extension brace or bivalved cylinder cast.
  - Lateral radiograph verifies no posterior tibial subluxation.
  - 2 weeks: 0-90 degrees of motion maintaining anterior tibial translation load. Patient sleeps in brace, no unsupervised knee motion.
  - 4 weeks: active quadriceps extension out of brace, 50% weight bearing, crutch support, maintain brace protection.
  - 5-6 weeks: wean from the brace and crutch support, rehabilitation.
- Acute PCL injuries with associated rupture to medial or posterolateral structures: delay reconstruction until neurovascular status and other injuries are resolved and major knee ligament surgery can be safely performed.
- Associated posterolateral ruptures: acute anatomic repair required within 14 days before scarring occurs.

PCL graft reconstruction in select athletes before secondary restraints stretch out with subsequent reinjury, arthritis.

PCL and Multiligament Injuries

- Acute disruption: delay reconstruction to resolve other injuries.
- Posterolateral injuries: perform anatomic repair within 14 days if possible.
- Displaced meniscus tear: repair as soon as possible, all-inside technique.
- Dislocated knees: majority treated in staged approach, surgery delayed, knee protected to prevent posterior tibial subluxation.
- MCL disruptions require cast 7 to 10 days that is then split into anterior and posterior shell to allow therapist-assisted range of motion.

Chronic Injuries

- Assess patient's symptoms, goals, athletic desires: may indicate PCL reconstruction required.
- Varus malalignment: osteotomy before PCL reconstruction.
- PCL plus medial or posterolateral ligament injury, complex instability pattern, usually surgical candidate.
- Severe arthrosis: not expected to benefit from PCL reconstruction.
- Nonoperative approach chronic PCL tears: warn that return to athletics carries uncertain prognosis, joint arthrosis may eventually ensue.
- Consider bone scan, MRI cartilage sequences.
- Initiate rehabilitation, patient's education, avoid high knee flexion activities.

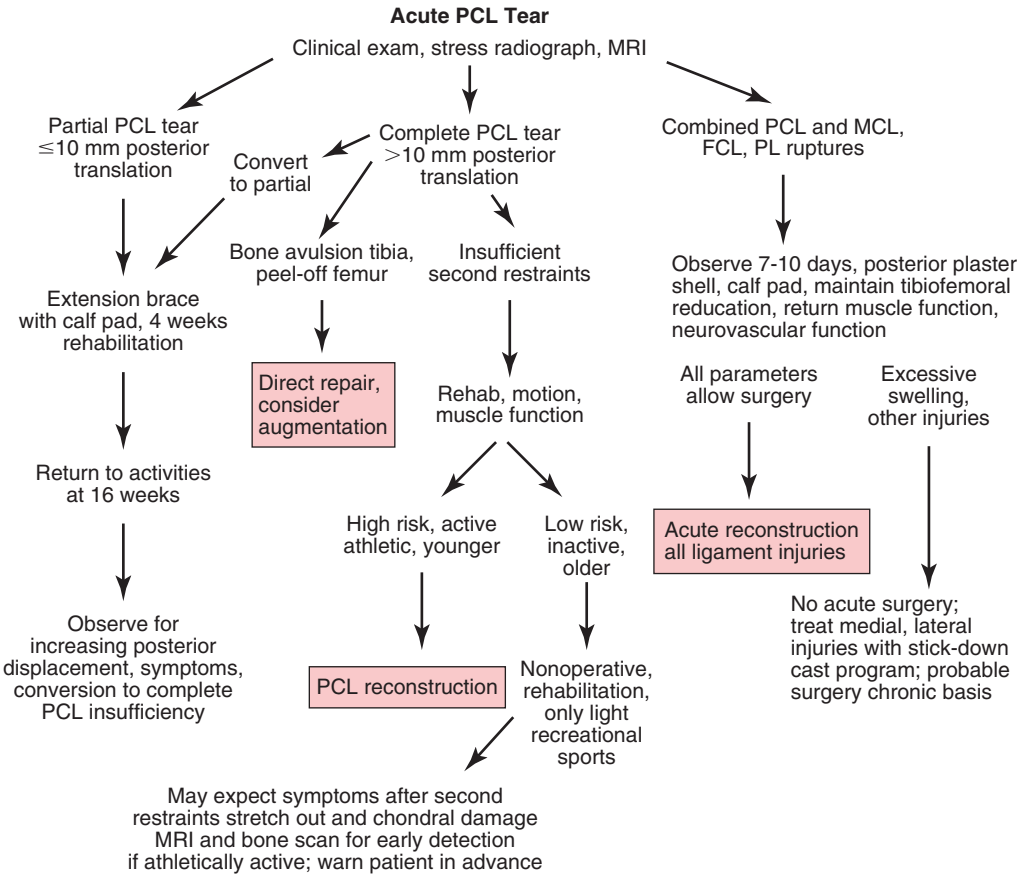


FIG 16-16 Treatment algorithm for acute posterior cruciate ligament (PCL) ruptures.

walking downstairs, or other high knee flexion activities that load the PCL. Even in knees with a complete PCL tear and more than 10 mm of increased posterior tibial displacement, healing of the disrupted PCL fibers may still occur, although a residual posterior tibial subluxation of a few millimeters (with a hard endpoint) will remain. These knees in which partial PCL function has been restored should be followed and repeat stress radiographs obtained at 6 months and over the next few years to determine PCL function. These partial PCL tears seldom require reconstruction. A repeat MRI with fast spin-echo cartilage sequences[182] helps determine the integrity of the articular cartilage and provides important information for counseling the patient on athletic activities to decrease the risk of future joint arthritis.

There are cases of complete isolated mid-substance PCL ruptures (>10 mm of increased posterior tibial displacement) in which the patient is seen late after the injury and the previously discussed program cannot be instituted. In athletes and patients involved in strenuous occupations, one treatment approach is PCL graft reconstruction before the secondary restraints stretch out with subsequent reinjury. We believe that PCL reconstructive procedures have advanced to the point where more predictable results can be expected to restore sufficient PCL function to prevent gross posterior tibial subluxation. Studies have demonstrated, at least in the short term, that the majority of patients with acute PCL ruptures treated with reconstruction are able to return to various levels of sports activities.[122,154] Additional factors to be weighed in the decision to perform early surgery on a complete isolated PCL rupture include athletic goals, body weight, medial meniscus damage, tibiofemoral joint damage, patellofemoral joint damage, and varus malalignment. These factors add to the effects of the residual posterior subluxation in increasing knee joint loads and subsequent joint deterioration. Future long-term clinical studies will confirm the importance of these factors in the operative decision of early restoration of PCL function in active younger individuals who subject their knee to high forces in sports or work activities. Sedentary patients with a complete PCL rupture and 10 mm of posterior translation (90 degrees of flexion) are not considered surgical candidates; however, they are followed as previously described.

Posterior Cruciate Ligament and Multiligament Injuries

Patients with a PCL disruption and other ligament injuries have an obvious posterior tibial dropback without a firm endpoint on posterior drawer testing (≥10 mm of posterior tibial subluxation). In almost all of these knees, some increase in medial or lateral joint opening or external tibial rotation can be detected, although the findings may be subtle. There may be physiologic laxity of other ligament structures without a true injury that allows for the gross posterior tibial subluxation (see Chapter 3).

In knees that present with acute disruption of the PCL and medial or posterolateral structures, reconstruction should be delayed until the neurovascular status and other injuries are evaluated and the decision reached that major knee ligament surgery can be safely performed. In knees that have associated posterolateral ruptures, acute anatomic repair is planned if possible within 14 days before scarring occurs and the ability to anatomically restore these structures is lost (see Chapter 17). A similar situation exists for the medial ligament structures; however, these tissues are easier to reconstruct later if surgery cannot be performed in the ideal time period for anatomic repair.

There may exist a displaced meniscus tear requiring early treatment. As a word of caution, a displaced meniscus should be reduced

into the tibiofemoral joint by 3 weeks to prevent meniscus shortening and scarring that compromise a future repair and result in loss of meniscus function. Even in knees that have marked soft tissue swelling and edema in which major ligament reconstruction is contraindicated, a meniscus repair using all-inside techniques can be performed to reduce the meniscus to a normal tibiofemoral position. The mistake is to wait until 6 weeks or later, expecting that the meniscus repair can be performed at that time.

Too frequently, major ligament surgery in dislocated knees performed under acute conditions results in joint arthrofibrosis, compromising the result. Patients should be carefully selected for acute multiligament repairs, realizing that there are proven techniques for reconstruction of the ruptured ligaments performed later under more ideal conditions. When surgery is performed on acute combined PCL and posterolateral ruptures, the procedure includes the use of appropriate grafts to restore lateral stability and allow an early protected range of knee motion program (see Chapter 17).

The majority of acute knee dislocations should be treated in a staged approach by first treating the acute injury and then determining if a ligament reconstruction should be performed either within the 10- to 14-day envelope or delayed. When early surgery is not advisable, the knee is protected for the first 4 weeks to prevent posterior tibial subluxation, as already described for acute isolated PCL ruptures. AP and lateral radiographs are obtained with the knee placed in a posterior plaster shell and a soft bolster positioned beneath the calf to prevent posterior tibial subluxation. The capsular tissues heal in 7 to 10 days to provide enough stability to prevent recurrence of dislocation.

If a nonoperative approach is selected with associated MCL and posteromedial capsular disruptions, the same program is followed with the lower limb placed in a cylinder cast to allow "stick-down" of the medial soft tissues. Plaster immobilization is required because a soft hinged brace, even if maintained at 0 degrees of extension, does not provide sufficient protection to maintain medial joint line closure to allow the disrupted medial tissues to heal. At 7 to 10 days, the cylinder cast is split into an anterior and posterior shell and the therapist assists the patient with range of motion from 0 to 90 degrees in a figure-four position with the hip joint externally rotated to protect the healing medial tissues. This program of "aggressive" nonoperative treatment of associated medial ligament injuries is described in further detail in Chapter 20.

In multiligament knee injuries, a deep venous thrombosis (DVT) program is instituted that involves assessment of risk factors such as family or personal history of DVT and use of estrogen products in women. A lower extremity ultrasound is obtained before surgery. Postoperative care includes initial use of compressive calf devices, ankle pumps, and early mobilization and ambulation to avoid unnecessary bed rest. In the absence of specific risk factors requiring chemical prophylaxis, we routinely use one aspirin (325 mg) twice daily and pay close attention for signs of a DVT.

Chronic Ruptures of the Posterior Cruciate Ligament

The algorithm for the treatment of chronic PCL ruptures is shown in Figure 16-17. The symptoms and clinical examination determine the functional limitations, particularly the component of symptoms because of medial tibiofemoral or patellofemoral arthritis because these problems are likely to persist after surgical stabilization. Knees with chronic PCL ruptures are arbitrarily divided into three categories: those with varus osseous malalignment (and rarely, valgus

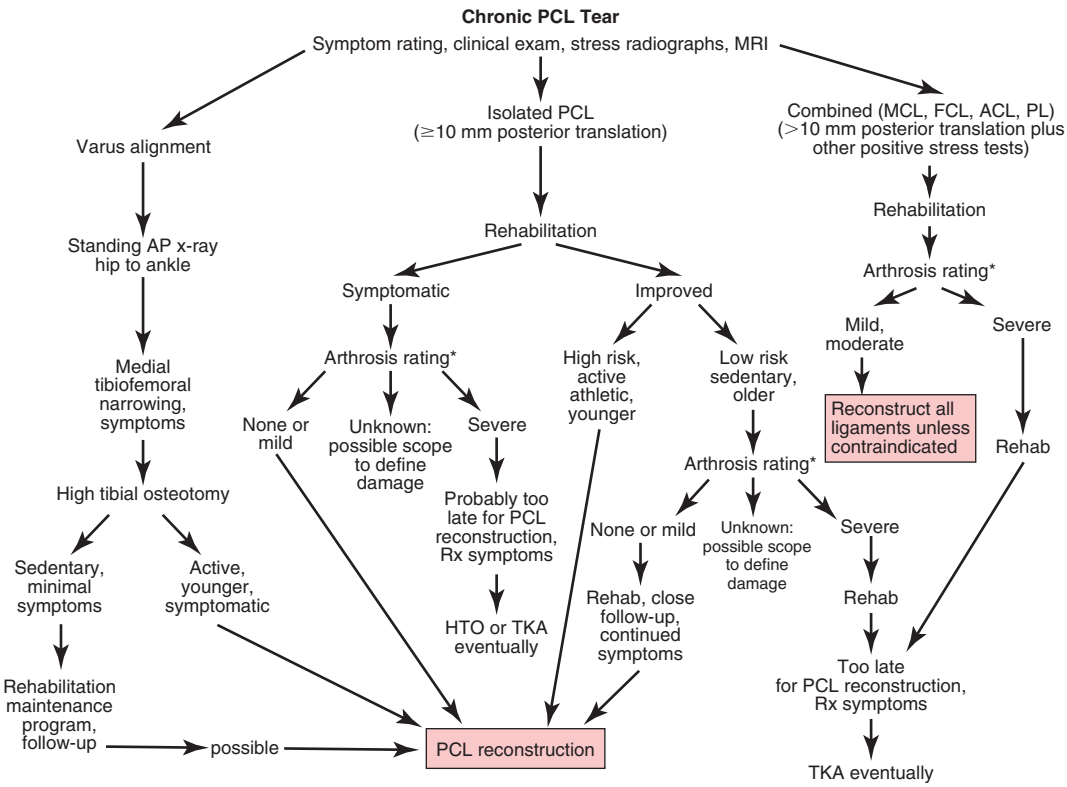


FIG 16-17 Treatment algorithm for chronic posterior cruciate ligament (PCL) ruptures. *Arthrosis rating: standing 45 degrees tibiofemoral and patellofemoral views or magnetic resonance imaging special cartilage sequences. *ACL*, Anterior cruciate ligament; *AP*, anteroposterior; *FCL*, fibular collateral ligament; *HTO*, high tibial osteotomy; *MCL*, medial collateral ligament; *PL*, posterolateral; *TKA*, total knee arthroplasty.

malalignment) in which an osteotomy must be considered, those with an isolated PCL rupture in which reconstruction may or may not be necessary, and those with significant combined ligament injuries that require reconstruction.

Patients are entered into a formal rehabilitation program to correct muscular weakness and gait-related problems (hyperextension) when required. The amount of joint arthritis must be determined with accuracy. Radiographs (merchant, standing PA at 45 degrees) and MRI articular cartilage fast spin-echo sequences provide valuable information.

In knees with no or only mild articular cartilage damage, an assessment of the patient's goals and athletic desires may indicate the need to proceed with PCL reconstruction. Combined ligament ruptures that produce complex instability patterns require careful clinical assessment to detect all of the joint subluxations and ligament deficiencies present.

Knees that have advanced arthritis are not expected to benefit from ligament reconstruction. In these knees, areas of exposed bone are frequently encountered in the medial tibiofemoral compartment, along with diffuse cartilage fragmentation in the patellofemoral joint. In these individuals, even mildly strenuous exercises aggravate the joint arthritis symptoms and cannot be performed. The patient's initial experience with rehabilitation, and the inability to perform the required exercises, provides important information regarding the amount of joint arthritis present and joint symptoms that are likely permanent.

If a nonoperative approach is elected, the clinician should warn the patient that the return to athletic activities may carry an uncertain prognosis, and that although sports may be resumed in the short term, some form of joint arthritis will eventually ensue. It is therefore important to follow the patient at regular intervals. A bone scan may be used to provide some indication of abnormal blood flow dynamics; however, it is our experience that the onset of pain and swelling usually indicates more advanced joint damage and a poor prognosis after PCL reconstruction. An MRI with fast spin-echo[182] sequences provides a baseline for repeated studies at 1- to 2-year intervals. The nonoperative treatment protocol for chronic PCL injuries involves educating the patient to avoid activities such as lunges and other high knee flexion activities that increase posterior tibial subluxation.[32,61,64]

INTRAOPERATIVE EVALUTION

The patient is instructed to use a chlorhexidine scrub of the body with emphasis on the operative limb ("toes to groin") 3 days before surgery and the evening before and the morning of surgery. Lower extremity hair is removed by clippers, not a shaver. Antibiotic infusion is begun 1 hour before surgery. A nonsteroidal antiinflammatory drug (NSAID) is given to the patient with a sip of water upon arising the morning of surgery (which is continued until the fifth postoperative day unless there are specific contraindications to the medicine). The use of an NSAID and a postoperative firm double-cotton, double-Ace compression dressing for 72 hours (cotton, Ace, cotton, Ace-layered dressing) has proven very effective in diminishing soft tissue swelling and is used in all knee surgery cases. In select knees that demonstrate soft tissue swelling before or after surgery, the judicious use of an intravenous corticosteroid for two to three days may be necessary. This is especially relevant in larger muscular patients in whom postoperative swelling of the entire lower extremity may occur. In complex multiligament surgery, the antibiotic is repeated at 4 hours and continued for 24 hours. A urinary indwelling catheter is not used unless there are specific indications. The patients' urinary output and total fluids are carefully monitored during the procedure and in the recovery room.

CRITICAL POINTS Intraoperative Evaluation

- Patient and staff identification of surgical procedure, "time-out," operative site signed by surgeon.
- Repeat all knee ligament subluxation tests under anesthesia.
- Rate all articular cartilage surfaces
  - Normal.
  - Grade 1, softening.
  - Grade 2 A, fissuring & fragmentation < ½ depth of the articular surface.
  - Grade 2 B, fissuring & fragmentation > ½ depth of the articular surface.
  - Grade 3, subchondral bone exposed.
- Medial and lateral gap test at arthroscopy
  - Knee 30 degrees of flexion.
  - Measure millimeters tibiofemoral compartment opening with calibrated nerve hook.

The knee skin area is initialized by the surgeon before entering the operating room, with a nurse observing the procedure. The identification process is repeated with all operative personnel with a "time out" before surgery to verify the patient's name and birth date, knee undergoing surgery, procedure, allergies, antibiotic infusion, and special precautions that apply. All personnel provide verbal agreement.

All knee ligament subluxation tests are performed after the induction of anesthesia in both the injured and contralateral limbs. The amount of increased anterior tibial translation, posterior tibial translation, lateral and medial joint opening, and external tibial rotation is documented. In acute knee injuries, arthroscopic pressure is maintained at a low setting with adequate outflow at all times to prevent fluid extravasation, which is carefully monitored during the procedures that follow. A thorough arthroscopic examination should be conducted, documenting articular cartilage surface abnormalities[170] and the condition of the menisci.

The medial and lateral tibiofemoral gap test is done during the arthroscopic examination (see Chapter 17).[161] The knee is flexed 30 degrees and a varus and valgus load of approximately 89 N applied. A calibrated nerve hook is used to measure the amount of lateral and medial tibiofemoral compartment opening. Twelve mm or more of joint opening at the periphery of the compartment indicates the need for a combined lateral or medial ligament reconstructive procedure to protect and unload the PCL reconstruction. The presence of 10 mm of opening is a gray zone that, in some instances, may require concurrent surgery. The goal is to restore the function of all ligament structures to normal or nearly normal and not leave a knee with a residual ligament insufficiency. This also applies to the ACL, which is reconstructed at the time of PCL surgery when deficient.

Appropriate arthroscopic procedures are performed as indicated including meniscus repairs or partial excision, debridement, and articular cartilage procedures.

OPERATIVE TECHNIQUES

PCL operative techniques continue to evolve and clinical outcome studies remain limited to allow precise decision making regarding the exact recommendations of one surgical procedure over another. This chapter describes the senior author's recommended surgical approach and relative advantages and disadvantages of each procedure, realizing that these are evolving treatment options (Table 16-5).

First, the surgical approach of the all-inside technique is chosen. The use of the open tibial inlay procedure has been completely replaced by most surgeons with modern all-inside arthroscopic techniques. The

TABLE 16-5 Recommended Surgical Approaches

All-Inside:

Single-Tibial Tunnel Approach

- Bone plug in tunnel at PCL attachment (same as inlay except tunnel)
- Avoids posterior dissection, operative time
- Projected results similar to tibial inlay

Two-Tunnel Femoral Approach

- Provides better anatomic positioning along oval PCL attachment
- Advantage of graft incorporation over single large-diameter graft
- Outside-in tunnel, graft interference screw with suture post
- Second option: single femoral tunnel for multiligament reconstruction where time and operative complexity warrant single tunnel

Tibial Inlay

- Reserved for revision knees to bypass misplaced tibial tunnel (staged bone graft may be required)

Graft Selection

Isolated PCL Rupture

- Quadriceps tendon-patellar bone autograft, ipsilateral (rarely contralateral)
- Bone-patellar tendon-bone allograft
- Achilles tendon-bone allograft

PCL Combined With Other Ligament Rupture

- Use allograft listed above
- Avoid large-diameter soft tissue allograft through tibial tunnel
- Bone plug placed at posterior tibial tunnel
- No autograft harvest same knee

CRITICAL POINTS Operative Techniques

- All-inside surgical approach.
- QT-PB or AT-B grafts provide more secure fixation, superior healing than soft tissue grafts.
- Place bone portion of graft at posterior tibial attachment.
- Select large-diameter graft that will fill majority of anatomic femoral and tibial footprints.
- Use two-tunnel technique at femoral attachment for larger patients.
- Graft fixation: use high-strength methods.
- Use QT-PB autograft in isolated PCL reconstruction in athletic patients.
- Use allografts in multiligament injuries.

tibial inlay procedure is described later for completeness and still has a role in PCL tibial avulsion fractures, in rare revision cases, or when arthroscopic techniques are not indicated.

The all-inside approach involves the decision regarding where to place the bone portion of the graft when a quadriceps tendon-patellar bone (QT-PB) or Achilles tendon-bone (AT-B) graft is used. We strongly advise use of a graft that has a tendon-bone construct owing to the predictable and prompt healing of the bone portion compared with delayed tendon-graft healing that occurs in bone tunnels. Our preferred technique places the bone portion of the PCL graft directly at the posterior tibial attachment, simulating the tibial inlay approach. This also allows the use of either one or two femoral tunnels for a single- or two-strand graft construct, as is discussed later.

In our experience, soft tissue grafts placed through a large tibial tunnel have an increased risk of failure owing to delayed graft incorporation that may lead to a revision procedure and necessity for staged bone grafting. A sclerotic line often forms in the bone tunnel about the graft periphery, with limited or often no bone ingrowth into the central regions of the graft. From an antidotal standpoint, an increased success rate of PCL reconstruction occurs when the bone portion of the graft is placed at the tibia, with one or two collagenous graft strands placed at the femoral site. Still, there are many publications that describe the historical technique of placing the bone plug at the femoral site (inside-out or outside-in tunnel) and the collagenous portion through a single tibial tunnel, most frequently using an AT-B allograft. This technique is perhaps the easiest to master and can be used when surgical time is an issue, because it is more difficult to pass the bone portion of the graft into the tibial tunnel.

Second, a large-diameter graft is selected that will fill the majority of the anatomic femoral and tibial footprints. At the femoral PCL attachment, a two-tunnel technique is preferred for larger patients; however, in smaller patients, a single large-diameter tunnel may also be used. It is probable that with either technique, only 75% of the femoral attachment site is covered. The mistake is to select a graft construct in which a smaller-diameter graft covers less of the footprint.

Third, an autograft or allograft construct is selected that, as already discussed, has a bone plug at one end for more secure fixation and superior healing compared with a soft tissue graft that does not contain bone plugs. It is important that high-strength graft fixation methods be used to withstand the large forces expected postoperatively. For example, the use of a single soft tissue interference screw to hold a PCL graft strand provides weak fixation strength and requires a back-up procedure with sutures for added graft fixation strength.

Fourth (the senior author's preference), an autogenous QT-PB graft is used in isolated PCL surgical procedures in athletic patients owing to a higher success rate and healing compared with allografts. It is now well appreciated in clinical outcome studies of ACL grafts that there is a 4 to 6 times higher failure rate of allografts and there is no apparent reason why this would not be applicable to PCL grafts. The exception would be an entirely sedentary patient who would not be loading the knee in athletic activities. In multiligament knee injuries, it is necessary to use allograft tissue, although an autogenous graft may be harvested from the contralateral side in rare select conditions. In combined ligament reconstructions, a QT-PT autograft is not removed from the same knee because this adds to the morbidity of the operative procedure.

Selection of Tibial Attachment Techniques: Arthroscopic All-Inside Versus Open Tibial Inlay Approach

The arthroscopic-assisted placement of the tibial tunnel or socket avoids the added operative time and complexity of the posteromedial tibial inlay approach. The surgeon must have extensive arthroscopic experience to safely perform an all-inside procedure to identify the PCL posterior tibial attachment site, avoid penetration into the posterior capsule and subsequent damage to the neurovascular structures, and place the tibial tunnel into the anatomic PCL tibial footprint. Specially designed instruments, drill guides with safety stops for guide pins, and drills are available to lessen the serious risk of inadvertent penetration of instruments posteriorly and damage to neurovascular structures.

The all-inside arthroscopic technique is particularly advantageous in knees with multiple ligament ruptures that require repair and reconstruction. In these knees, high-strength grafts are used to reconstruct the PCL and ACL, which are appropriately tensioned and fixed to reduce the tibiofemoral joint to its normal AP position. Medial or lateral operative approaches are used for concurrent medial and posterolateral ligament and soft tissue repairs or reconstructions. A combined ACL/PCL/MCL injury involves an all-arthroscopic approach for the ACL and PCL, followed by a limited medial dissection for repair of the medial tissues and meniscus attachments.

Combined ligament injuries, particularly those involving medial ligament and muscle tissues, have a high rate of postoperative motion problems and arthrofibrosis. In these knees, an open posterior tibial inlay procedure and popliteal dissection may be avoided by using the all-inside arthroscopic approach. One exception is a PCL avulsion fracture from the tibial attachment. Another exception is a PCL revision knee where a prior tibial tunnel was used and a tibial inlay graft is required to bypass this tunnel. In these cases, there may exist loss of the normal bony architecture about the posterior tibial PCL attachment and a tibial inlay bone graft is required. However, in PCL revision cases that have enlarged tibial tunnels, a staged bone graft procedure is more commonly used under arthroscopic control to remove the disrupted tibial tunnel graft and place a freeze-dried core allograft. An autogenous iliac crest graft is required only in exceptional cases, in which there is a large loss of bone (see Chapter 26).

From a historical standpoint, the open posteromedial tibial inlay technique did have the advantage of placing a tibial inlay graft securely into the posterior PCL tibial attachment site. This approach was often selected when only the PCL required reconstruction. The tibial inlay graft provides ideal graft fixation and early healing. A two-strand autogenous QT-PB graft with two femoral tunnels has been previously described and the clinical outcomes published.[152,153]

One theoretical disadvantage of the all-inside technique is the potential for the collagenous portion of the graft abrading against the angulated posterior tibial tunnel. There are operative techniques designed to diminish this problem. These include creating a more oblique tibial tunnel drilled through the anterolateral tibia and carefully chamfering the tunnel exit. Collagen grafts with a large cross-sectional area and diameter are favored over those with a smaller area and diameter, in which any abrasion compromises graft strength. To decrease soft tissue graft abrasion at the tibial tunnel, the bone portion of the graft may be placed in a tibial tunnel directly adjacent to the tunnel exit or placed in an all-inside tibial socket. The goal is to match the beneficial effect of the tibial inlay procedure to allow prompt osseous healing.

CRITICAL POINTS Selection of Tibial Attachment Techniques: Arthroscopic All-Inside Versus Open Tibial Inlay Approach

- Arthroscopic-assisted placement tibial tunnel preferred, requires extensive arthroscopic experience.
- All-inside arthroscopic technique advantageous in dislocations, multiple-ligament reconstructions.
- Combined ACL + PCL injury: all-arthroscopic approach ACL and PCL; limited dissection for medial or lateral repairs.
- PCL avulsion fracture or revision knee may require tibial inlay procedure.
- Techniques available to diminish problem of graft abrasion in posterior tibial tunnel, as well as femoral attachment site, in all-inside procedure.

Biomechanical studies of PCL reconstructions conducted at our facilities have shown the potential for graft abrasion and failure at the femoral attachment.[198] Operative techniques to protect against graft failure and abrasion are required at both tibial and femoral attachment sites, and repetitive knee motion in the early postoperative time period is limited, as will be described.

Selection of Posterior Cruciate Ligament Femoral Attachment Technique: Two-Tunnel Versus Single-Tunnel Options

It is not difficult from a technical standpoint to use two well-placed femoral tunnels within the PCL femoral footprint from outside-in, and this is a recommended preferred technique to master. The outside-in technique, with a limited anteromedial subvastus or muscle-splitting approach, allows graft tensioning, a long femoral tunnel for tendon graft incorporation, and graft fixation with an interference screw and suture post. The posteromedial graft is usually shorter by 15 mm than the anterolateral graft. The outside-in tunnel approach allows accurate tensioning, fixation, and visualization of the graft length change during knee flexion. This allows the surgeon to determine the ideal knee flexion position for graft fixation. This is our preferred technique with either an autograft or allograft.

When a single femoral graft is selected, the femoral tunnel may be drilled from inside-out or outside-in. There is an increased obliquity with the inside-out approach; however, in either case, the posterior or deep portion of the tunnel needs to be radicalized and smoothed to decrease graft abrasion effects. A FlipCutter (Arthrex) may be selected to create the femoral socket and TightRope (Arthrex) fixation may be used along with a soft tissue interference screw. This avoids a vastus medialis obliquus (VMO) incision, maintains the medial femoral cortex, and is less invasive.

In the alternative technique described in which the bone portion of the PCL graft is placed at the femoral site, a rectangular femoral slot technique has a theoretical advantage. The bone plug is fixed using an inside-out arthroscopic technique. The rectangular slot technique places the bone within the PCL femoral footprint and is more ideal than a single large-diameter tunnel, although either technique may be used. We advocate only one tibial tunnel for the collagenous portion of the graft. In a PCL revision procedure, there may exist a misplaced femoral tunnel in which the bone portion of the graft is required for adequate femoral graft placement and fixation instead of one or two soft tissue femoral graft tunnels.

A single femoral tunnel drilled from an inside-out anterolateral portal is more difficult because of the narrow intercondylar notch,

CRITICAL POINTS Selection of Posterior Cruciate Ligament Femoral Attachment Technique: Two-Tunnel Versus Single-Tunnel Options

- Two well-placed femoral tunnels within PCL femoral footprint from outside-in most ideal technique to master.
- Single femoral socket: FlipCutter may be used to create, TightRope fixation in addition to interference screw.
- Alternative technique: bone portion of graft placed at femoral site, rectangular femoral slot technique or circular tunnel (FlipCutter).
- Single femoral tunnel from inside-out approach more difficult because of narrow intercondylar notch, proximity of lateral femoral condyle.
- Advantageous to select graft fixation methods that provide for maximum tensile strength of graft construct.

proximity of the lateral femoral condyle, placement of the tunnel within the PCL footprint, and exact placement required to avoid portions of the graft located outside the PCL footprint. Accordingly the surgeon has the ability to select the most desired technique; however, the outside-in drilling approach or FlipCutter approach for a single large-diameter femoral graft tunnel is often more advantageous.[21]

Tables 16-6 and 16-7 provide a reference to studies on graft fixation and can be extrapolated to the fixation of the PCL bone portion of the graft. Techniques for fixation of soft tissue grafts at the femoral attachment site using interference screws alone provide a weaker fixation construct[82] and result in lower attachment strength. The outside-in approach allows graft sutures and a suture post to be incorporated (Tables 16-8 and 16-9), or TightRope fixation may be used that is similar to an EndoButton configuration. PCL reconstructions are under high in vivo loads and it is advantageous to select graft fixation methods that provide for a high tensile strength of the graft construct.[30,136,205]

Selection of Single-Strand Versus Two-Strand Posterior Cruciate Ligament Graft Constructs

The advantages and disadvantages of one- and two-strand PCL graft techniques are summarized in Table 16-10. The goal of adding a second strand is to place additional collagenous tissue within the PCL footprint to increase the cross-sectional area of the graft and more closely replicate the native PCL attachment. This theoretical advantage is sometimes referred to as the *mass action effect* of adding additional collagen within the PCL footprint. The improved stability and clinical success of a two-strand graft construct compared with a single-strand graft have not been proven from a clinical standpoint.[106] There are clinical studies that show patients who received a single-strand PCL graft reconstruction obtained results similar to those that underwent a two-strand PCL procedure.[49,101,104,122,202]

The incorporation of a second graft strand has the theoretical advantage of providing additional collagen tissue for load sharing that decreases stress in the collagen fibers, increases graft strength, and reduces cyclic fatigue of the graft construct.[198,233] The two graft strands are tensioned at surgery to share loads to decrease the loads compared with those of a single PCL graft construct. This has been shown in a majority of (but not all[135]) biomechanical studies that compared single- with two-strand graft constructs. Studies report that the two graft strands placed in the distal two-thirds of the PCL femoral footprint will function to resist posterior tibial translation with increasing knee flexion (see Chapter 15). Alternatively, when two graft strands are placed in a proximal and distal (deep and shallow) portion of the PCL footprint, graft loading occurs in a reciprocal manner and the graft strands are under higher loads, which is less ideal. As previously noted, the length and tension changes in grafts are governed for the most part by the femoral attachment and any graft fibers in the distal two-thirds are subjected to increasing tension and elongation with knee flexion.[68,203]

In Chapter 15, the function of single- and two-strand PCL grafts is described in detail. The usual description of a PMB that resists tension with knee extension and an ALB that resists tension with knee flexion represents an oversimplification of PCL fiber behaviors. In this chapter, the rule of thirds (see Fig. 16-10) is used to described PCL graft placement at surgery, as already discussed.[16,17,74,133,197]

A justification to add a second PCL strand is the observation in clinical studies of a residual posterior tibial subluxation at high knee

TABLE 16-6 Femoral Fixation Options for Bone Graft

Study	Construct	Failure (*n*)	Stiffness (N/mm)	Failure Mode
Martin et al[137] (2002)	Metal interference screw	710 ± 224	298 ± 36	Not reported
Pena et al[180] (1996)	Metal interference screw	640 ± 201	Not reported	Pull-out and bone block fracture
Steiner et al[210] (1994)	Endoscopic interference screw	588 ± 282	33 ± 14	Bone plug fractured, femoral screw pull-out, bone tendon rupture
Johnson et al[90] (1996)	Biodegradable interference screw	565	Not reported	Failure between the cortical and cancellous bone of the bone plug
Caborn et al[27] (1997)	Metal endoscopic interference screw	558 ± 68	Not reported	Femoral fixation failure, fracture of bone plug, tearing of graft
Brand et al[21] (2000)	EndoButton	554 ± 276	27 ± 13	Tibial bone block fracture or suture breakage, tibial side fixation failure
Caborn et al[27] (1997)	BioScrew endoscopic interference screw	552 ± 56	Not reported	Femoral fixation failure, fracture of bone plug, tearing of graft
Brand et al[21] (2000)	Mitek device	511 ± 350	18 ± 8	Patellar tendon failure, fracture tibial bone block, sutures tore through bone block
Johnson et al[90] (1996)	Metal interference screw	436	Not reported	Failure between the cortical and cancellous bone of the bone plug
Steiner et al[210] (1994)	Interference screw from outside-in	423 ± 175	46 ± 24	Pull-out around the screw
Pena et al[180] (1996)	BioScrew interference screw	418 ± 118	Not reported	Bone block pull-out
Brand et al[21] (2000)	Press-fit	350 ± 48	37 ± 16.3	Tibial bone plug pull-out, fracture tibial bone block, patellar tendon failed
Brown et al[23] (1993)	Endoscopic interference screw	256 ± 130	70 ± 29	Bone block pull-out, bone block fracture
Brown et al[23] (1993)	Interference screw outside-in	235 ± 124	83 ± 30	Bone block pull-out, bone block fracture

Cadaveric studies have varying results, particularly when older specimens are used, with osteopenia compromising fixation strength.

TABLE 16-7 Tibial Fixation Options for Bone Graft

Study	Construct	Failure (*n*)	Stiffness (N/mm)	Failure Mode
Gupta et al[71] (2009)	Two bioabsorbable polylactic acid screws	638 ± 492	106 ± 44	Tibial insertion site, tibial bone block fractured at screws.
Gupta et al[71] (2009)	Two stainless steel screws	461 ± 231	116 ± 22	Tibial insertion site, tibial bone block fractured at screws.
Campbell et al[29] (2007)	Two 4.0-mm cancellous lag screws	762 ± 343	89.8 ± 18.9	Bone block rotated, moved superiorly, partial avulsion of tendon attachment or a part of the tibial socket
Gerich et al[59] (1997)	9-mm interference screw	758 ± 139	49 ± 2	Tendon tearing or bone plug slippage
Kohn et al[109] (1994)	9-mm interference screw	678	68	Tendon tore, slipped out of bone plug
Kurosaka et al[110] (1987)	9-mm interference screw	476 ± 111	58 ± 4	Grafts pulled out of tunnel
Kohn et al[109] (1994)	7-mm interference screw	461	47	Tendon tore, slipped out of bone plug
Brand[20] (1999)	9-mm biodegradable screw	293	42	Bone plug slipped, tendon tore
Kurosaka et al[110] (1987)	6.5-mm AO interference screw	215 ± 39	23 ± 3	Grafts pulled out of tunnel
Steiner et al[210] (1994)	Interference screw and suture with a post	674 ± 206	50 ± 21	Bone plug fractured, pull-out around tibial screw, suture rupture
Campbell et al[29] (2007)	Two No. 5 Ethibond sutures tied over button	582 ± 126	85.1 ± 12.6	Bone block rotated, moved superiorly, partial avulsion of tendon attachment or a part of the tibial socket
Kurosaka et al[110] (1987)	No. 5 suture tied over button	248 ± 40	13 ± 2	Button failed, suture pulled through bone plug
Steiner et al[210] (1994)	Suture and post	396 ± 124	27 ± 13	Bone-tendon rupture, bone plug fracture, tibial post pull-out
Kurosaka et al[110] (1987)	Staple patellar tendon	129 ± 16	11 ± 2	Graft slipped under staple
Gerich et al[59] (1997)	Doubled staples on patellar tendon in a trough	588 ± 62	86 ± 16	Graft slipped under staple, 27% bone block breakage

Cadaveric studies have varying results, particularly when older specimens are used, with osteopenia compromising fixation strength.

TABLE 16-8 Femoral Fixation Options for Soft Tissue Graft Plug in a Bone Tunnel

Study	Construct	Failure (*n*)	Stiffness (N/mm)	Failure Mode
Brand et al[21] (2000)	QHT with EndoButton and three No. 5 sutures	699 ± 210	30.2 ± 8.5	Implant pulled through bone, tibial fixation failure, suture failure, tendon failure
Martin et al[137] (2002)	QHT with EndoButton and Endotape	644 ± 91	182 ± 20	Tape broke
Martin et al[137] (2002)	QHT with EndoButton and continuous loop 20 mm	1345 ± 179	179 ± 39	Tape broke
Rowden et al[187] (1997)	Semitendinosus fixed with EndoButton and tibial post	612 ± 73	47 ± 19	Not reported
Martin et al[137] (2002)	QHT with Bone Mulch	977 ± 238	257 ± 50	Tip bending at junction with screw
Steenlage et al[209] (1999)	QHT BioScrew, 0.5-mm graft sleeves	530 ± 186	Not reported	Graft slipped
Martin et al[137] (2002)	QHT with Trans-Fix	934 ± 296	240 ± 74	Cross-pin toggled cancellous bone, pin bending, tendons slipped off
Brand et al[21] (2000)	QHT with an EndoButton, mersilene tape	520 ± 50	34.8 ± 22.3	Tape broke
Brand et al[22] (2005)	QHT BioScrew	485 ± 224	71 ± 28	Pull-out from bone tunnel
Martin et al[137] (2002)	QHT with Mitek	687 ± 129	230 ± 32	Breaking at junction of eyelet pin
Brand et al[22] (2005)	QHT with RCI titanium screw	246 ± 99	29 ± 12	Pull-out from bone tunnel
Caborn et al[26] (1998)	QHT with BioScrew	341 ± 163	Not reported	Graft slipped
Caborn et al[26] (1998)	QHT with RCI titanium screw	242 ± 90.7	Not reported	Graft slipped

Cadaveric studies have varying results, particularly when older specimens are used, with osteopenia compromising fixation strength.
QHT, Quadrupled hamstring graft.

TABLE 16-9 Tibial Fixation Options for Soft Tissue Graft

Study	Construct	Failure (*n*)	Stiffness (N/mm)	Failure Mode
Ruberte Thiele et al[188] (2010)	AT allograft, cylindrical bone plug 12-mm diameter, one No. 2 FiberWire looped around bone plug, tied on anterior tibial cortex, one No. 2 FiberWire ship-stitched through AT, passed through bone plug hole	580 ± 161	93 ± 30	Tendon avulsion off bone or bone plug fracture
Ruberte Thiele et al[188] (2010)	AT allograft, figure-of-8 bone plug 12 × 18 mm, one No. 2 FiberWire looped around bone plug, tied on anterior tibial cortex	586 ± 142	88 ± 24	Sutures tore through tibial plateau in majority
Lee et al[118] (2009)	QHT or two-strand tibialis allograft with Bio-TransFix (Arthrex) device	570.8 ± 96.9	58.1 ± 17.1	Deformation with or without graft pullout or breakage
Lee et al[118] (2009)	QHT or two-strand tibialis allograft with 10-mm biointerference screw	371.3 ± 106.2	27.6 ± 16.7	Graft pullout at tibial fixation site
Lim et al[123] (2009)	AT allograft with two cross pins with bone blocks	917.8 ± 102.4	302.3 ± 52.9	Fixation fracture
Lim et al[123] (2009)	AT allograft with 10-mm interference screw fixation with bone blocks	514.58 ± 148.4	193.5 ± 12.1	Pullout
Lim et al[123] (2009)	AT allograft with two cross-pins of soft tissue with backup fixation (6.5-mm cancellous screw with a spike washer)	1023.75 ± 94.4	341.5 ± 64.9	Graft laceration, fixation failure
Lim et al[123] (2009)	AT allograft with interference screw fixation of soft tissue with backup fixation (6.5-mm cancellous screw with a spike washer)	816.81 ± 115.3	223.5 ± 38.1	Pullout
Magen et al[130] (1999)	QHT with washer plate	905 ± 291	273 ± 56	Not reported
Selby et al[195] (2001)	QHT with tapered 35-mm screw	825	76	Graft slipped past screw in tunnel
Nyland et al[171] (2004)	Doubled tibialis anterior allograft with bioabsorbable interference screw	825 ± 124	71 ± 18	Tunnel pull-out
Steiner et al[210] (1994)	QHT with screw and a soft tissue washer	821 ± 219	29 ± 7	Tendon stretch or tibial screw pull-out
Caborn et al[25] (2004)	QHT with Intrafix device	796 ± 193	49 ± 22	Pull-out from tibial tunnel
Caborn et al[25] (2004)	QHT with tapered bioabsorbable interference screw	647 ± 269	65 ± 22	Tunnel pull-out
Selby et al[195] (2001)	QHT with 28-mm screw	595	66	Graft slipped past screw in tunnel
Steiner et al[210] (1994)	QHT with suture and post	573 ± 109	18 ± 5	Suture tendon stretches, post pull-out
Magen et al[130] (1999)	QHT with RCI titanium screw	350 ± 134	248 ± 52	Not reported
Steenlage et al[209] (1999)	QHT with biodegradable interference screw 0.5-mm graft sleeves	308 ± 207	Not reported	Graft slipped around tibial screw
Brand et al[22] (2005)	QHT with BioScrew	289 ± 205	40 ± 33	Pull-out from bone tunnel
Brand et al[22] (2005)	QHT with RCI titanium interference screw	252 ± 88	32 ± 15	Pull-out from bone tunnel
Steenlage et al[209] (1999)	QHT with biodegradable interference screw 1-mm graft sleeves	222 ± 75	Not reported	Graft slipped around tibial screw
Brand et al[21] (2000)	QHT with RCI titanium screw	214 ± 79	9 ± 7	Tendon pull-out or slip
Kurosaka et al[110] (1987)	Stapled semitendinosus	137 ± 23	9 ± 1	Tendon pulled out of staple

Cadaveric studies have varying results, particularly when older specimens are used, with osteopenia compromising fixation strength.
QHT, Quadrupled hamstring graft.

TABLE 16-10 Basis for Selection of Single- Versus Two-Strand Posterior Cruciate Ligament Reconstruction

	Single Strand	Two Strand
Greater area	–	+
Load-sharing (decreased tensile forces in each graft strand)	–	+
Operative complexity	+	–
Cyclic fatigue	–	+
Clinical results (residual posterior tibial translation)*	Unknown	Unknown

*Proven by objective measurements, including stress radiography at 90 degrees of knee flexion.
+, Relative advantage; –, relative disadvantage.

CRITICAL POINTS Selection of Single-Strand Versus Two-Strand Posterior Cruciate Ligament Graft Constructs

- Goal of second strand: place additional collagenous tissue within PCL footprint, increase cross-sectional area of graft, and more closely replicate native PCL attachment. Decreases stress in collagen fibers, increases graft strength, and reduces cyclic fatigue of graft construct.
- Second strand placed in distal two-thirds of footprint functions to resist posterior tibial translation with increasing knee flexion.
- Biomechanical studies justify two-strand reconstruction restores posterior tibial translation to normal values.
- Preferred technique:
  - QT-PB: bone plug placed tibial tunnel. Tendon placed femoral attachment and split into two strands, tensioned separately.
- Controversy exists between well-placed single-strand and two-strand grafts owing to inadequate clinical data.
- Our opinion: sound theoretical reasons exist to warrant two-strand PCL reconstruction when clinically feasible.
- Multiligament reconstructions require modification to single-strand PCL graft constructs.

flexion after single-strand PCL reconstructions.[106,154] Current PCL surgical procedures do not uniformly produce functional restoration of normal joint kinematics and stability postoperatively. This problem is discussed in detail in the Clinical Studies section of this chapter. The concern is that a residual posterior tibial displacement changes tibiofemoral contact positions (more anterior on the tibia), with altered and high cartilage pressures and decreased function of the medial meniscus.[126,179,204] Increases in patellofemoral contact pressures have also been reported.[60]

There are many different types of two-strand PCL graft constructs reported in the literature. One type consists of two separate grafts placed into two separate femoral and tibial tunnels, or two separate femoral tunnels with both graft strands through one tibial tunnel. For purposes of differential load sharing between two graft strands with knee flexion, it is assumed that two separate femoral attachments and a single tibial attachment obviates the necessity and operative complexity of two tibial tunnels.

When an AT-B allograft is selected, it is important that the graft be inspected to discard those that have a narrow tendon section just adjacent to the bone attachment. A QT-PB allograft is a more suitable PCL substitute because of the larger cross-sectional area of the tendon; however, this graft has to have sufficient length and is more difficult to obtain from tissue banks. It should be noted that, in some patients, the (autogenous) quadriceps tendon portion of the graft is not robust enough to produce two graft strands. In these cases, a single graft is used that represents a large-diameter graft.

Multicenter randomized controlled trials of one- and two-strand PCL reconstructions are required in the future to provide a more scientific basis for selection of one type of PCL reconstructive technique over another. The surgeon is currently faced with small clinical trials with level 4 evidence described later in this chapter. For this reason, more than one PCL technique is described, with recommendations made regarding the technical issues to maximize the clinical result. Our preferred PCL graft procedures are provided, along with the justification and rationale for these selections.

In summary, it does appear there are sound theoretical reasons to warrant a two-strand PCL reconstruction when clinically feasible (Table 16-10). These conditions include isolated PCL reconstructions when the added time required to perform a two-strand PCL graft does not represent a contraindication in terms of operative time and complexity. In multiligament reconstructions, the primary goal is to repair and reconstruct all ruptured ligaments. Adding a second femoral tunnel, and tensioning and securing two graft strands, is time-consuming to an already complex surgical reconstruction. Therefore the surgeon should be prepared, based on the operative findings, to modify the preoperative plan when required. In certain multiligament injured knees, a single-strand PCL graft construct may offer a reasonable opportunity to restore functional stability (Fig. 16-18).[135] Given the complex PCL fiber microgeometry, either a one- or two-strand graft construct still represents an imperfect substitution, providing only a check rein effect in controlling joint motions and subluxations.

Selection of Posterior Cruciate Ligament Grafts Based on Biomechanical Properties

The mechanical properties of grafts commonly used to reconstruct the PCL are shown in Table 16-11. The goal of PCL surgery is to select a graft that matches the structural properties of the PCL as closely as possible. The problem is that the PCL is a highly complex ligament composed of fibers of different lengths that are brought into the loading configuration based on the knee flexion and tibial rotation positions. The data show initial graft mechanical properties that are expected to decline after graft implantation and in vivo remodeling. It is therefore not possible to match the complex PCL microgeometry with any tendon substitute.

The cadaver age in the investigation by Race and Amis[184] ranges from 53 to 98 years. Previous investigations by the senior author[166] and others[237] documented significant reductions in strength and stiffness properties of ligament units with advancing age. For instance, one study[166] documented that, although ultimate failure of ACL-bone grafts occurred at a mean of 1730 N in young cadavers (aged 16 to 26 years), this value decreased to a mean of 734 N in older cadavers (aged 48 to 86 years). Race and Amis[184] estimated that a PCL reconstruction should be designed to match a native PCL with a strength of 4000 N, and not the approximate 2000 N shown in Table 16-11 (for both bundles combined).

Harner and associates,[76] in a study of 14 cadaveric PCL specimens (mean age, 52 years; range, 30-83 years), reported a mean ultimate load to failure of the ALB of approximately 1200 N and of the PMB of 400 N. This provides an ultimate failure load of the entire PCL in the 1600- to 1700-N range, well below that expected; this is most likely because of the advanced age of the cadaver specimens.

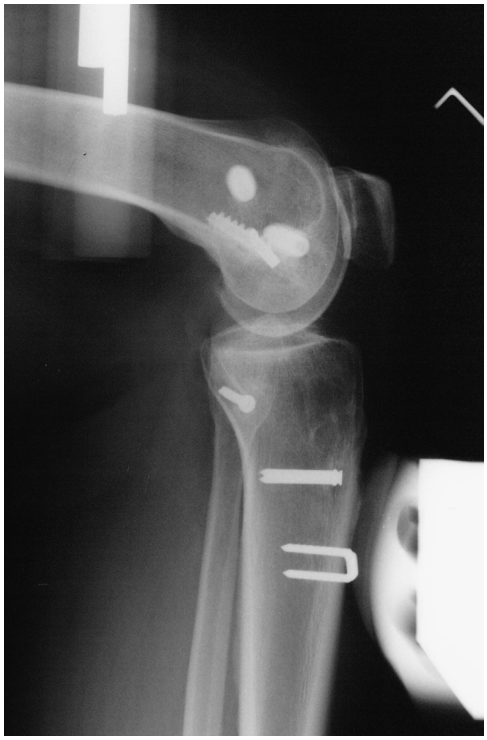


FIG 16-18 Posterior stress radiograph of a patient 2 years after a single-strand posterior cruciate ligament quadriceps tendon-patellar bone autograft shows only 2 mm of increased posterior tibial translation. The patient had sustained a knee dislocation and also underwent an anterior cruciate ligament bone-patellar tendon-bone allograft reconstruction, and an anatomic posterolateral reconstruction.

In a similar manner, there may exist large variations in reported strength and stiffness data based on the testing apparatus and manner in which soft tissues are grasped without inducing premature failure. For example, the strength of the quadriceps tendon construct shown in Table 16-11 is 2353 N; however, the mean cross-sectional area is 65 mm^2. There are different methods used to measure cross-sectional area that affect these values. The senior author previously described a method that induced a low level of compressive force to compress the soft tissues into a block of defined dimensions that provided an accurate cross-sectional measurement.[164] The data shown in Table 16-11 are derived from investigations that used different area measurement systems, making comparisons difficult.

Preparation of Quadriceps Tendon-Patellar Bone Autograft

A tourniquet is inflated to 275 mm Hg. This is usually the only time the tourniquet is used in the reconstructive procedure. An incision is made just medial to the superior pole of the patella and extended proximally 5 to 6 cm (Fig. 16-19). The incision allows access to the anteromedial aspect of the medial femoral condyle and VMO for subvastus placement of the femoral tunnels. A cosmetic approach is used, with subcutaneous dissection performed circumferentially about the incision to allow the skin to be mobilized superiorly and inferiorly for the graft harvest. With this technique, no incision is required over the patella.

The graft length and thickness is marked on the tendon and the proximal musculotendinous junction is avoided because it would weaken the extensor mechanism. The quadriceps tendon appears narrower proximally and it is important not to remove more than one third of the tendon. In rare instances, there is a shortened quadriceps tendon that is not suitable for harvest; the patient is advised preoperatively and provides consent for either an autograft or allograft approach. A suitable quadriceps tendon must be a minimum of 70 mm, not counting the 22- to 24-mm patellar bone plug. The full-thickness quadriceps tendon graft is taken from the central tendon and is 10 to 12 mm in width and thickness, respectively, depending on the overall size of the tendon. A general rule is to take approximately 30% of the tendon in the middle portion, realizing there may be some narrowing of the tendon proximally. The quadriceps tendon consists of three layers: rectus tendon, VMO-vastus lateralis oblique (VLO) combined tendon, and vastus intermedius tendon. A meticulous technique is followed to incise all three layers in a perpendicular fashion with a new blade. There is a tendency not to harvest the deep layer or to allow the blade to assume an oblique plane rather than a perpendicular plane. A curved instrument is placed behind the three tendon layers at the proximal aspect of the tendon harvest site to protect the underlying joint synovium. If the synovium is entered, it is closed along with the remaining quadriceps tendon closure to maintain joint distention for the arthroscopic procedure.

An Ellis clamp is placed about the three ends of the tendon to maintain tension. Care is taken at the quadriceps tendon attachment to the patella, because the tendon attachment is located at the proximal and anterior third of the proximal patella. There is a plane established at this point just behind the quadriceps tendon attachment to preserve the posterior underlying synovial attachment and adjacent soft tissues. These tissues provide a superior buttress for the bone grafting of the patella to close the defect and secure the bone graft.

The patellar bone block matches the quadriceps width. The bone block length is 22 to 24 mm and has a depth of 8 to 10 mm. A thin powered saw blade is marked with a Steri-Strip to a depth of 10 mm to prevent a deep penetration. The saw is kept perpendicular to the patellar anterior surface for all cuts. After the anterior bone cuts are made, the quadriceps tendon is lifted anteriorly at its attachment site. The posterior portion of the bone block is cut in a transverse plane beneath the quadriceps tendon attachment to a depth of 8 to 10 mm. This allows the bone block to be gently removed for graft preparation. The tourniquet is deflated and hemostasis obtained.

The graft is prepared based on whether the one-strand or two-strand technique is selected. The tendon portion must be 11 to 12 mm

CRITICAL POINTS Preparation of Quadriceps Tendon-Patellar Bone Autograft

- Incision just medial to superior pole of patella, extend proximally 5-6 cm.
- Cosmetic approach, subcutaneous dissection circumferentially about skin incision.
- Quadriceps tendon ≥70 mm plus 22-24 mm patellar bone plug for suitable graft.
- Graft is taken from central tendon, 10-12 mm in width and thickness.
- Incise prepatellar retinaculum in midline, dissect to width of graft, protected for later closure over bone-grafted patellar defect.
- Match patellar bone block width to quadriceps width. Bone block length 22-24 mm, full-thickness depth 8-10 mm.
- Graft prepared based on size and whether one- or two-strand technique is selected.
- Graft strands sutured in meticulous manner using 1-0 or 2-0 FiberLoop or FiberWire sutures.
- Close quadriceps tendon (Z-plasty technique) and synovium to provide a fluid tight closure, allows joint distention.
- Patellar bone defect later grafted with bone obtained by core reamer.

TABLE 16-11 Structural Properties of Intact Anterior Cruciate Ligament, Intact Posterior Cruciate Ligament, and Various Graft Constructs

Cruciate, Construct	Maximum Strength (*n*)	Stiffness (N/mm)	Cross-Sectional Area (mm^2)	Length (mm)	Cadaver Age (yr)
Intact ACL	2160 ± 157*	242 ± 26*			22-35*
	1725 ± 269†		44 ± 4.6†	27 ± 1.1†	20-32†
				38‡	NA‡
			31§		48-77§
Intact PCL:					
Entire femur-PCL tibia unit			41§		48-77§
AL bundle	1620 ± 500¶	347 ± 140¶	43 ± 11.3¶	35 ± 3.4¶	53-98¶
	1120 ± 362§	120 ± 37§			30-83§
PM bundle	258 ± 83¶	77 ± 32¶	10 ± 1.3¶	34 ± 3.2¶	53-98¶
	419 ± 128§	57 ± 22§			30-83§
Graft Constructs					
B-PT-B (10 mm)	3057 ± 351‖	455 ± 56‖			21-34‖
B-PT-B (10 mm)	2376 ± 152**	621 ± 122**	37 ± 5.7**	52 ± 4.8**	19-32**
B-PT-B (14 mm)	2900 ± 260†		50 ± 2.8†	49 ± 3.8†	20-32†
QT (10 mm)	2353 ± 495**	326 ± 70**	65 ± 8.4**	86 ± 9.0**	19-32**
STG four-strand	4090 ± 295††	776 ± 204††	53 ± 5††		37-88††
Two gracilis strands	1550 ± 369††	370 ± 108††			37-88††
Two semitendinosus strands	2640 ± 320††	534 ± 76††			37-88††
One semitendinosus strand	1216 ± 50†		14 ± 0.5†	37 ± 3.1†	20-32†

*Woo SL-Y, Hollis JM, Adams DJ, et al. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med.* 1991;19:217-225.
†Noyes FR, Butler DL, Grood ES, et al. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg Am.* 1984;66:344-352.
‡Girgis FG, Marshall JL, Monajem AL. The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. *Clin Orthop.* 1975;106:216-231.
§Harner CD, Zerogeanes JW, Livesay GA, et al. The human posterior cruciate ligament complex: an interdisciplinary study. Ligament morphology and biomechanical evaluation. *Am J Sports Med.* 1995;23:736-745.
¶Race A, Amis AA. The mechanical properties of the two bundles of the human posterior cruciate ligaments. *J Biomech.* 1994;27:13-24.
‖Cooper DE, Deng XH, Burstein AL, Warren RF. The strength of the central third patellar tendon graft. A biomechanical study. *Am J Sports Med.* 1993;21:818-824.
**Staubli H-U, Schatzmann L, Brunner P, et al. Quadriceps tendon and patellar ligament: cryosectional anatomy and structural properties in young adults. *Knee Surg Sports Traumatol.* 1996;4:100-110.
††Hamner DL, Brown CH Jr, Steiner MF, et al. Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: biomechanical evaluation of the use of multiple strands and tensioning techniques. *J Bone Joint Surg Am.* 1999;81:549-557.
ACL, Anterior cruciate ligament; *AL*, anterolateral; *B-PT-B*, bone-patellar tendon-bone; *NA*, not available; *PCL*, posterior cruciate ligament; *PM*, posteromedial; *QT*, quadriceps tendon; *STG*, semitendinosus-gracilis tendons.

wide and thick to be able to fashion graft strands that are 7 to 8 mm in diameter. In smaller patients, a single 10-mm quadriceps tendon with a reduced thickness does not provide sufficient tendon for a robust two-strand graft; therefore a single-strand construct must be selected. The tendon graft strands are sutured in a meticulous manner using a 1-0 or 2-0 FiberLoop or FiberWire sutures (Arthrex). The graft diameter is sized for the appropriate tunnel to be drilled. Two 2-0 FiberWire sutures are passed in the distal end of the patellar bone. A blood-soaked sponge is wrapped around the graft to provide protection, keep the tissues moist, and potentially maintain some cell viability.

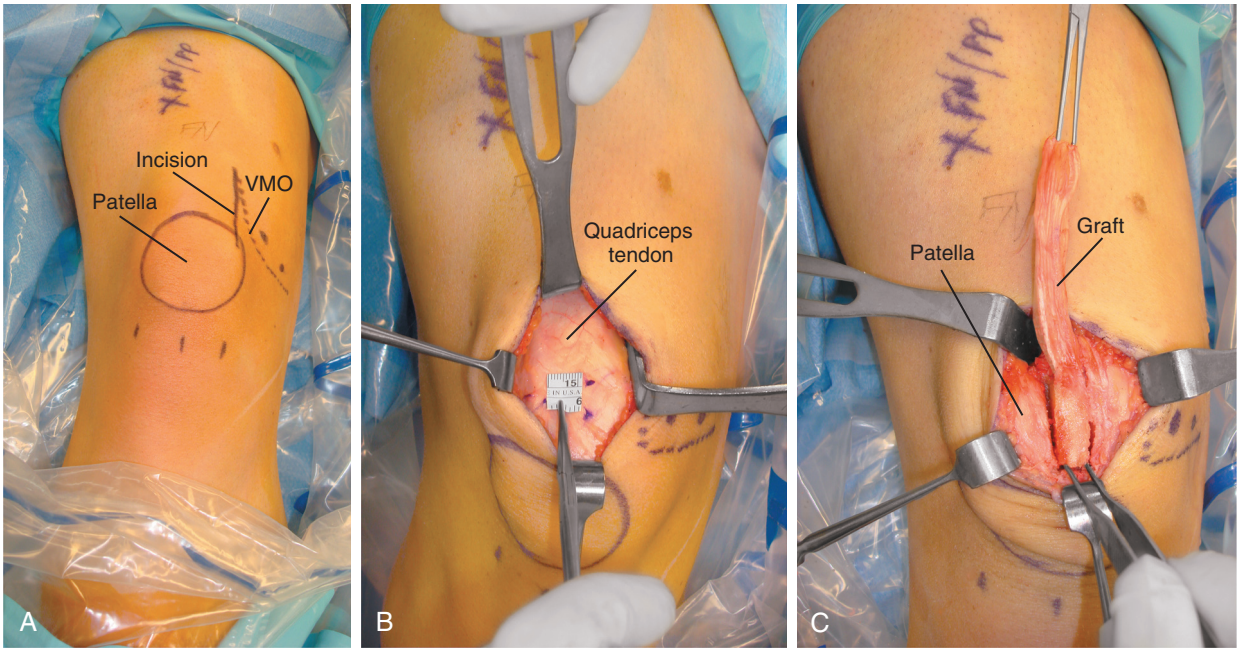
In the optional all-inside technique with the patellar bone block placed into the PCL femoral attachment, either a one-strand or two-strand technique may be selected for the graft strands placed through the tibial tunnel. There is a theoretical advantage of tensioning the two graft strands separately; however, insufficient clinical outcome data exist in this regard.

The quadriceps tendon and synovium are closed to provide a fluid tight closure, allowing joint distention. The quadriceps tendon defect is loosely closed with nonabsorbable zero sutures. The tendon is closed in a Z-plasty manner, in which portions of the quadriceps tendon layers are brought together to avoid the circumferential tight sutures placed through all three tendon layers. This technique decreases medial-to-lateral tension in the extensor mechanism.

The patellar bone defect is later bone grafted in a meticulous manner with bone obtained with a coring reamer during preparation of the femoral graft tunnels. It is important to obtain a bone graft that completely fills the defect, because bone shavings from the tunnel preparations are insufficient. Postoperatively, a bone defect that was meticulously grafted heals without a palpable patellar defect and decreases the incidence of graft harvest site pain.

Preparation of Achilles Tendon-Bone Allograft

The preparation of an AT-B allograft is performed in a manner similar to that of QT-PB already described and is the most commonly used single-strand construct. It is necessary to tube or roll the wide proximal fan-shaped portion of the tendon. In the optional technique described, the bone plug is placed into a rectangular femoral site for all-inside placement, or a 10- to 11-mm diameter graft for a single femoral



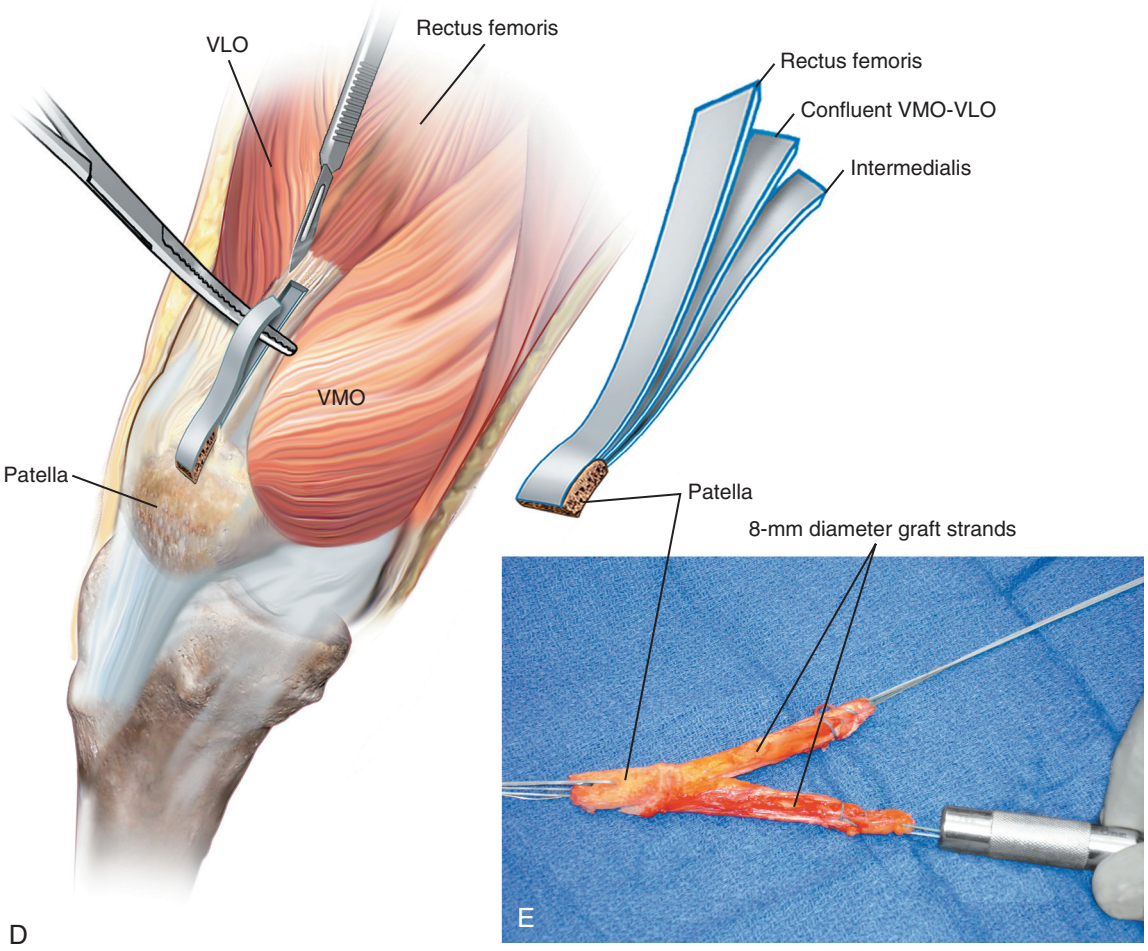


FIG 16-19 Quadriceps tendon-patellar bone autograft harvest. **A,** Medial incision. **B,** The quadriceps tendon is carefully marked to remove only 30% of its width and not extend to the musculotendinous junction. **C,** A central 11- to 12-mm wide full-thickness quadriceps tendon graft is harvested. The defect is later closed to maintain arthroscopic joint distention. **D,** Illustration of graft harvest. **E,** Two-strand 8-mm tendon graft with patellar bone is prepared. *VLO*, Vastus lateralis obliquus; *VMO,* vastus medialis obliquus.

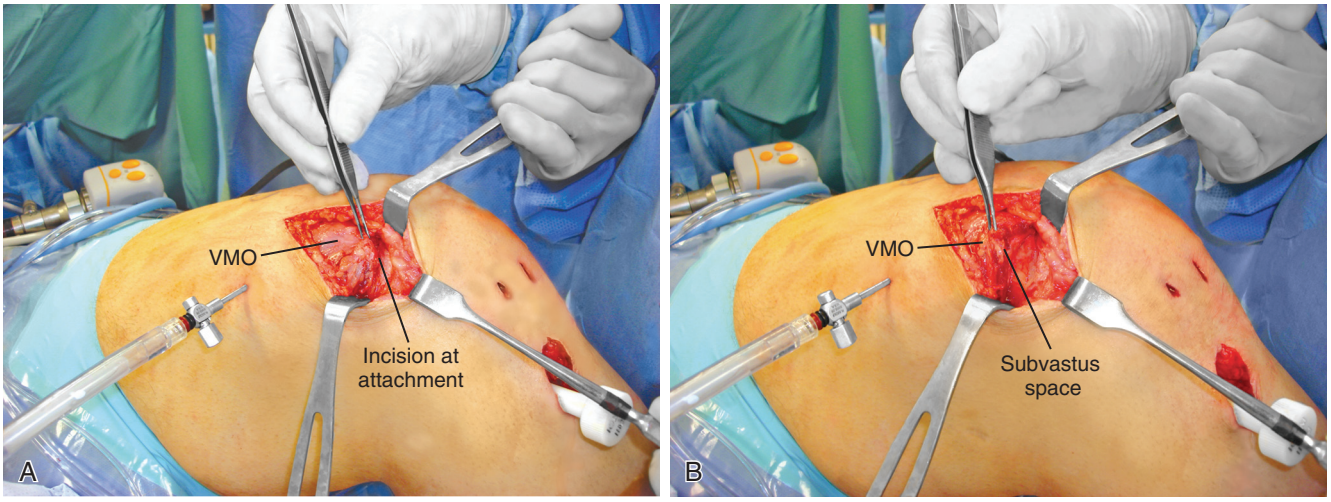


FIG 16-20 In this revision knee with a quadriceps autograft, the tendon harvest site is used to perform the subvastus approach. **A,** An incision is made at the vastus medialis obliquus (VMO)-retinacular attachment. **B,** The VMO is gently reflected proximally in an extracapsular blunt dissection. If a single femoral tunnel is selected, a smaller skin incision and muscle-splitting approach are used.

CRITICAL POINTS Preparation of Achilles Tendon-Bone Allograft

- Each portion of single or double-strand graft is tubed, Achilles tendon has a wide fan shape at its proximal aspect.
- AT-B graft used for single tibial or femoral tunnel applications.

tunnel is placed using an outside-in technique through a VMO muscle-splitting approach.

Surgical Technique for Anteromedial Approach and Outside-in Femoral Tunnels

This approach is selected when two femoral tunnels are used and is less traumatic than a muscle-splitting approach, in which the VMO is split for 5 to 6 cm for proper visualization. In addition, this approach allows for good visualization of the graft and suture post fixation. When a single femoral tunnel is selected, a limited muscle-splitting approach is performed. A vertical skin incision of 3 to 4 cm is made over the anteromedial vastus medialis proximal to the knee joint and just medial to the quadriceps tendon. When an ipsilateral QT-PB is harvested, the same skin incision is used (Fig. 16-20).

The key to the anteromedial approach is to identify the VMO anterior attachment to the medial retinaculum and dissect in this plane, thereby avoiding the muscle and achieving a subvastus elevation of the VMO. Note that no incision is made into the VMO attachment to the patella and the medial patellofemoral ligament is not incised. Only a limited subvastus exposure is required. The synovium beneath the VMO is protected and not entered. The VMO nerve innervation proximally is not disturbed. A branch of the superior genicular artery that traverses the inferior border of the VMO is protected.

The outside location of the 1 o'clock femoral tunnel entrance is identified with the drill guide. The guide pin is placed 12 mm proximal to the articular cartilage of the medial femoral condyle, and an equal distance medially from the medial trochlear border. The articular cartilage border is carefully palpated. The more distal femoral tunnel decreases graft tunnel angulation at the entrance within the joint. The tunnel should be in line with the obliquity of the PCL graft, but not located too far distally adjacent to the articular cartilage to prevent a

CRITICAL POINTS Surgical Technique for Anteromedial Approach and Outside-In Femoral Tunnels

- Less traumatic than muscle-splitting approach, selected when two femoral tunnels will be used.
- Single femoral tunnel, limited muscle-splitting approach or FlipCutter.
- Vertical skin incision, 3-4 cm.
- Key: identify VMO anterior attachment to medial retinaculum and dissect in this plane, avoids muscle and achieves subvastus elevation of VMO.
- Only limited subvastus exposure required.
- Outside location 1 o'clock graft femoral tunnel entrance identified with drill guide.
- Guide pin placed 12 mm proximal to articular cartilage of medial femoral condyle and an equal distance medially from posterior from medial trochlear border.
- Tunnel located in line with the obliquity of the PCL graft.
- 4 o'clock graft femoral tunnel located 12 mm from medial articular cartilage margin, just anterior to femoral epicondyle.

breakout of the tunnel into the distal femoral condyle. The location of the 4 o'clock femoral tunnel, to maintain an adequate bone bridge at both the entrance and exit of both tunnels, is also 12 mm from the medial articular cartilage margin and just anterior to the femoral epicondyle.

At the time of graft fixation, the surgeon uses a headlight to view the graft in the tunnels. The graft length is observed as the knee is flexed to determine the knee flexion angle at which the greatest graft length is produced. In addition, the headlight provides for adequate visualization for the placement of the interference screw and a graft suture post for added fixation. Routine closure is performed with absorbable sutures used for the VMO retinaculum attachment and subcutaneous tissues.

Recommendations for Surgeons on Selecting a Posterior Cruciate Ligament Operative Technique

The operative techniques available to the surgeon require experience and knowledge at an expert arthroscopic level. There is a building level

CRITICAL POINTS Recommendations for Surgeons on Selecting a Posterior Cruciate Ligament Operative Technique

- Levels of difficulty in PCL reconstruction options, marked variability among surgeons in techniques and grafts selected.
- Initial level: all soft tissue graft. Concern exists with allograft tissue in athletes; low strength fixation of interference screws. Low recommendation.
- Next level: graft with bone in one portion (AT-B allograft). Tendon portion placed in tibial tunnel, bone plug secured in femoral tunnel. Ease of tibial graft passage.
- Next level: placement of bone portion in tibial tunnel. Distinct advantage in revision cases. Added benefit secure graft fixation and healing.
- Next level: additional second femoral tunnel in larger patients with larger PCL footprint.
- Next level: harvest QT-PB autograft in athletic patients: one- or two-strand femoral tunnel, bone in tibial tunnel

of difficulty in PCL reconstructive techniques and the literature reflects marked variability among surgeons in surgical options and graft choices. Based on the senior author's experience, a few suggestions are provided for consideration of this selection process.

Starting from the initial level of surgical complexity, a soft tissue graft (without a bone portion) is the easiest to prepare, pass into the knee joint, and fixate in well-placed femoral and tibial tunnels. There are a variety of fixation methods available. The senior author expresses a level of concern with allograft tissue, particularly in an athletic patient, owing to delayed remodeling and lack of a beneficial graft hypertrophy after implantation that occurs with autografts. In addition, the use of soft tissue interference screws alone provides a relatively low strength attachment fixation.

The next level of complexity is a PCL graft that has bone attached on one end, such as an AT-B allograft. There is the opportunity for ease of passage, with the tendon portion placed in the tibial tunnel and secure fixation accomplished with an interference screw of the bone plug at the femoral tunnel. The tendon is passed first into the knee joint through an enlarged anterior portal, and then into the tibial tunnel. This allows the bone portion of the graft to be passed next into the joint and docked by a leading suture within the femoral tunnel and fixed with an interference screw. The tendon portion in the tibial tunnel allows double fixation with an interference screw and back-up suture post. This is a recommended graft construct for surgeons and probably one of the most frequently used graft constructs with either an AT-B or QT-PB graft.

The placement of the bone portion of an autograft or allograft within the tibial tunnel is an added level of difficulty because the bone portion is introduced into the knee joint through an enlarged portal and then guided by a leading suture (always at the end of the bone) and nerve hook into the tibial tunnel. This requires the bone plug to be angled close to a right angle to enter into the tibial tunnel entrance. The tibial tunnel is enlarged 2 mm greater than the bone portion of the graft. With experience, the gentle docking technique of the bone plug within the tibial tunnel is successful. After the bone plug is in the tibial tunnel, the tendon portion is brought into the joint and easily passed into the femoral tunnel. This allows the overall graft to be displaced proximal to distal for appropriate graft lengths in the tunnels and final fixation. The senior author believes the fixation of the bone plug within the tibial tunnel is a distinct advantage. The clinical experience at our center has shown (in revision cases) a relatively poor healing ability of large allografts within a large-diameter tibial tunnel. The bone plug is fixed with both an interference screw and back-up suture post. Accordingly, this represents the preferred technique recommended in this chapter. In addition, two tibial tunnels are not necessary to achieve successful results and therefore one well-placed tibial tunnel is selected in all PCL surgical cases.

The final level of complexity is adding a second femoral tunnel; the recommendations for the double-graft construct have already been presented. In summary, the primary indication is in larger patients with corresponding larger PCL femoral attachment sites where a single graft replaces 50% or less of the femoral attachment area. Future well-designed level 1 studies of sufficient numbers of patients are necessary to resolve these controversies; however, the recommendations discussed in this chapter appear warranted at this time.

Posterior Cruciate Ligament All-Inside Technique: One- and Two-Strand Graft Reconstructions Using Quadriceps Tendon-Patellar Bone Autograft (Preferred Technique for Athletic Patients)

Our graft preference for isolated PCL reconstruction using the all-inside technique is a QT-PB autograft, using a one- or two-strand femoral placement based on the size of the quadriceps tendon, as discussed. This approach is recommended for athletic patients. The bone plug is placed and fixated in a posterior tibial tunnel directly at the posterior entrance under fluoroscopic control (see Table 16-12). The goal is to match the results of the tibial inlay procedure, with the bone plug placed directly at the posterior PCL attachment using an oblique tunnel instead of a tibial inlay that requires an open posteromedial approach. In a sedentary patient or multiligament knee injury, an AT-B graft is selected with the bone plug placed in either the femoral or tibial tunnel. The operative steps for these techniques are described in the following sections. There are other PCL procedures and potential options for tibial and femoral placement and tunnels, based on the graft selected (see Table 16-13).

Patient Positioning and Setup

An examination under anesthesia is performed to confirm the diagnosis and carefully compare the injured knee with the opposite normal knee. It is important to palpate the medial tibiofemoral step-off at 90 degrees of flexion in both knees. At surgery, the PCL grafts will be tensioned in knee flexion and the medial tibiofemoral step-off used as verification that the abnormal posterior translation has been corrected.

The patient is placed supine on the operating table with appropriate padding (Fig. 16-21). The operating table is placed in a 15-degree reflexed position to prevent hyperextension of the spine and produce mild flexion of the hip to relieve undue tension on the right and left femoral nerves. The knee portion of the bed is flexed to 70 degrees. A thigh tourniquet is placed over cast padding. The opposite limb is positioned in a foam leg holder with the hip slightly flexed. A thigh-high compression hose is placed on the opposite extremity. After appropriate draping, a 4-inch flat padded bolster is placed underneath the operative thigh to protect the tissues and allow for knee flexion during the operative procedure. The operative procedure is performed with the knee flexed from 60 to 90 degrees; however, further knee flexion is possible by adjusting the operative table or using an additional thigh bolster. No undue pressure should be placed against the posterior thigh and sciatic nerve during the operative procedure. For this reason, an arthroscopic thigh holder is usually not used. In prolonged surgical cases, a rigid thigh holder may place abnormal

TABLE 16-12 All-Inside Posterior Cruciate Ligament Graft Options

	Two-Strand Grafts	Single-Strand Grafts
Preferred	QT-PB autograft 1. Single tibial tunnel: bone plug at posterior tunnel exit 2. Femur: two-strand, two tunnels or one-strand, one tunnel based on graft size	QT-PB autograft 1. Tibial tunnel: bone plug at posterior tunnel exit 2. Femoral tunnel: one-strand FlipCutter femoral socket TightRope plus interference screw
Alternatives	Femoral attachment, two tunnels QT-PB allograft AT-B allograft	QT-PB allograft AT-B allograft
Principles	Allografts have lower success rate, delayed healing Bone graft plug provides secure fixation, faster healing, and increased graft construct tensile strength compared with all soft tissue grafts. Rehabilitation, return to activity are delayed with allografts. Avoid single small-diameter B-PT-B autograft; second graft is required to achieve native PCL width. Graft selection rules are still empiric until randomized controlled clinical trials are performed.	Allograft provides acceptable results in multiligament reconstructions, dislocated knees when operative complexity and time warrant single-tunnel procedure. Preference for bone plug at posterior tibial tunnel to avoid large-diameter soft tissue graft through tibia with delayed graft incorporation.

AT-B, Achilles tendon-bone; *B-PT-B*; bone-patellar tendon-bone; *PCL*, posterior cruciate ligament; *QT-PB*, quadriceps tendon-patellar bone.

TABLE 16-13 Posterior Cruciate Ligament All-Inside Procedures

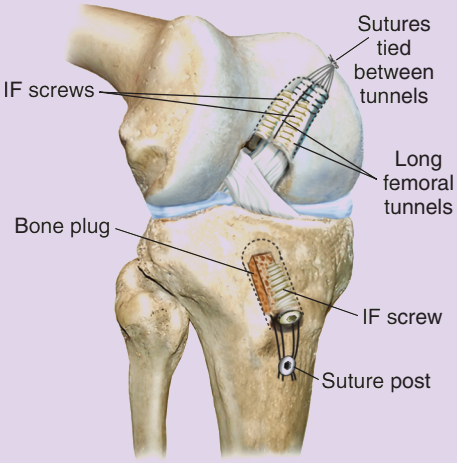
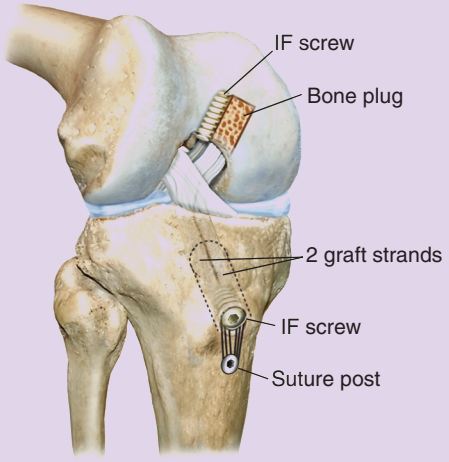
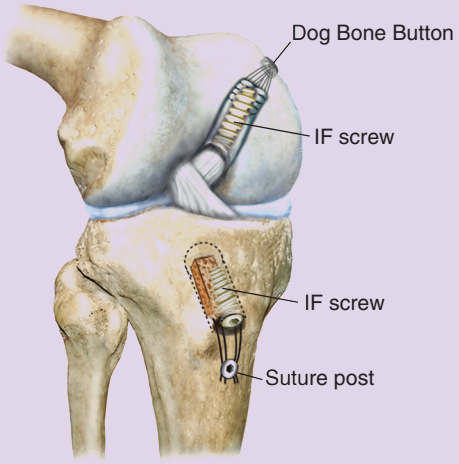
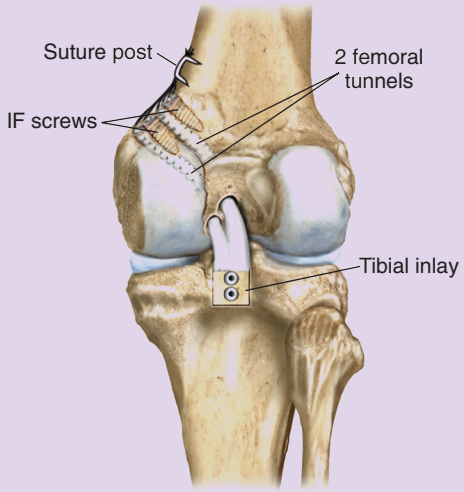
Surgical Procedure	Advantages	Disadvantages	Options
QT-PB two-strand autograft* 	Replaces femoral footprint, secure fixation, tensioning two strands (our preference for athletic patients)	Autograft harvest adds time and postoperative pain	Single-strand graft, femoral socket with FlipCutter and TightRope fixation, tibial tunnel entrance lateral to tibial tubercle
QT-PB, AT-B allograft 	All-inside femoral socket, FlipCutter, IF screw, single tibial tunnel, tensioning two strands	Delayed healing with allograft	Single-strand graft tensioned at tibia, rectangular bone plug, tibial tunnel entrance lateral to tibial tubercle

TABLE 16-13 Posterior Cruciate Ligament All-Inside Procedures—cont'd

Surgical Procedure	Advantages	Disadvantages	Options
QT-PB, AT-B allograft 	All-inside femoral socket, TightRope replaces suture post, single tibial and femoral tunnel, bone fixation tibial tunnel	Delayed healing with allograft	Tibial socket all-inside fixation using FlipCutter
QT-PB two-strand autograft tibial inlay 	Replaces femoral footprint, secure fixation, tensioning two strands	Open posteromedial approach, time and complexity	Single femoral tunnel, QT-PB, AT-B allografts, replaced by all-inside arthroscopic procedures

*Our preference for athletic patients.
AT-B, Achilles tendon-bone; *B-PT-B*, bone-patellar tendon-bone; *IF*, interference; *PCL*, posterior cruciate ligament; *QT-PB*, quadriceps tendon-patellar bone; *STG*, semitendinosus-gracilis tendons.

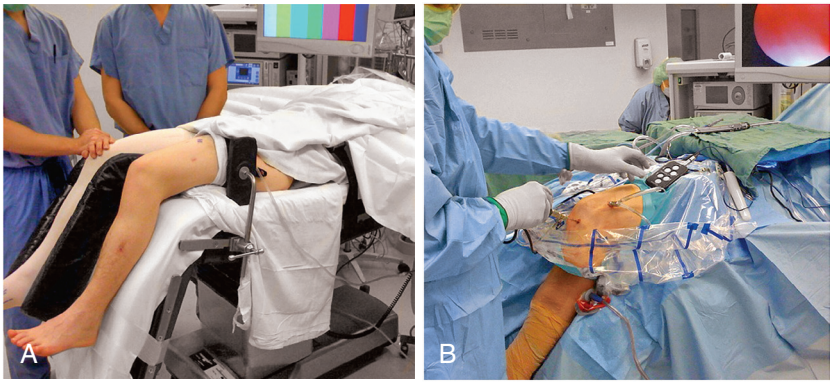


FIG 16-21 Patient position with the knee flexed to 70 degrees. Note the bed is flexed to maintain hip flexion. There is no pressure against the posterior popliteal space. The opposite leg is well padded. The knee flexion angle is adjusted as required.

pressures on the posterior thigh, which compromises the neurovascular structures. Posterior thigh muscle ischemia and peroneal tibial nerve damage are avoided by ensuring no undue posterior pressures occur.

When a meniscus repair is required, an arthroscopic thigh holder is initially used to allow for adequate joint opening for an inside-out meniscus repair using the patient and limb positioning described. The knee position of the bed is flexed as required. After the meniscus repair is performed, the thigh holder is removed and appropriate posterior thigh padding placed as necessary.

Arthroscopy of the knee begins with a pressure-regulated pump that is adjusted to provide mild joint distention and prevent fluid extravasation. The pump is required to maintain joint distention, particularly during the drilling of the tibial tunnel, so that the fluid expands the posterior capsule out of the operative field. Modern pressure- and volume-regulated pumps allow for a controlled inflow and outflow that maintain a safe pressure. In addition, sufficient fluid inflow is maintained so that a tourniquet is used only selectively during the operative procedure.

Routine arthroscopic anteromedial, anterolateral, and superolateral portals are created (Fig. 16-22). During the PCL reconstruction, a transpatellar central portal is required. Many surgeons recommend a posteromedial portal to debride the PCL tibial fibers and visualize the PCL tibial attachment. The senior author performs a technique in which the posteromedial portal, in most cases, is not required. The use of three anterior portals is advantageous because inadvertent fluid extravasation into the popliteal fossa is avoided, which may limit posterior capsule distention and visualization during drilling of the tibial tunnel.

A standard arthroscopic examination is performed. The gap test is used to assess lateral and medial joint opening at 20 degrees of knee flexion with a varus and valgus stress. Any meniscal repairs or partial resections, debridement, or other arthroscopic procedures are performed.

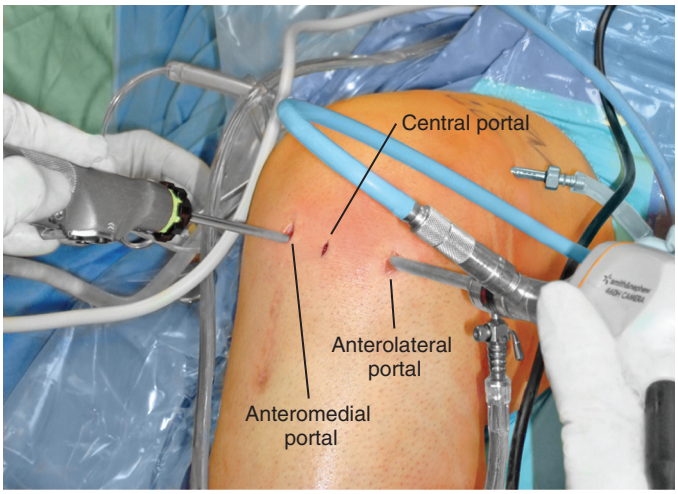


FIG 16-22 Arthroscopic preparation of the tibial and femoral posterior cruciate ligament graft sites through anteromedial, central, and anterolateral portals.

Tibial Tunnel Preparation

The most difficult part of the operative procedure is preparation of the tibial tunnel, (located in the distal PCL attachment position), without injuring the popliteal neurovascular structures. To maintain joint distention and allow full visualization, the tourniquet is inflated, a pressure-regulated arthroscopic pump is used, and the femoral tunnels and ipsilateral graft harvest are completed after preparation of the tibial tunnel.

The knee is positioned at 70 degrees of flexion to prevent pressure against the popliteal structures posteriorly and a proximal thigh pad is used to elevate the thigh. This allows the posterior neurovascular structures to drop away from the posterior aspect of the knee. Matava and coworkers[139] reported that the mean distance of the PCL from the popliteal artery from 0 to 100 degrees of flexion was 7.6 mm in the axial plane and 7.2 mm in the sagittal plane; however, there may be individual variation between knees. During the operative procedure, the surgeon is constantly aware of the joint pressure, fluid inflow and outflow, increased thigh tension, and any lack of joint distention. Intermittent palpation of the popliteal and calf region is performed during the operative procedure to detect fluid extravasation by an inadvertent puncture of the posterior capsule.[169]

The preparation of the tibial tunnel is more difficult when the ACL is intact. It is first necessary to identify residual PCL fibers adjacent to the ACL, which are removed with a shaver or basket through the anteromedial portal with the arthroscope in the anterolateral portal. The middle genicular artery enters into the proximal aspect of the PCL and requires electrocoagulation. Some PCL fibers are left on the

CRITICAL POINTS Posterior Cruciate Ligament All-Inside Technique: Patient Positioning and Setup

- Palpate medial tibiofemoral step-off (90 degrees of flexion) in both knees, will be used to verify correction of abnormal posterior translation at end of procedure.
- Operating table 15 degrees reflexed position, knee portion flexed to 70 degrees. A 4-inch flat padded bolster placed under operative thigh.
- Begin arthroscopy with pressure regulated pump: required to maintain joint distention.
- Routine arthroscopic anteromedial, anterolateral, and superolateral portals.
- Measure lateral and medial joint opening 20 degrees of flexion with gap test. Perform meniscus repair or resection, debridement, other arthroscopic procedures as required.
- Remove leg holder for PCL reconstruction, avoids prolonged posterior thigh pressure.

CRITICAL POINTS Posterior Cruciate Ligament All-Inside Technique: Tibial Tunnel Preparation

- Knee 70 degrees of flexion to protect neurovascular structures.
- Surgeon monitors joint pressure, fluid inflow and outflow, increased thigh tension, any lack of joint distention.
- Remove residual PCL fibers at femoral attachment, some fibers left for later identification and placement of the graft tunnels.
- 30-degree arthroscope placed into anteromedial portal, positioned high in notch adjacent to PCL femoral attachment.
- Pass curved elevator, gently free up capsular space behind remaining PCL fibers.
- Protect medial and lateral meniscus posterior tibial attachments adjacent to the PCL tibial fossa.
- Remove PCL stump.
- View entire posterior PCL tibial fossa to identify correct placement of tibial tunnel.
- Do not violate distal capsule attachment at tibial ridge.

femoral attachment for later identification and placement of the graft tunnels. The anterior meniscofemoral ligament (AMFL) and posterior meniscofemoral (PMFL) ligament are identified if present. It is usually possible to preserve the PMFL. If these structures impede visualization, they may be removed as long as the lateral meniscus has a confirmed posterior horn attachment to the posterior tibia and is not an anatomic variant, in which the posterior horn is attached by a meniscofemoral attachment.

The 30-degree arthroscope is next placed into the anteromedial portal and positioned high in the notch adjacent to the PCL femoral attachment. This allows the posterior capsular recess and remaining PCL stump at the tibial attachment to be viewed and instruments to be passed medial to the ACL.

A critical step is the passage of a curved Cobb elevator or commercially available curved Acufex (Smith & Nephew Endoscopy) PCL elevator (Fig. 16-23), which has a 90-degree curve and is used to gently free up the capsular space behind the remaining PCL fibers. In some knees, the posterior capsule becomes adherent to the PCL fibers. The PCL elevator is used to tease the capsule gently off of the PCL fibers and avoid rupture of the posterior capsule. This step requires a gentle approach to push the posterior capsule distally to the level of the distal PCL and capsule attachments, which are at the level of the posterior tibial step-off. Again, this step is emphasized as the key step to prevent damage to the neurovascular structures, because the posterior capsular pocket behind the PCL tibial attachment is restored. This allows the PCL elevator to be placed into this posterior position behind the tibial attachment during the tibial drilling.

If the posterior capsule is violated, a decrease in pump pressure is required and a large anterior fluid outflow portal is established. Close monitoring of any fluid extravasation into the popliteal space and calf is performed. It is usually safe to proceed under low pressure conditions; however, if there is any question of visualization and popliteal space distention, the operative procedure is postponed to allow for capsule healing.

The medial and lateral meniscus posterior tibial attachments adjacent to the PCL tibial fossa are viewed with the 30-degree arthroscope placed adjacent to the medial femoral condyle through the anteromedial portal. The shiny white attachment of the medial meniscus is well visualized and the adjacent lateral meniscus attachment is protected at all times during the preparation of the tibial tunnel. These meniscal

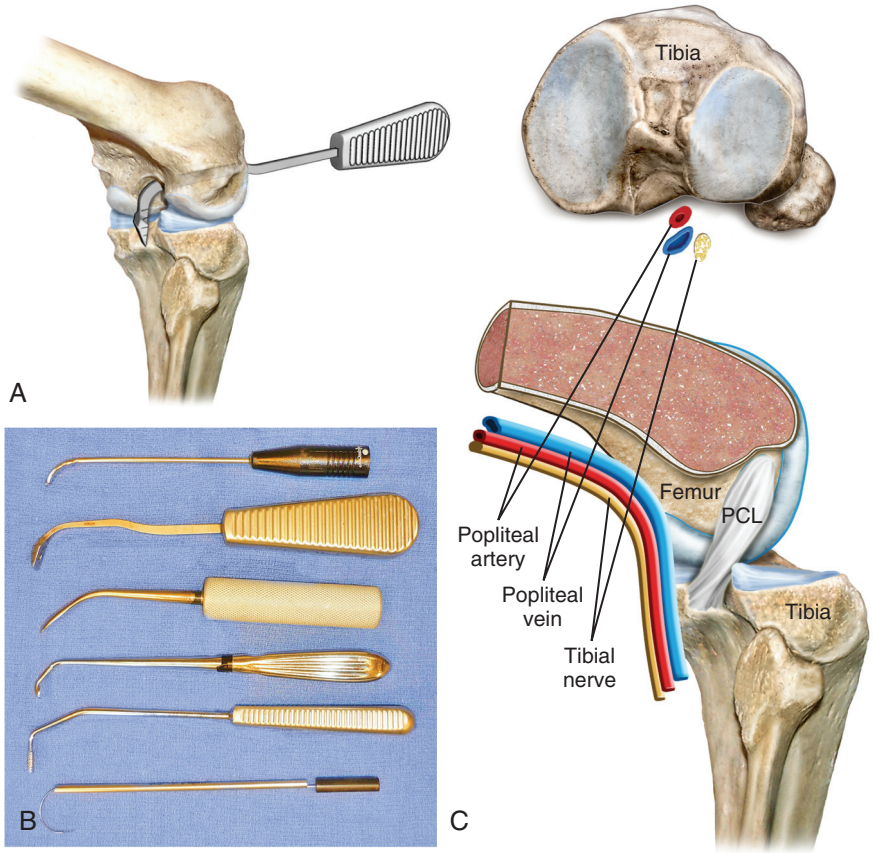


FIG 16-23 **A** and **B,** Tibial preparation. A 30-degree arthroscope is placed through the anteromedial portal. The scope is placed high in the notch adjacent to the medial condyle to view the posterior region of the joint. Instruments are placed through a central portal, medial to the anterior cruciate ligament, carefully protecting the ligament. **A,** The Acufex posterior cruciate ligament (PCL) elevator is inserted through the notch to carefully free the posterior capsule and recreate the normal capsular recess behind the PCL, because the capsule may be adherent to the ruptured PCL fibers. This step allows the capsule to displace posteriorly with fluid distention protecting the neurovascular structures. **B,** The tibial PCL stump is removed under direct visualization using curved shavers, baskets, Cobb elevators, and radiofrequency instruments. The posterior medial and lateral meniscus attachments are protected at all times. **C,** Anatomic illustration shows the close proximity of popliteal neurovascular structures.

attachments are located within a few millimeters of the PCL attachment and may be easily damaged during drilling of the tibial tunnel if it is too proximal or angled to the medial or lateral aspect of the PCL fossa.

The PCL stump is removed with arthroscopic instruments of the surgeon's preference. There are a variety of curved instruments, including baskets, shavers, and curettes, that are helpful. The senior author prefers an electrocoagulation cautery instrument that is manually bent to a 45-degree curve to initially cauterize the PCL fibers at the most proximal portion of the PCL fossa, immediately posterior to the ACL tibial attachment. This initiates a safe plane directly on cortical bone, which is then continued distally to the main PCL attachment. At times, there are remaining PCL fibers that are adherent to the posterior capsule. These fibers are left alone, or they may be easily displaced posteriorly while exposing the bony PCL fossa distally to the capsular attachment at the posterior tibial champagne glass step-off. The capsule attachment is not violated to prevent fluid extravasation into the popliteal space. At the conclusion of these steps, the entire posterior PCL tibial fossa (to the level of the posterior capsule attachment) is viewed for identification of the correct placement of the tibial tunnel.

Tibial Tunnel Drilling

A medial skin incision 3 to 4 cm is made 1 cm medially to the tibial tubercle. The tunnel entrance is medial or lateral to the tibial tubercle (Fig. 16-24). There may be a theoretical advantage for the tunnel to be started just lateral to the tibial tubercle to produce less posterior tunnel graft angulation. However, either tunnel location is acceptable. The senior author usually prefers an entrance medial to the tibial tubercle. When an ACL reconstruction is also performed with a medial tunnel, the PCL graft is placed through a tunnel lateral to the tibial tubercle.

The arthroscope is placed in the anteromedial portal and positioned high in the notch to view the posterior aspect of the tibial PCL attachment to the capsular attachment. In the majority of cases, the 30-degree arthroscope provides an excellent view. On occasion, a 70-degree arthroscope is required. As already discussed, an alternative approach is to place the arthroscope in a posteromedial portal and view the drill guide placed through the anteromedial portal; however, this is seldom required and avoids the potential for posterior fluid extravasation.

The drilling of the tibial tunnel is shown in Figure 16-25. The drill guide is placed through the central transpatellar tendon portal. The tip of the guide is placed so that the guide pin exits 6 mm proximal to the level of the posterior capsule insertion on the tibia, just before the posterior tibial step-off. This is a critical step because a guide pin placed directly at the bony tibial ridge would allow a large-diameter drill to enter distal to the capsular attachment into the popliteal space. At all times, the drill pin and drill are proximal to the distal capsular attachment of the PCL fossa. Another error is to place the guide pin too proximal in the PCL fossa, which produces a near-vertical PCL graft with limited ability to resist posterior tibial subluxation. The goal

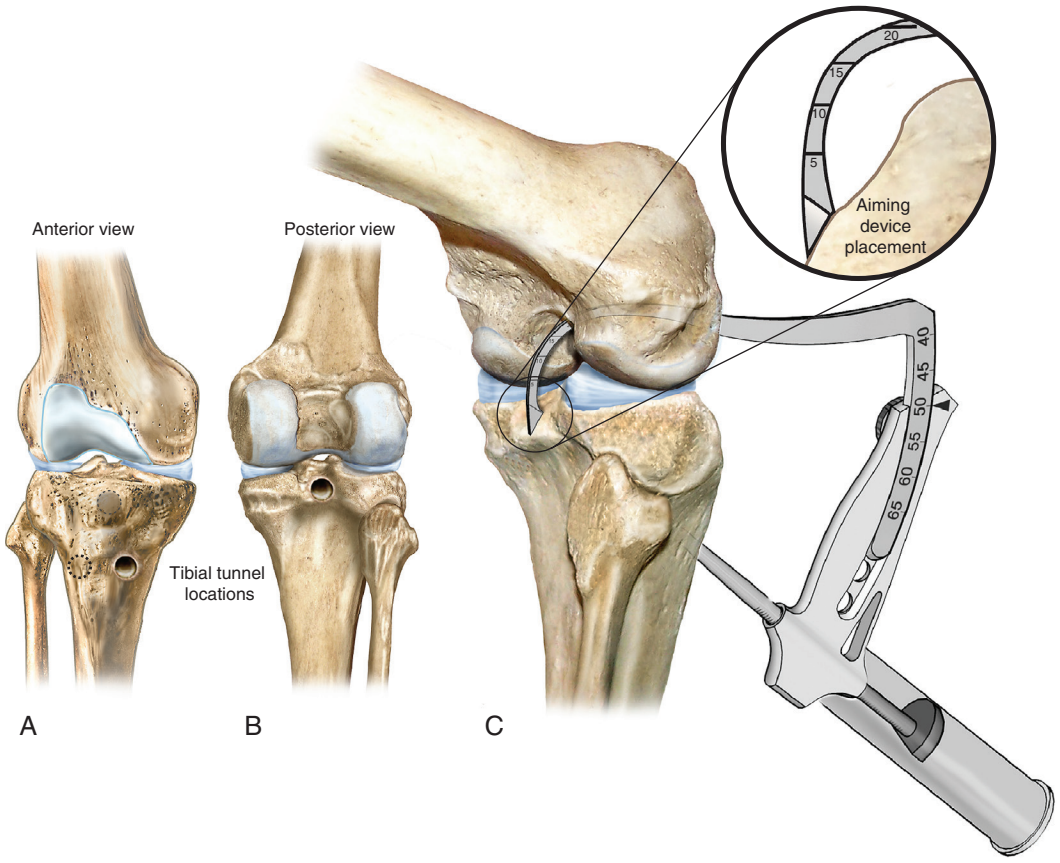


FIG 16-24 Location of tibial tunnel. **A,** Tunnel position may be medial or lateral (*dotted circle*) to the tibial tubercle 3-4 cm distal to the joint line. The tunnel position is at a 50-degree angle or greater to decrease the acute angulation at the posterior tibia. **B,** Posterior tibial tunnel at distal posterior cruciate ligament (PCL) attachment site. **C,** Acufex Director PCL Tibial Aimer is placed through the central portal with the tip of the guide resting on the posterior capsule insertion, with the target 5 mm proximal to the distal aspect of the PCL footprint. This allows sufficient tibial bone proximal to the tunnel to prevent anterior graft migration.

is to place the guide pin in the distal central portion of the PCL fossa, 20 to 25 mm from the proximal entrance of the PCL fossa. This leaves 15 mm of the posterior fossa to retain the posterior graft position and prevent a vertical PCL graft. This is a key step of the procedure. The drill guide is angled 50 to 55 degrees to produce an oblique tibial tunnel that will decrease graft angulation effects.

The next step involves use of the drill guide Safety Stop system (Acufex). This is a unique feature of this drill guide system. The guide pin is chucked to a fixed distance with the safety stop mounted on the drill guide. The safety stop controls the depth of guide pin penetration into the tibia, irrespective of the angle or position of the PCL tibial aimer, and prevents the guide pin from passing beyond the guide tip and damaging neurovascular structures.

The guide pin is drilled into the selected tibial tunnel location. The depth of the guide pin is measured and used during the drilling process to determine the depth of drill penetration. The final position of the guide pin is viewed and again confirmed that the guide pin is distal in the PCL fossa. Fluoroscopic confirmation of the guide pin position is recommended.

The tibial tunnel is drilled to the desired diameter using safety procedures to be described. A commercially available PCL guide pin protector (Acufex) has a wide shape, with a central recess 5 mm from its tip to engage the tibial guide pin before and during the drilling procedure. The tip of the pin is viewed at all times during the drilling process with the arthroscope. The instrument prevents posterior migration of the pin and drill bit. The drilling process involves use of a drill with a drill tip and not a drill twist extending the length of the drill. The drill tip only extends 10 mm with a smooth shank. The drill is advanced in a slow manner. The depth of drill penetration is measured by the calibrated drill and prior drill guide pin measurements. As the drill tip reaches the posterior cortex, there is a noticeable resistance. At this point, the drill is slowly advanced without sudden penetration. A second option is to remove the power and place a hand chuck over the drill bit to complete the tunnel through the posterior tibial cortex. In younger patients with a thick posterior tibial cortex at the PCL fossa, a two-stage drilling process is used, starting with an 8-mm drill and then progressing to an 11- or 12-mm drill.

When the FlipCutter (Arthrex) technique is selected, a 4-mm drill is initially used to establish the tibial tunnel. The FlipCutter is then advanced under arthroscopic visualization to exit the posterior tibial tunnel. The drill is flipped and held against the posterior tibial cortex and the tunnel is carefully drilled in a retrograde manner to the desired depth that is determined by the measured length of the FlipCutter. The PCL dilator remains in place posteriorly at all times to displace the posterior capsule away from the drilling procedure and prevent inadvertent capsule penetration. This technique requires practice and, importantly, requires an enlarged posterior capsular recess so the drill tip does not engage the capsular tissues when it is first engaged.

To summarize, there are specific safety procedures built into this technique to protect the neurovascular structures. First, use of the drill guide system with the Safety Stop and controlled depth of guide pin penetration, with the guide pin placed 5 mm proximal to the distal posterior capsule insertion. Second, placement of the guide pin protector and slow drill penetration, with direct viewing of the guide pin. Third, the final drill penetration of the posterior tibial cortex with complete protection posteriorly to prevent inadvertent deep drill penetration.

The proximal edge of the tibial tunnel is carefully chamfered with a rasp to limit graft abrasion effects (Fig. 16-26). Any remaining PCL fibers are removed so that the tibial tunnel entrance does not have soft tissue that would limit graft passage and to ensure the graft will lie flat against the PCL tibial fossa. Again, it is necessary to have 15 mm of the posterior tibial fossa and an intact posterior intraspinous area proximal to the tunnel. This maintains the angulation of the PCL graft from the tibial attachment to the femoral attachment to prevent a vertical graft and decrease graft tunnel enlargement (windshield-wiper effect). The most common technical mistake is to place the tibial tunnel at the proximal entrance of the PCL fossa, which is proximal to the native PCL tibial attachment.

Femoral Graft Technique

An important aspect of a successful PCL reconstruction is to have a clear understanding of PCL anatomy and changes in fiber-length and tension with knee flexion as already described. The anatomic "rule of thirds" to describe the PCL attachment assists the surgeon in defining the anterior-to-posterior plane and the proximal-to-distal plane of the native PCL (see Fig. 16-10, *A* and *B*).

As described previously, the PCL attachment is elliptical in shape, extending from high in the notch of the distal medial condyle from an approximate 11:30 to 5 o'clock position (left knee). The PCL footprint follows the articular cartilage, with the anterior portion within 2 to

CRITICAL POINTS Posterior Cruciate Ligament All-Inside Technique: Drilling of Tibial Tunnel

- Medial skin incision 3 to 4 cm, 1 cm medial or lateral to tibial tubercle.
- Place arthroscope in anteromedial portal, position high in notch to view posteriorly.
- Place drill guide through transpatellar portal.
- Do not place guide pin too proximal in PCL fossa, produces vertical PCL graft.
- Place guide pin in distal portion of PCL fossa 5-6 mm proximal to distal capsule attachment tibial ridge.
- Angle drill guide 50 to 55 degrees to produce oblique tibial tunnel.
- Chuck guide pin to fixed distance with safety stop mounted on drill guide.
- Measure depth of guide pin to determine depth of drill penetration, confirm with fluoroscopy.
- Drill tip only extends 10 mm with a smooth shank, advance slowly. As drill tip reaches the posterior cortex, advance slowly. In dense cortical bone, consider smaller-diameter drill.
- FlipCutter technique another option; however, requires added exposure and experience.
- Chamfer proximal edge tibial tunnel.

CRITICAL POINTS Posterior Cruciate Ligament All-Inside Technique: Posterior Cruciate Ligament Femoral Graft Technique

- Anatomic rule of thirds used to define the anterior-to-posterior and the proximal-to-distal planes of native PCL.
- PCL footprint follows articular cartilage, anterior portion within 2-3 mm of its edge.
- At 4 o'clock position, PCL attachment is 4-5 mm from articular cartilage edge.
- If anterior meniscofemoral ligament present, footprint appears to be 1-2 mm from cartilage edge.
- Anatomic variability in femoral attachment; map out using remaining PCL fibers to locate desired graft position.

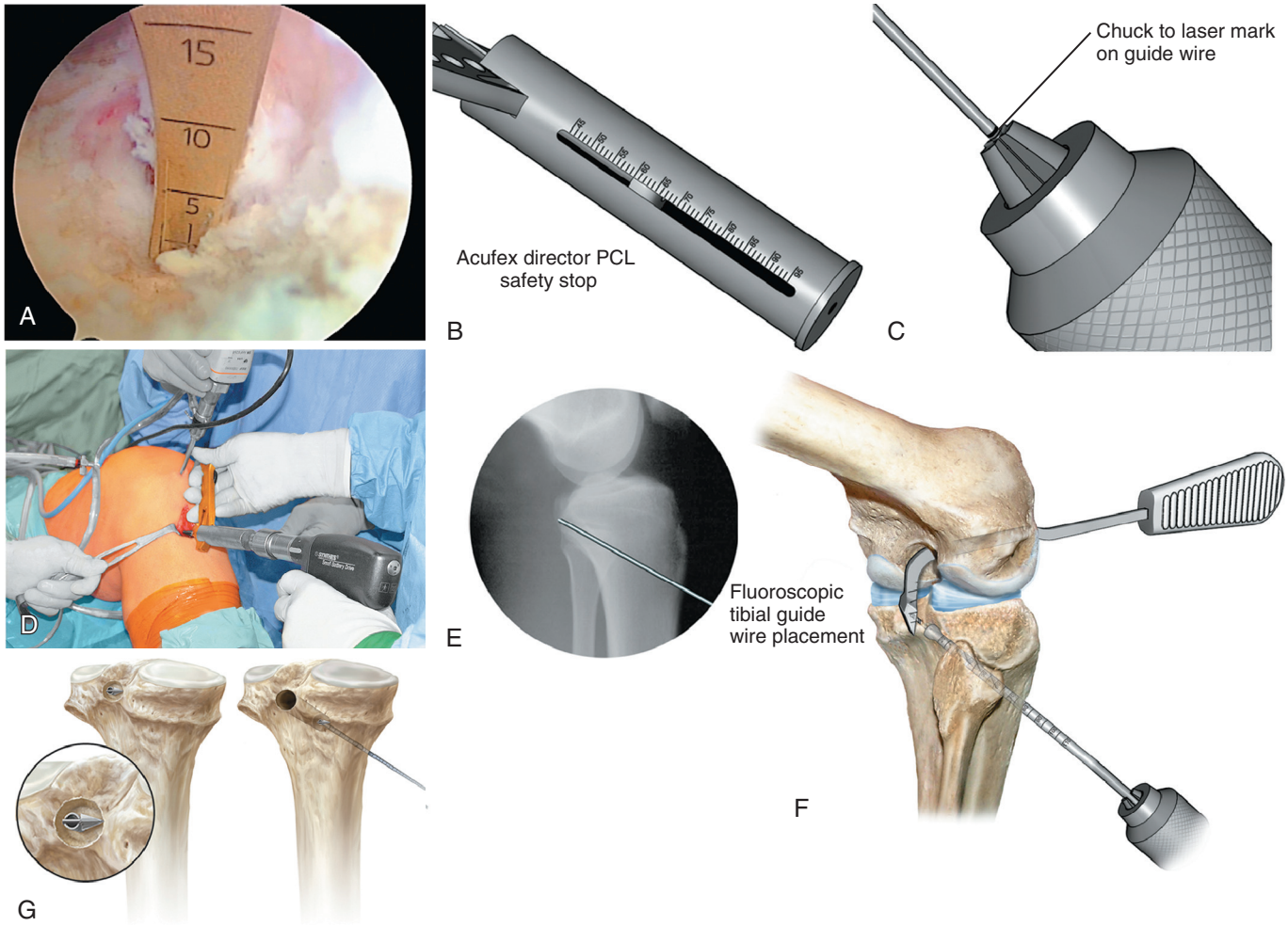


FIG 16-25 Drilling of tibial tunnel. **A,** Drill guide at the distal posterior cruciate ligament (PCL) attachment adjacent to the posterior capsule insertion. **B,** Acufex guide pin safety stop is attached to the drill guide. **C,** The guidewire is chucked on the power drill to the laser mark, which is the maximum length from the safety stop to the drill guide tip. This prevents the guidewire from being advanced beyond the drill guide after passing through the posterior cortex. **D,** Placement of guide pin using drill guide system at surgery. **E,** Fluoroscopy verifies guidewire placement. **F,** Tibial tunnel drilling with PCL elevator/wire catcher to protect posterior neurovascular structures. **G,** Alternative technique using a "flip-drill" to make a posterior tibial socket for the PCL graft bone plug. Four FiberWire sutures placed through the plug are passed to the anterior tibia for graft fixation.

3 mm of its edge, depending on the reference system used.[144] At the 4 o'clock position, the PCL attachment is approximately 4 to 5 mm from the articular cartilage edge.[189] However, if the AMFL is present, the footprint will appear to be 1 to 2 mm from the cartilage edge. There is anatomic variability in the normal proximal to distal width of the PCL, and in some knees a more oval appearance exists because of an increased width of the middle third of the PCL attachment. Because of anatomic variability in the PCL femoral attachment, it is necessary to map out the attachment using remaining PCL fibers to locate the desired graft position within the PCL attachment grid represented by the rule of thirds. The reference system axis used to describe the PCL attachment is distal to proximal and anterior to posterior with the knee in full extension. However, the surgeon views the PCL with the knee flexed and it is also helpful to communicate a graft position as deep or shallow and high or low in the femoral notch on the medial femoral condyle.

There are two main techniques used for PCL graft femoral placement and fixation. The first technique (our preference) incorporates two separate femoral tunnels with two separate graft strands. The second technique involves a single femoral tunnel when operative time and complexity of the surgery are factors, or if the graft does not allow two separate graft strands to be prepared.

Technique for Femoral Placement of One or Two Tunnels and Graft Passage

The technique for femoral placement of two tunnels and graft passage is shown in Figure 16-27. The PCL footprint is mapped with a calibrated probe and electrocoagulation. The 12, 1, and 4 o'clock position marks on the medial femoral condyle are made. The goal is to create two separate femoral tunnels in the distal two-thirds of the native PCL attachment. This places a graft with an approximate area of 100 mm^2 in cross section, occupying up to 75% or more of the PCL attachment.

If the PCL graft is placed too distal or shallow in the notch, it will be subjected to high tensile forces with knee flexion, resulting in constraining flexion and probable graft failure. If the graft is placed too

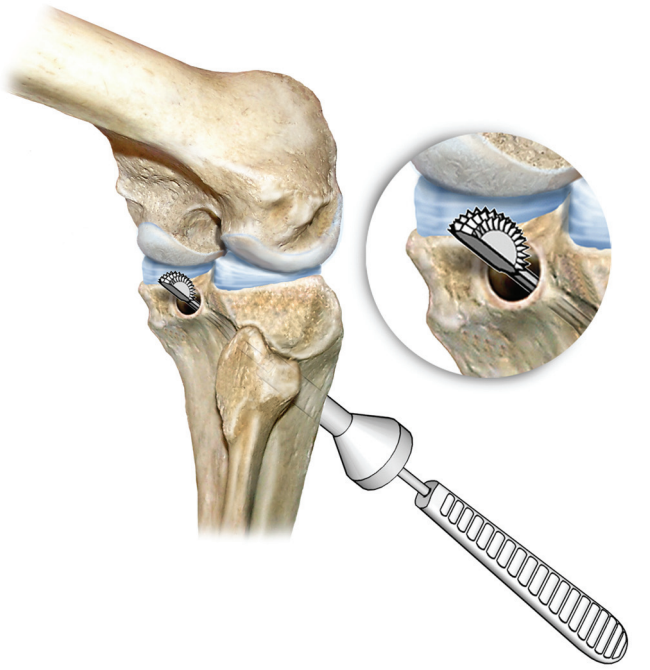


FIG 16-26 Chamfering of the tibial tunnel with a rasp to decrease graft abrasion effects. It is necessary to have 15 mm of bone retained in the posterior tibial fossa above the posterior cruciate ligament footprint to prevent the graft from migrating through the tibia.

CRITICAL POINTS Posterior Cruciate Ligament All-Inside Technique: Technique for Femoral Placement of Two Tunnels and Graft Passage

- Map PCL femoral footprint, mark 12, 1, and 4 o'clock positions.
- Two separate femoral tunnels in distal two-thirds native PCL attachment.
- Anterior tunnel centered 1 o'clock, 6 to 8 mm deep to articular cartilage.
- Posterior tunnel centered 4 o'clock, 8 mm proximal (deep) to articular cartilage edge.
- Tunnels placed anterior-to-posterior direction to allow for 2- to 3-mm bone bridge.
- Femoral tunnels drilled outside-in subvastus technique.
- Core reamer used for 1 o'clock tunnel (for bone graft patellar defect).
- 20-gauge wire passed through tibial tunnel, out anterolateral portal.
- 22-gauge wires passed through separate femoral tunnels, out anterolateral portal.
- Tibial bone plug passed in joint, assist with nerve hook to orient graft to enter tibial tunnel.
- Pass two femoral graft strands, confirm correct placement.
- Confirm placement of bone plug with fluoroscopy, arthroscope.
- Tie sutures to tibial suture post. Final interference screw fixation under fluoroscopic control.

proximal or deep in the notch, the graft will slacken with knee flexion and allow posterior tibial subluxation. The recommended placement within the PCL footprint is shown in Figure 16-27, in which the graft replaces the distal two-thirds of the PCL that functions in resisting posterior tibial subluxation with knee flexion.

The PCL guide is used for two separate femoral tunnels to prevent overlap. The anterior tunnel is centered at the 1 o'clock position, 6 to 8 mm deep to the articular cartilage based on the size of the graft and footprint that allows the graft tunnel to come within 1 to 2 mm of the articular cartilage edge. The posterior tunnel is centered at the 4 o'clock position, 8 mm proximal (deep) to the articular cartilage edge. A mark is made at the center position of each tunnel with cautery, and then defined with a curette or sharp awl passed from the anterolateral portal. The bone beneath the PCL attachment is dense and requires making a well-defined small entrance hole for the two drill guide pins. Following this technique, the first tunnel is located in the anterior half of the PCL attachment, and in the distal two-thirds in the proximal to distal direction. The second tunnel is located in the posterior half of the PCL attachment, also in the distal two-thirds. The tunnels are carefully placed in the anterior to posterior direction to allow for a 2- to 3-mm bone bridge between tunnels. This placement of the two tunnels ensures that both graft strands will resist posterior tibial translation with knee flexion, sharing the load and not placed too deeply in the notch.

The two femoral tunnels are drilled using the outside-in subvastus technique previously presented. The entrance of the 1 o'clock tunnel is 12 mm proximal to the femoral articular cartilage border and medial to the trochlea. The 4 o'clock tunnel entrance is also 12 mm proximal to the articular cartilage border and anterior to the femoral epicondyle. A core reamer is used for the 1 o'clock tunnel to obtain a bone graft for the patellar defect (QT-PB graft, Fig. 16-28). Careful chamfering of the tunnel edges is performed to decrease graft abrasion. A flexible ruler is passed through the tibial and femoral tunnels to measure the intraarticular length of the two graft strands.

The passage of the graft is performed in a stepwise fashion (Fig. 16-29). A 20-gauge wire is passed through the tibial tunnel and brought out the anterolateral portal which is enlarged sufficiently to accept the PCL graft. A 22-gauge wire is passed through each of the two femoral tunnels and a grasper or nerve hook is used to bring the two wires out of the same anterolateral portal. The 1 o'clock and 4 o'clock wires are marked.

The tibial tunnel bone plug is first passed into the knee joint with the arthroscope placed in the anteromedial portal. A nerve hook facilitates passage adjacent and medial to the ACL and into the tibial tunnel. It is important that all soft tissues have been removed about the tibial tunnel, which is 2 mm larger than the graft to facilitate passage. The nerve hook is used to angle the bone to facilitate the initial entrance into the tibial tunnel. The two femoral graft strands are then passed through the enlarged anterolateral portal and viewed through the anteromedial portal to have the correct orientation in the 1 and 4 o'clock tunnels. It is preferable to first pass the 4 o'clock, and then the 1 o'clock graft.

Fluoroscopy is used to confirm final placement of the bone plug in the tibial tunnel (Fig. 16-30). The graft is marked at the collagenous fiber-bone junction and is viewed arthroscopically to confirm that the bone plug is entirely within the tibial tunnel and placed directly at the posterior tibial tunnel entrance. The sutures are tied over a tibial suture post. An absorbable interference screw (1 mm smaller than the diameter of the tunnel) is used for bone plug fixation at the tibial tunnel, verified by fluoroscopy. The final tensioning of the graft at the femoral site is performed next.

With the selection of one single femoral tunnel, the technique is modified as follows. A FlipCutter is used for the femoral tunnel, the center of which is located at the 2 o'clock position to span the center two-thirds of the PCL attachment. This is located approximately 8 mm from the articular cartilage edge to produce a graft tunnel that comes to within 1 to 2 mm of the cartilage margin. A TightRope (Arthrex) fixation for the tendon portion of the graft is used. Three No. 2 FiberLoop (Arthrex) sutures are passed in a locking stitch at the end of the

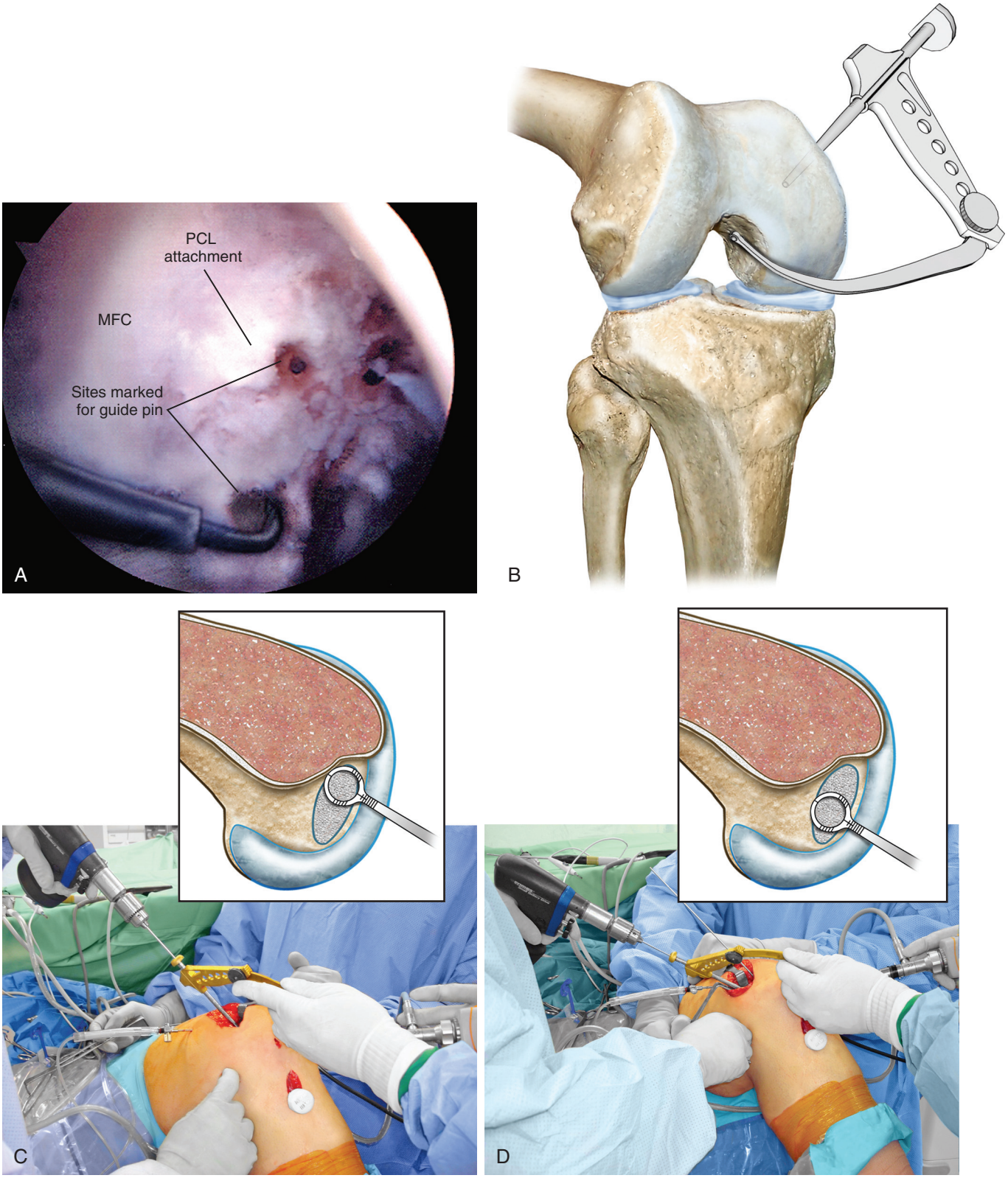


FIG 16-27 Placement of two femoral tunnels. **A,** Arthroscopic view of two posterior cruciate ligament (PCL) attachment shows 1 o'clock and 4 o'clock guide pin marks, 6 to 7 mm from the articular cartilage. **B,** PCL guide 15 mm proximal to the outside articular cartilage border. **C,** Placement of the 1 o'clock tunnel. **D,** Placement of the 4 o'clock tunnel. *MFC*, Medial femoral condyle.

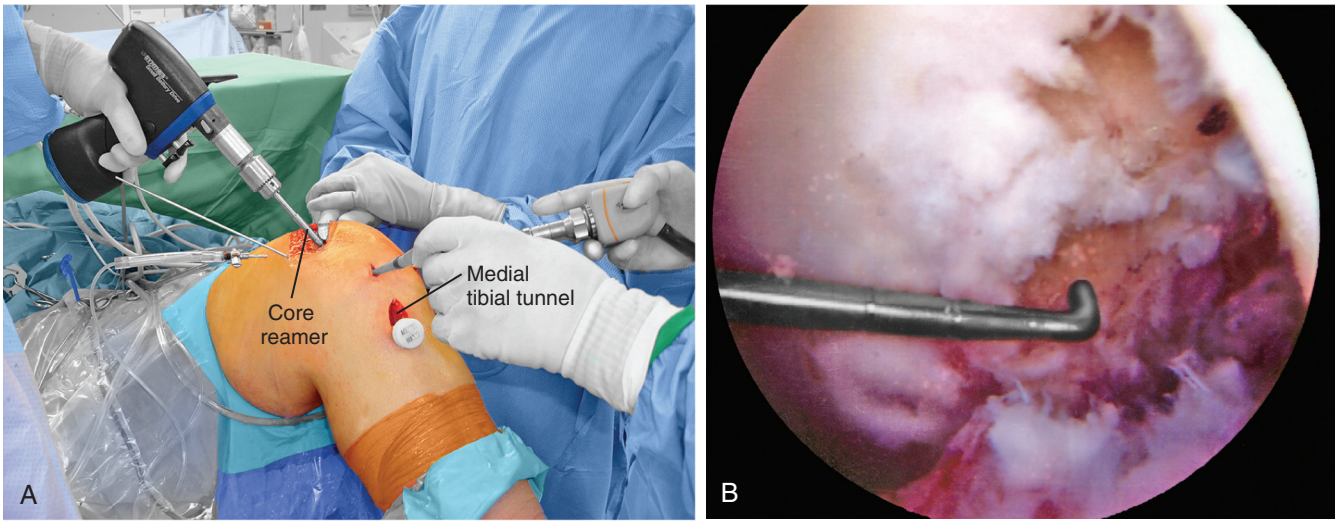


FIG 16-28 **A,** Use of the core reamer to obtain bone graft for a patellar bone defect. **B,** Arthroscopic view shows final appearance of two femoral graft tunnels.

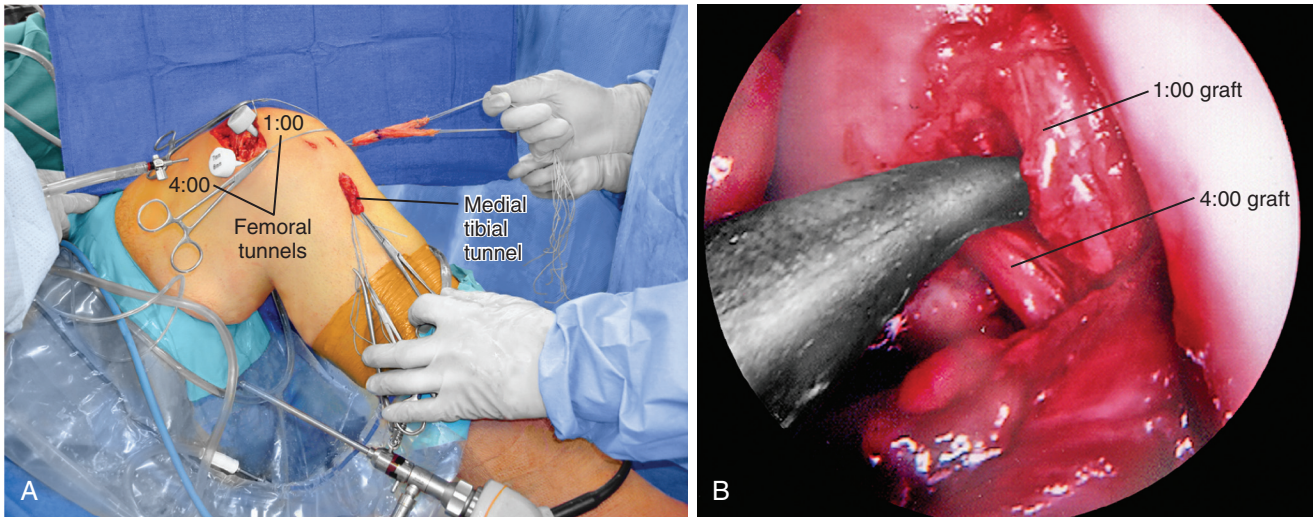


FIG 16-29 **A,** Passage of the quadriceps-bone two-strand graft through enlarged anterolateral portal. **B,** Final appearance of the two-strand graft within the femoral tunnels.



FIG 16-30 Fluoroscopy confirms that the patellar bone plug is directly at the posterior tibial tunnel exit.

graft that is tied to the TightRope. The graft passage is the same as already described with the bone portion passed into the tibial tunnel and the TightRope sutures passed through the femoral tunnel.

Graft Tensioning and Fixation

The graft tensioning and fixation steps are the same for all grafts. For grafts with the bone block in the tibial tunnel, initial fixation is performed at the tibia (as already described) and final tensioning and fixation are performed at the femoral site. For bone blocks placed at the femoral site, fixation is first performed at the femoral site and final tensioning and fixation are performed at the tibial site (Fig. 16-31).

After the initial fixation of the graft at either the femoral or tibial site, the knee is taken through a full range of motion with an assistant displacing the tibia forward to correct for the weight of the leg and maintain joint reduction.

The knee flexion position for graft fixation is checked by determining the flexion angle at which the graft strand is the longest (functional zone) to ensure that the graft is not tensioned in its shortest position, which would overconstrain the joint and produce graft failure. A nonserrated hemostat is placed on each set of graft strand sutures exiting

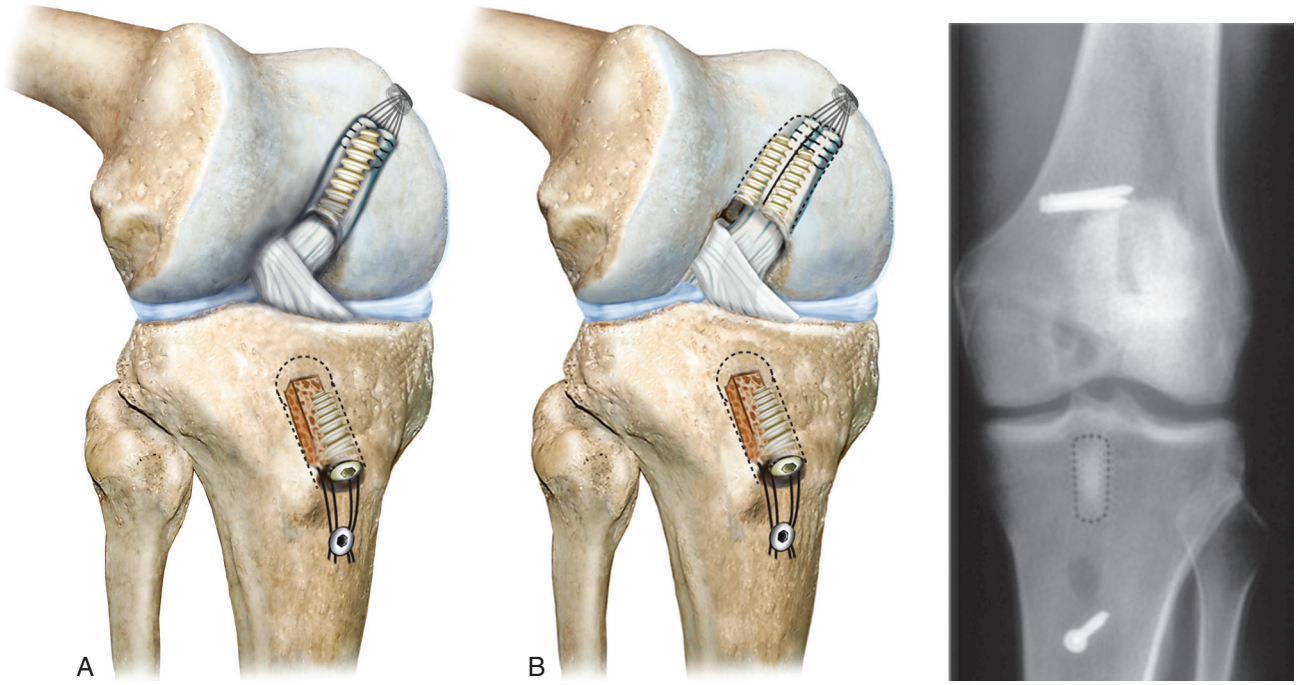


FIG 16-31 Two femoral techniques are shown and used based on surgeon preference of either a single tunnel **(A)** or two tunnels **(B)**; see text. **C,** Anteroposterior radiograph of a posterior cruciate ligament single tibial tunnel reconstruction; the bone plug (dotted line) is placed in the posterior tunnel exit and fixed with an absorbable interference screw and suture post.

CRITICAL POINTS Posterior Cruciate Ligament All-Inside Technique: Graft Tensioning and Fixation for All-Inside Grafts

- Bone plug in tibial tunnel: initial fixation at tibia, final tensioning and fixation at femoral site.
- Bone plug at femoral site: initial fixation at femoral site, final tensioning and fixation at tibial site.
- After initial fixation, at one end of graft, knee taken through full range of motion.
- Check knee flexion position for graft fixation by determining the flexion angle at which the graft strand is the longest.
- Condition graft 0-120 degrees of flexion.
- Verify normal medial tibiofemoral step-off at 90 degrees.
- Tie sutures for each graft stand over femoral or tibial post, verify final position of medial tibiofemoral joint. Absorbable interference screw added.
- Use arthroscopically placed nerve hook to confirm tension in PCL graft strands.
- With ACL reconstruction:
  - Tension PCL graft, avoid anterior tibial subluxation.
  - Verify tibiofemoral position at 0 and 90 degrees and graft tension with extension-flexion.
  - Confirm arthroscopic normal femoral condyle, anterior medial and lateral meniscus relationship.

from either the femoral or tibial tunnel(s) and circumferentially wound onto the clamp. The clamp is used to apply a 10 lb (44-N) load to each graft strand. The graft strands are conditioned by taking the knee joint through 0 to 120 degrees of flexion. The knee is placed at 90 degrees of flexion and a normal medial tibiofemoral step-off is palpated and confirmed. This is done with the assistant placing approximately 10 lb (44 N) of pressure against the calf to apply an anterior tibial force (assuming the ACL is intact). The knee is again taken through a full range of motion and the change in length of both graft strands noted. With increasing knee flexion, there will be increased tension and a pulling of the sutures and clamp into the tunnel of only 0 to 2 mm as the 90-degree position is reached.

The graft is longest at high knee flexion angles, which is the position selected for graft fixation. In most knees, the 70-degree flexion angle has the same graft length behavior as 90 degrees and this position is selected. There are commercially available graft-tensioning devices[53] (as used in ACL reconstructions) that provide measurable length-tension data and may be used for measurement of graft-tensioning loads. The sutures for each graft strand are tied over a femoral or tibial post, maintaining the 44 N of graft load and 44 N of anterior tibial load. These are empiric loading profiles.

The final position of the medial tibiofemoral joint is again verified. An absorbable interference screw is added to the fixation. The arthroscope is again placed and with a nerve hook, the tension in the PCL graft strand(s) is confirmed. The knee is taken through 0 to 110 degrees of flexion.

Although techniques have been described in the literature for the second posterior tunnel to be placed in a deeper, more proximal position, we recommend placing the tunnels in the middle and distal two-thirds of the PCL attachment as described. This allows both graft strands to share the loading and therefore tensioning is at the 70-degree flexion position for both grafts.

It should be noted that if one or both femoral tunnels are too proximal (deep in the notch), the graft strand length decreases with knee flexion (allowing posterior subluxation), because the graft strand is longest closer to full extension. In this situation, the final graft fixation is done at the more extended position. The more proximal graft strand will function in a reciprocal manner and the desired load sharing between grafts will not be achieved.

Alternatively, if the graft tibiofemoral attachment length is longer at 45 to 60 degrees of knee flexion, as the graft is pulled into the tunnel with knee flexion, then the femoral tunnels are too distal (shallow).

This is not an acceptable position and the femoral tunnel is reconfigured, removing 5 mm of the proximal aspect of the tunnel to allow the graft to assume a deeper position. The interference femoral screws are placed distal in the femoral tunnels to secure the grafts in a more proximal (deep) position. With the technique described in the placement of the femoral tunnels, it would be unusual for this graft tunnel adjustment to be performed.

In knees that undergo ACL reconstruction, it is important to determine as accurately as possible the neutral AP position of the medial and lateral tibiofemoral joints (without added internal or external tibial rotation). There is a tendency to displace the tibia into an abnormal anterior position by over tensioning the PCL graft. When the ACL is intact, the graft forces displace the tibia anteriorly, loading the ACL under low loads. When the ACL is insufficient, to prevent anterior tibial subluxation, the following steps are performed:

1. Place the knee at full extension with a 10-lb (44-N) force on each graft (or 20 lb for a single graft) and sufficient anterior loading on the calf to overcome gravity weight effects of the leg. This achieves a reduced tibiofemoral joint position when one or both of the medial or fibular collateral ligaments are present.
2. Flex the knee to 90 degrees, maintaining the same approximate graft load and anteriorly directed load on the calf. An anteriorly subluxated tibia at 90 degrees (compared with 0 degrees) will have abnormally increased tibiofemoral attachment site distances and the graft can be observed to piston into the tibial tunnel. In essence, the graft should be nearly similar in its tibial position at both 0 and 90 degrees of flexion.
3. Palpate for a normal tibiofemoral step-off and arthroscopically visualize a normal anterior relationship of the anterior portion of the medial and lateral meniscus in relationship to the respective femoral condyles. If there is any question, a lateral fluoroscopic or radiograph may be obtained intraoperatively. This is especially helpful in large limbs where the neutral AP position is difficult to determine with accuracy.

Femoral Placement of a Single Tunnel: Outside-In Technique

The drill guide is introduced into the anteromedial portal and the desired femoral tunnel position is located. The arthroscope is placed in the anterolateral portal. The goal is to place the tunnel into the middle two-thirds of the PCL attachment, avoiding too proximal a placement. The entrance of the guide pin is at the 2 o'clock position and approximately 8 mm from the articular cartilage edge. This should produce a tunnel that is 2 mm from the articular cartilage edge. A note of caution is that there is a tendency to place the drill tunnel too proximal (deep in femoral notch) and out of the PCL femoral footprint, producing a graft that only functions at low flexion angles. The ability to determine the native PCL footprint in the patient's knee carefully is important for correct tunnel placement. The preference is for a femoral tunnel of 11 to 12 mm in most knees. If the drill diameter is larger, portions of the graft will be too deep in the notch and outside of the normal PCL footprint.

The entrance position of the guide pin in the outside-in technique is midway between the femoral epicondyle and trochlea, at least 12 mm proximal to the articular cartilage edge. A more proximally placed guide pin would increase the tunnel angulation entering the joint and potentially increase graft abrasion effects.

A small skin incision and VMO muscle-splitting incision is made. A larger incision is not required because the bone block fixation is done with a cancellous screw without an added fixation device. The guide pin is overreamed or, alternatively, a coring reamer may be used to harvest a bone graft. The tunnel entrance into the knee joint is chamfered to limit graft abrasion effects.

CRITICAL POINTS Posterior Cruciate Ligament All-Inside Technique: Femoral Placement of a Single Tunnel: Outside-In Technique

- Drill guide in anteromedial portal, locate desired femoral tunnel position.
- Entrance of guide pin: 2 o'clock position, 8 mm from articular cartilage edge.
- Tunnel size: 11 to 12 mm.
- Small skin incision, VMO muscle-splitting approach or use FlipCutter placed from outside-in.
- Over-ream guide pin or use coring reamer to harvest bone graft.
- Chamfer tunnel entrance into knee joint.
- Graft passage: inside-out.
- Femoral graft fixation with TightRope adjustment of tension, interference screw placed through anterolateral portal.

A modification of this technique is used with a FlipCutter placed from outside-in instead of the guide pin and the femoral socket drilled from inside-out (Fig. 16-32). This is an easier technique than placing the femoral tunnel through the anterolateral portal. When a femoral or socket is placed with the FlipCutter, the technique involves overdrilling the socket depth so that graft positioning and tensioning are possible.

At the time of graft passage, either an inside-out passage (preferred; enlarged anterolateral portal used for graft passage into the knee) or an outside-in passage (retrograde guide wire from tibial tunnel out through femoral tunnel) is used. The process of graft positioning in the tunnels, graft conditioning, and fixation at the tibial tunnel is the same as described earlier. Femoral graft fixation is easily performed with the TightRope adjustment of tension, and an interference screw is also placed through the anterolateral portal (usually 8-mm diameter, 2 to 3 mm less than the tunnel diameter). With the VMO muscle-splitting approach, the final tension is the same except it is performed on the femoral side with an interference screw and added suture post. The surgeon uses a headlight and adequate exposure to advance an interference screw into the anterior aspect of the femoral tunnel for graft fixation. Arthroscopic examination confirms that the screw is not advanced into the knee joint.

There are publications that describe the all-inside drilling of a large single tunnel at the femoral attachment. However, the outside-in approach or inside-out FlipCutter is preferred for the femoral tunnel. From a technical standpoint, the drilling of a large-diameter tunnel is difficult owing to the proximity of the lateral condylar articular cartilage and the ACL, and the tendency exists to have a tunnel entrance that is markedly angled distally. In the senior author's experience, a more precise and less angulated tunnel is obtained with the outside-in approach.

Alternative Posterior Cruciate Ligament All-Inside Techniques

Femoral Placement of Rectangular (Oval) Tunnel for Bone Plug

An all-inside technique using the QT-PB autograft or allograft or AT-B allograft is described in which the bone plug is placed at the femoral site and the soft tissue graft is placed through a tibial tunnel. This procedure has the advantage of easy passage of the soft tissue graft through the posterior tibial tunnel. This is used in select knees in which operative time is a factor. In addition, in revision knees, there may be displaced femoral tunnels where the bone plug provides a more stable

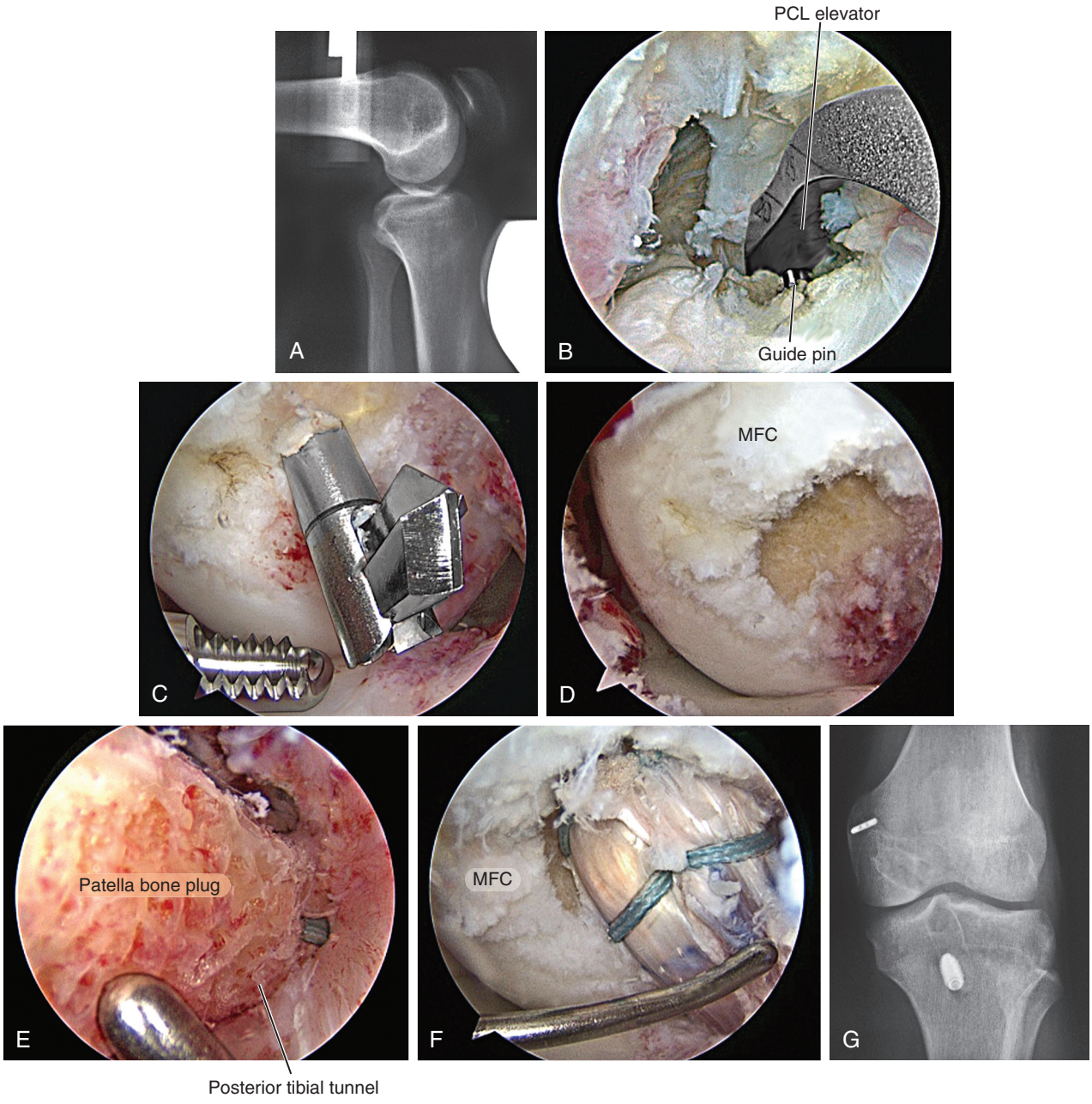


FIG 16-32 A 19-year-old male athlete presented with chronic posterior cruciate ligament (PCL) rupture and giving-way symptoms. An all-inside quadriceps tendon-patellar bone autograft was elected because of the athletic status of the patient. **A,** Stress radiograph shows abnormal posterior tibial subluxation. **B,** The arthroscope placed in the anteromedial portal views the PCL fossa. The PCL elevator rests on the posterior attachment of the capsule at the posterior tibial ridge. This shows that an excellent exposure can be obtained through the anteromedial portal, without requiring a posteromedial portal. The guide pin is shown exiting 5 mm above the posterior capsular attachment. **C,** The FlipCutter (Arthrex) is placed at the center of the PCL attachment on the femur for a single-tunnel construct (see text for description of placement). **D,** The femoral PCL tunnel occupies at least 75% of the PCL attachment. **E,** The bone plug is passed into the tibial tunnel through an enlarged anterolateral portal. **F,** The QT is passed into a 30-mm long femoral tunnel, using a TightRope suture construct. A soft tissue interference screw is also used for added fixation strength at the femoral site. **G,** Postoperative radiograph. *MFC,* Medial collateral ligament; *PCL*, posterior cruciate ligament.

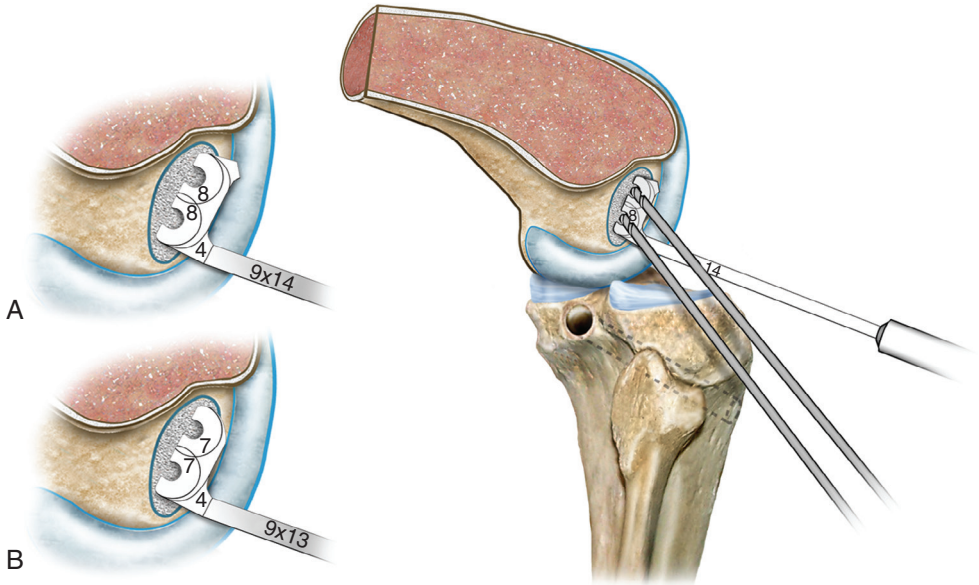


FIG 16-33 A and **B,** All-inside femoral tunnel. The PCL femoral template (Acufex) is placed through the anteromedial portal with the arthroscope in the central portal that defines the position of two overlapping 7- or 8-mm tunnels. The top edge of the template is placed 2 mm from the articular margin and the bottom edge is 4 mm from the articular margin. This places the center of the anterior tunnel 6 to7 mm from the articular cartilage margin and the center of the posterior tunnel 8 mm from the articular cartilage margin.

CRITICAL POINTS Alternative Posterior Cruciate Ligament All-Inside Techniques: Femoral Placement of Rectangular (Oval) Tunnel for Bone Plug

- Bone plug placed at femoral site using rectangular femoral slot or femoral tunnel, soft tissue graft placed through tibial tunnel.
- Use when operative time is a factor, revision knees.
- Goal: create 9 × 13 mm rectangular slot that extends from 1 to 4 o'clock in distal two-thirds of PCL attachment.
- Mark 12 o'clock, 4 o'clock positions on medial femoral condyle.
- 2.4-mm guide pin placed through anterolateral portal, knee flexed 90 degrees, and advanced through medial femoral condyle 25 mm in depth.
- Place second guide pin, overream with endoscopic drill.
- Avoid lateral femoral condyle articular cartilage as the drill is introduced into knee joint.
- Single femoral tunnel: consider FlipCutter.
- Chamfer and rasp distal aspect of femoral oval opening.
- Femoral fixation: interference screw.
- Tibial fixation: soft tissue interference screw and suture post.

fixation at the femoral site. As noted, the senior author prefers to reverse the graft with the bone plug at the posterior tibial tunnel.

The patient's positioning and initial surgical approach are similar to the all-inside technique described. The posterior PCL stump is removed and PCL tibial attachment is prepared for one tibial tunnel.

The technique for the femoral PCL graft attachment of the bone portion of the graft involves using a rectangular femoral slot or a femoral tunnel. The all-inside technique for the rectangular slot has a theoretical advantage of placing a greater portion of the graft within the PCL femoral footprint, in which approximately 75% of the footprint is occupied by the graft.

The goal is to create a 9 × 13 mm rectangular slot that extends from 1 to 4 o'clock in the distal two-thirds of the PCL footprint. The 12 and 4 o'clock marks are made on the medial femoral condyle. Again, the guide pin mark is 7 to 8 mm from the articular cartilage of the medial femoral condyle for the anterior and posterior tunnels (Fig. 16-33), verified by observing the PCL footprint and the two tunnels in the distal two-thirds of the footprint. A small curette or awl is used to penetrate and define the pilot hole for each tunnel. A 2.4-mm guide pin is placed through the anterolateral portal into the anterior tunnel location, the knee is flexed to 90 degrees, and the guide pin is advanced through the medial femoral condyle, approximately 25 mm deep, based on the patellar bone length.

The second guide pin is placed into the second marked position. The guide pins are overreamed with an endoscopic drill (Fig. 16-34) to form an oblong tunnel entrance to a depth that corresponds to the graft bone. Care is taken to avoid the lateral femoral condyle articular cartilage as the drill is introduced into the knee joint. The remaining central bone bridge is removed with a curette or burr.

The PCL Dilator (Fig. 16-35) produces an oval 9 × 13 mm shape that is approximately 1 mm larger than the bone portion of the graft. Care is taken to use low forces in dilating the rectangular slot to avoid fracture of the femoral condyle. In the senior author's experience, this has not been reported; however, it is worth a cautionary note. The PCL Dilator has a graft sizing slot on the handle for a 9 × 13 mm bone block that is used in preparation of the graft. The distal aspect of the femoral oval opening is chamfered and rasped to create a gentle slope to limit graft abrasion.

The passage of the graft (Fig. 16-36), conditioning, and final fixation are the same as already described. The femoral bone is fixed first with an interference screw and the tibia portion of the graft is fixed next with a soft tissue interference screw and suture post (Fig. 16-37). The option exists to use two graft strands that are tensioned separately in the tibial tunnel; however, there are no data to determine whether this is required.

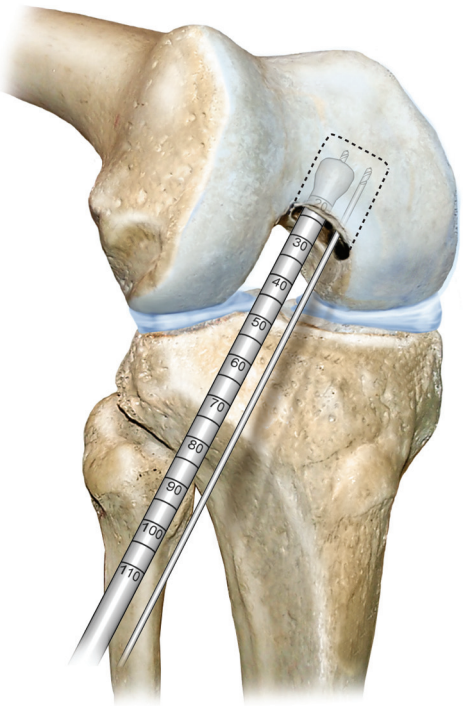


FIG 16-34 The guide pins are placed and then overreamed with an endoscopic drill to a depth of 25 mm, avoiding passage of the drill through the femoral cortex. The central bone bridge is removed with a curette and burr.



FIG 16-35 The PCL dilator (Acufex) is used to gently conform the femoral oval footprint to 9 × 13 mm and to an appropriate depth. There is a matching oval opening in the PCL dilator handle of 9 × 13 mm to size the bone block.

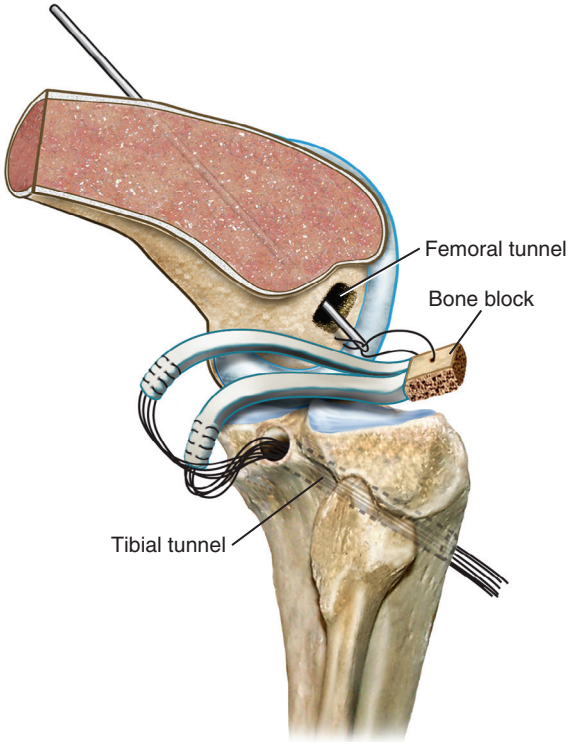


FIG 16-36 All-inside graft passage. A 20-gauge wire is passed through the tibial tunnel and grasped anteriorly through the anterolateral arthrotomy. The tibial portion of the graft is passed through the single tibial tunnel. The pin is then passed through the anterolateral portal into the femoral tunnel. The bone block is passed through the enlarged anterolateral portal and carefully oriented into the correct position with the cancellous bone surface oriented deep in the oval opening.

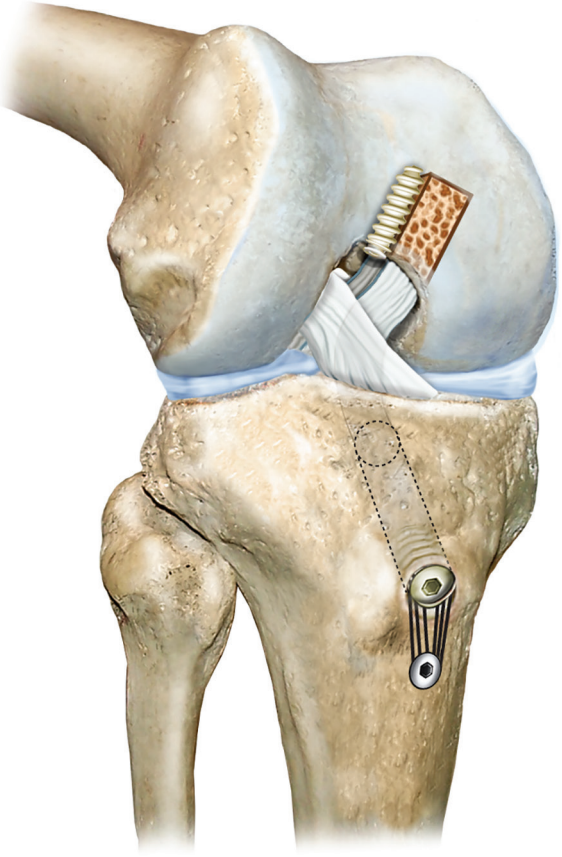


FIG 16-37 The final configuration of the single-tunnel technique.



FIG 16-38 Patient positioning. The patient is in a supine position with an inflatable beanbag, safety belt, and kidney rest (not shown) to secure the patient to the operating table.

Posterior Cruciate Ligament Arthroscopic-Assisted Open Tibial Inlay Technique

Patient Positioning and Setup

An examination under anesthesia of both knees is performed to confirm the preoperative diagnosis and detect any subtle instability. The medial tibiofemoral step-off at 90 degrees of flexion with a posterior tibial load is noted and the joint is reduced to normal and compared with the uninvolved knee. The reduced position and normal medial tibiofemoral step-off will later be reproduced with graft tensioning. Varus-valgus and tibial rotation tests for joint subluxation are performed as already described and compared between involved and uninvolved knees as concurrent ligament injuries, particularly to the posterolateral structures, are frequent and require reconstruction.

The patient is placed in a supine position on an inflatable beanbag (Fig. 16-38). The distal end of the beanbag is placed at the gluteal crease so it does not interfere with the tourniquet and the external rotation of the lower limb during the posteromedial tibial inlay approach. The beanbag is inflated and contoured to the patient's thorax and pelvis. A safety belt and kidney rest are placed to further secure the patient to the operating table when it is externally rotated (operative side down) during the posteromedial approach. A thigh tourniquet is placed over cast padding and only used intermittently for short periods during graft harvest and the posteromedial approach. The table is reflexed at its midpoint to decrease spine hyperextension, produce mild hip flexion, and prevent tension on the femoral nerve from a hip hyperextension position. The opposite extremity is placed in a thigh high compression hose and posterior padded leg support to avoid hip hyperextension or abnormal pressures on the posterior thigh during operative procedure.

The correct positioning of the operative extremity deserves special emphasis as described. During prolonged arthroscopic-assisted procedures, pressure on the posterior thigh may interfere with the vascular supply of the biceps muscle and peroneal nerve, and although rare, muscle necrosis and nerve injury have been reported. A leg holder is not used unless a meniscus repair is required, at which time the leg holder is used initially to allow adequate tibiofemoral joint opening, and is then removed for the remainder of the operative procedure.

CRITICAL POINTS Posterior Cruciate Ligament Arthroscopic-Assisted Open Tibial Inlay Technique

- Note medial tibiofemoral step-off 90 degrees of flexion with posterior tibial load, reduce joint to normal, compared with uninvolved knee.
- Patient supine position on beanbag, inflated and contoured to patient's thorax and pelvis.
- Use safety belt and kidney rest, table externally rotated (operative side down) during posteromedial approach.
- Thigh tourniquet used for short periods during graft harvest and posteromedial approach.
- Emphasis on correct positioning and padding, no leg holder used.
- Perform initial arthroscopic procedure, regulate pressure with inflow and outflow arthroscopic pump, and monitor joint distention continuously.
- Identify PCL femoral attachment, graft location as in all-inside technique.
- Use VMO approach for femoral tunnels with outside-in technique.
- Pass 22-gauge wire through femoral tunnels into the posterior aspect of the knee adjacent to PCL fossa for later graft passage.
- Patient supine, partial figure-four knee position (45 degrees of external hip rotation, 45 degrees of knee flexion).
- 7- to 8-cm longitudinal incision, 2 cm proximal to knee flexion crease, distally over medial head of gastrocnemius, posterior border of semitendinosus tendon.
- Protect saphenous nerve, posterior to the sartorious muscle and the infrapatellar branches crossing the sartorius superficially.
- Incise fascia along posterior border of semitendinosus tendon and medial border of the gastrocnemius.
- Dissect between semimembranosus muscle and gastrocnemius tendon.
- Maintain posterior exposure, avoid undue retraction forces on gastrocnemius and underlying neuromuscular structures.
- Subperiosteal dissection popliteus muscle at distal PCL fossa.
- Enter joint proximal and above semimembranosus tendon, avoiding medial meniscus attachments.
- Use Richardson retractor to retract medial gastrocnemius muscle. Replace with two Steinmann pins placed just lateral and distal to PCL fossa.
- Remove posterior tibial slot for inlay procedure.
- Placement, adjustment of position of PCL graft.
- Guide wires retrieved, strands passed beginning with 1 o'clock strand.
- Graft strands brought out respective femoral tunnels, positions adjusted proximal-distal direction.
- Tibial fixation graft bone with two 4.0-mm cannulated cancellous screws.
- Arthroscopically confirm proper placement both graft strands.
- Graft condition, tension, and confirmation isometric as described for all-inside technique.
- Tie each suture 44 N (10 lb) on each graft strand, 70 to 90 degrees of flexion, and 44-N (10-lb) anterior tibial load to produce a normal medial tibiofemoral step-off.
- Soft tissue interference screw added each tunnel.
- Arthroscopically confirm tension, fixation, and return of stability.
- Graft patellar defect.
- Soft hinged knee brace locked at 5 degrees of flexion with a 3-inch cotton roll behind proximal calf.

General anesthesia is used and a urinary catheter placed when multiple operative procedures will be performed and the anesthesia time prolonged. Even though all dislocated knees have vascular consultation and ankle-brachial index studies, if there is any question of diminished pulses or vascular supply, the foot is draped in a sterile plastic bag to allow palpation of pulses and observation of color during the operative procedure.

The initial arthroscopic procedure is performed to thoroughly examine the knee joint including patellofemoral tracking, articular cartilage lesions, and medial and lateral tibiofemoral joint opening "gap tests" to exclude associated ligament injuries. At this time, debridement or meniscus procedures are performed as required. A pressure regulated inflow and outflow arthroscopic pump is necessary and joint distention is monitored continuously by the surgeon. The arthroscopic pump is set to the lowest pressure and volume for visualization, which avoids the requirement of a tourniquet.

The autograft harvest procedure or preparation of the allograft is completed as described.

Identification of the Femoral Posterior Cruciate Ligament Attachment: Vastus Medialis Obliquus Approach

The identification of the femoral PCL attachment has been described in the previous all-inside two-tunnel technique section. The femoral tunnels are prepared as described using a VMO outside-in approach. Two 22-gauge wires are passed and placed by arthroscopic visualization adjacent to the PCL tibial attachment posteriorly to be later brought out through the posteromedial capsular incision.

Posteromedial Approach

With the patient in a supine position, the posteromedial aspect of the knee is viewed by rolling the table 25 degrees with the operative side in the down position.[151,160,168] The tourniquet is inflated. A partial figure-four knee position is assumed (45 degrees of external hip rotation, 45 degrees of knee flexion). The operative limb is elevated and the foot placed on a padded (pillow) Mayo stand to lift the knee away from the table. An assistant externally rotates the foot and controls the lower limb position on the Mayo stand during the procedure. The surgeon and assistant are seated at the side of the operative table directly viewing the entire posteromedial aspect of the knee. Operative headlights are used.

An alternative approach is for the surgeon to be seated between the patient's lower extremities by flexing the knee portion of the table and elevating the nonoperative limb into a flexed and abducted position. The senior author has not found it necessary to use this position. In either of the two limb positions, one person must be dedicated to maintain the operative limb in a safe elevated and externally rotated position supported by the padded Mayo stand.

Numerous surgical approaches that provide access to the popliteal fossa PCL tibial attachment have been described.[1,14,15,24,143,145,215] These approaches use either an S-shaped popliteal incision,[14] an L-shaped popliteal incision,[24,145] or a medial incision.[119,148] The senior author recommends a medial incision as described to avoid the popliteal neurovascular structures.

A 7- to 8-cm longitudinal incision, beginning approximately 2 cm proximal to the flexion crease of the knee, is carried distally over the medial head of the gastrocnemius and the posterior border of the semitendinosus tendon (Fig. 16-39). The straight posteromedial incision, compared with an S-shaped popliteal incision, avoids the horizontal popliteal skin crease with less skin retraction necessary and possible wound breakdown.[145]

Dissection is carried down sharply through the skin and subcutaneous tissues. Care is taken to protect the saphenous nerve posterior to the sartorius muscle and the infrapatellar branches that cross the sartorius superficially. The long saphenous vein and the saphenous branch of the descending genicular artery follow the course of the saphenous nerve and are protected as well. The gracilis and semitendinosus lie deep to the sartorius and are palpated.

The first key to the approach is to incise the fascia[228] along the posterior border of the semitendinosus tendon adjacent to the medial

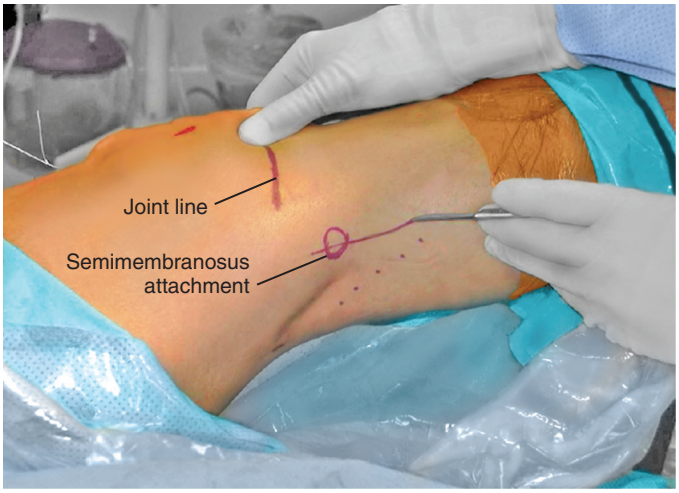


FIG 16-39 Intraoperative photograph of the left knee with the lower extremity in a figure-four position. The longitudinal incision begins approximately 2 cm proximal to the flexion crease of the knee. The incision is carried distally over the medial head of the gastrocnemius and the posterior border of the semitendinosus tendon. (From Noyes FR, Medvecky MJ, Bhargava M. Arthroscopically assisted quadriceps double-bundle tibial inlay posterior cruciate ligament reconstruction: an analysis of techniques and a safe operative approach to the popliteal fossa. *Arthroscopy*. 2003;19:894-905.)

border of the gastrocnemius muscle. The three pes tendons are then retracted anteriorly (taking the saphenous nerve) and the semimembranosus tendon is visualized (Fig. 16-40).

The second key to the procedure is the dissection between the semimembranosus muscle and the gastrocnemius tendon. Understanding the anatomy of the posteromedial corner of the knee and the semimembranosus is important to obtain good exposure by mobilization of the semimembranosus tendon for the next portion of the dissection. The dissection uses the interval between the medial border of the gastrocnemius and the posterior border of the common semimembranosus tendon. To mobilize the semimembranosus medially and improve exposure, the tendon sheath extensions are incised to allow full mobilization of the semimembranosus tendon (Fig. 16-41). Anterior to the semimembranosus, the posterior oblique ligament is partially incised from the attachment to the semimembranosus tendon to improve exposure. These capsular attachments are later repaired at the end of the procedure. With lateral retraction of the medial gastrocnemius, the inferolateral semimembranosus tendon sheath expansion to the popliteus is visualized and dissected from its attachment to the posterior border of the common semimembranosus tendon. In this way, the insertion of tendon directly onto the posteromedial tibia is exposed.

The third key is maintaining the posterior exposure and avoiding undue retraction forces on the gastrocnemius and underlying neuromuscular structures. An S-shaped retractor is placed extraarticularly between the semimembranosus tendon and the medial femoral condyle and levered anteriorly, allowing for anterior retraction of the semimembranosus and pes anserinus tendons and muscle bellies. The medial head of the gastrocnemius is carefully retracted laterally with a Richardson retractor, allowing for exposure of the popliteus muscle belly on the posterior tibia. Care must be exercised at this juncture in the procedure, as undue retraction can avulse branches off the popliteal artery.

The neurovascular structures are not visualized and remain medial to the gastrocnemius muscle (medial head). The anterior tibial artery

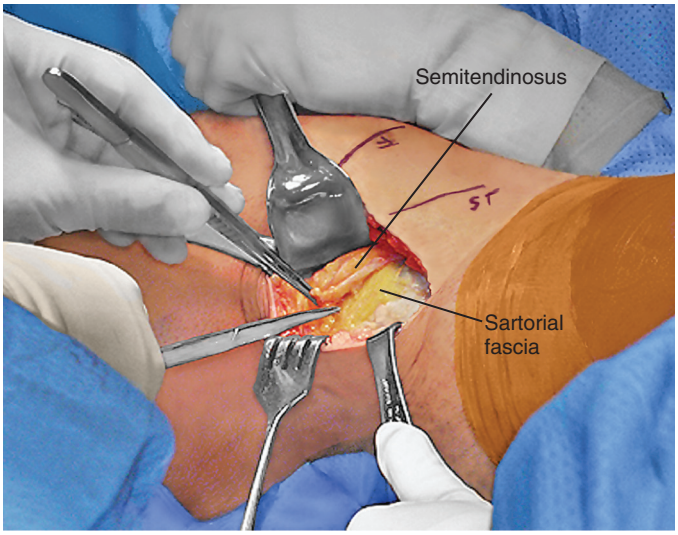


FIG 16-40 Surgical exposure of the left knee shows the development of the interval between the semitendinosus (ST) tendon and the gastrocnemius muscle belly. The sartorial fascia is incised along the posterior border of the ST tendon. The forceps is on the ST tendon. During the superficial dissection, care is taken to protect the main trunk as well as superficial branches of the saphenous nerve. The infrapatellar branch of the saphenous nerve is vulnerable as it superficially crosses the sartorius. (From Noyes FR, Medvecky MJ, Bhargava M. Arthroscopically assisted quadriceps double-bundle tibial inlay posterior cruciate ligament reconstruction: an analysis of techniques and a safe operative approach to the popliteal fossa. *Arthroscopy.* 2003;19:894-905.)

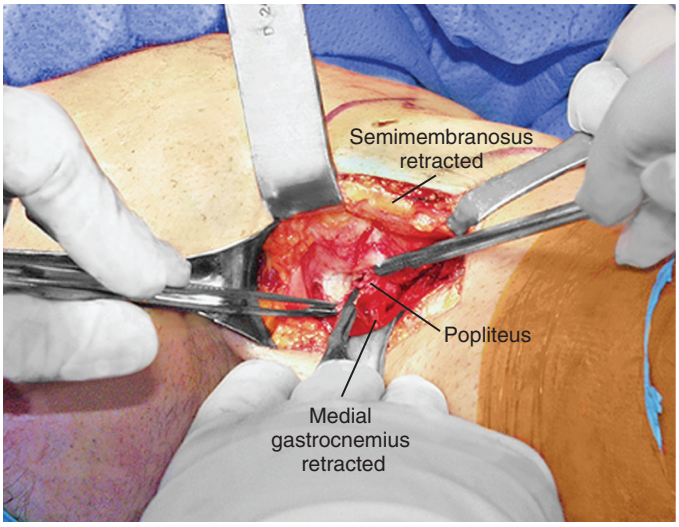


FIG 16-41 Surgical exposure shows the popliteus muscle exposure. The gastrocnemius muscle belly is retraced laterally and the pes tendons and the semimembranosus muscle are retracted by an S-shaped retractor away from the popliteal space, exposing the posterior cruciate ligament fossa. Caution must be exercised with the lateral retraction of the gastrocnemius muscle because the neurovascular structures are not fully protected and the retractor should not be placed deep to the gastrocnemius muscle belly. (From Noyes FR, Medvecky MJ, Bhargava M. Arthroscopically assisted quadriceps double-bundle tibial inlay posterior cruciate ligament reconstruction: an analysis of techniques and a safe operative approach to the popliteal fossa. *Arthroscopy.* 2003;19:894-905.)

may lie directly on the popliteal muscle over the PCL fossa, or pierce the popliteal muscle just distal to the PCL fossa as already described (see Fig. 16-13).

The fourth key to the procedure is the subperiosteal dissection of the popliteus muscle. Care is taken to gently dissect the popliteal muscle superior border in a distal direction to allow better subperiosteal exposure to the posterior tibia and PCL fossa for later placement of the tibial inlay graft. The inferior medial genicular artery and vein are at the superior border of the popliteus muscle and are easily identified and protected during this step, as the dissection is in a subperiosteal plane anterior and deep to the genicular artery.

Identification of Posterior Tibial Posterior Cruciate Ligament Attachment

The PCL tibial attachment site is palpated as a midline depression in the proximal tibial metaphysis, between the two tibial condyles. The width of the PCL is approximately 15 mm[63] and the distal extent of the PCL is marked by a small ridge (posterior tibial step-off) that coincides with the proximal border of the popliteus.[183]

The fifth key to the exposure is to enter the joint proximal and just behind the semimembranosus tendon, avoiding the medial meniscus attachments. The posterior slope of the proximal tibia and the PCL fossa are palpated and the posterior capsule and OPL are incised sharply, starting proximal and superior on the lateral aspect of the medial femoral condyle. The posterior portion of the medial femoral condyle is easily palpated. The posterior capsule just lateral to the medial femoral condyle is incised. The joint is entered directly over the inner aspect of the medial femoral condyle to establish from proximal-to-distal a safe plane of dissection (Fig. 16-42; see also Fig. 16-41). The dissection of the capsule is performed in the midline directly over the PCL fossa with care at the joint line to avoid injury to the posterior medial meniscus tibial attachment. This capsular incision is extended distally and connected to the popliteus subperiosteal exposure, which will be closed at the conclusion of the procedure. The entire PCL tibial attachment site is easily identified. The remaining PCL stump is removed.

The sixth key to the exposure involves the Richardson retractor, used to retract the medial gastrocnemius muscle that is replaced with two Steinmann pins placed under direct vision just lateral and distal to the PCL fossa. The pins allow for excellent exposure during the tibial inlay procedure and avoids undue lateral retraction and pressure against the neurovascular structures by the surgical assistant.

The seventh key is the removal of the posterior tibial slot for the inlay procedure. A 10-mm osteotome is used to cut a rectangular slot into the PCL fossa at the proximal tibia. The slot is started 1 cm distal to the normal PCL attachment, which allows for the proximal bone block and collagenous portion of the graft to assume a normal anatomic position and preserve the proximal 15 mm of the PCL fossa. The posterior interspinous tibial bone just proximal to the PCL fossa is preserved to prevent a vertical PCL graft orientation. The rectangular bone block of the graft is placed flush into the inlay, avoiding too deep of a slot, which would produce a vertical PCL graft.

The eighth key is the placement and adjustment of the position of the PCL graft. The previously positioned guide wires are retrieved from the posteromedial capsular recess within the joint. The two strands of the sagittally split graft are identified (lateral arm, 1 o'clock tunnel; medial arm, 3 o'clock tunnel) and are passed individually starting with the 1 o'clock graft strand (Fig. 16-43). Care is taken that there is no soft tissue or native PCL fibers so the graft strands lie directly against the posterior tibial PCL fossa in a normal anatomic position.

The two graft strands are brought out of their respective femoral tunnels and the position of the overall graft position is adjusted 5 to

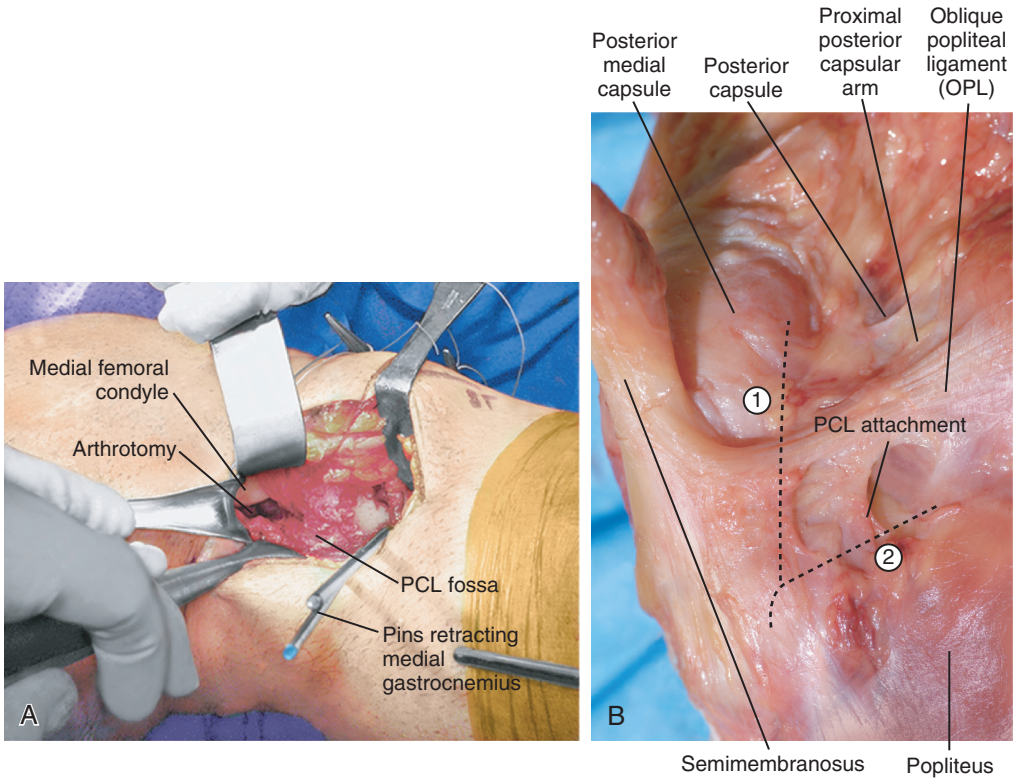


FIG 16-42 **A,** Surgical exposure shows the posterior arthrotomy over the inner aspect of the medial femoral condyle. The suture-passing wires are retrieved from within the joint. Care is taken during the arthrotomy to avoid injury to the medial meniscus. The subperiosteal dissection is carried to the lateral ridge of the posterior cruciate ligament (PCL) fossa to allow for creation of the tibial slot at the anatomic PCL attachment site. An S-shaped retractor assists in positioning the semimembranosus out of the operative field, allowing for better visualization of the PCL fossa. The creation of the subperiosteal popliteus flap adds an additional layer of protection and provides a safer exposure, because vascular anatomic variations may exist. Two Steinmann pins allow for retraction of the popliteus and gastrocnemius muscle. **B,** Anatomic specimen shows line of incision into posteromedial capsule and superior to popliteal muscle to expose PCL tibial attachment. (From Noyes FR, Medvecky MJ, Bhargava M. Arthroscopically assisted quadriceps double-bundle tibial inlay posterior cruciate ligament reconstruction: an analysis of techniques and a safe operative approach to the popliteal fossa. *Arthroscopy*. 2003;19:894-905.)

10 mm by observing the graft strand in the femoral tunnel (VMO approach). The graft position is adjusted in a proximal-distal direction to ensure the collagen graft strands have the appropriate length for the femoral tunnels. In the alternative procedure, when a bone-patella tendon-bone (B-PT-B) graft is used (rather than a QT-PB graft), too proximal a placement of the tibia inlay allows the bone plug to protrude from the femoral tunnel proximally, compromising interference screw fixation. If the placement of the tibial inlay is too distal, it may shorten the graft in the femoral tunnels, also compromising femoral graft fixation. Visualization of both strands of the graft with an outside-in femoral tunnel approach allows for proximal-to-distal graft positioning and final fixation.

Tibial fixation of the graft bone is achieved with two 4.0-mm cannulated cancellous screws. The guide wires for the cannulated drill bit are angled distally to avoid intraarticular penetration, especially as the knee is positioned in a flexed position. A lateral radiograph may be taken intraoperatively to confirm the position of the screws. The length of the screws is usually 30 to 35 mm for adequate purchase.

The capsulotomy is closed, the Steinmann pins removed and the posteromedial capsule incision and OPL repaired (Fig. 16-44). The tourniquet is deflated and hemostasis verified. Vascular clips are available should the inferior medial genicular artery or other bleeding sources be identified. The subcutaneous tissues and wound are not closed at this stage to allow for any extravasation of fluid during the final arthroscopic portion of the procedure. After graft fixation, the posteromedial wound is closed in a routine fashion.

Graft Conditioning, Tensioning, and Fixation

Arthroscopic visualization of the graft confirms proper placement of both strands before fixation. The graft tensioning and fixation steps have been previously described in detail in the all-inside technique. A staple post is placed proximal to the femoral tunnels. Fixation is accomplished by tying each suture with approximately 44 N (10 lb) on each graft strand, at 70 to 90 degrees of flexion, and a 44-N (10-lb) anterior tibial load to produce a normal medial tibiofemoral step-off, which is confirmed. A soft tissue absorbable interference screw is added for each tunnel (Fig. 16-45). Arthroscopic evaluation of the graft confirms tension, fixation, and return of stability.

The patellar defect is carefully grafted with bone from the core reamer as described. The anteromedial and posterolateral approaches are closed. The knee is carefully padded in a sterile compression

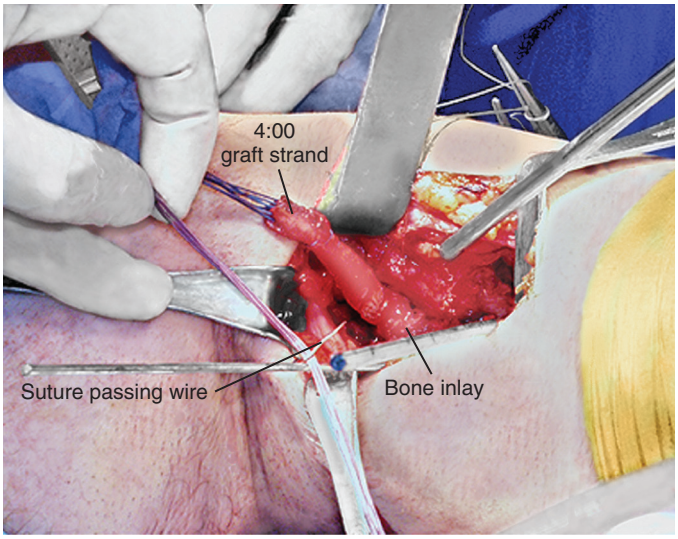


FIG 16-43 Surgical exposure shows placement of the quadriceps tendon autograft. The rectangular bone portion of the graft has been fixated to the proximal tibia with two 4.0-mm partially threaded cancellous screws. The sutures on the medial and lateral graft strands will be pulled intraarticularly with the suture-passing wires. The graft strands lay directly against the posterior tibia, recreating the normal anatomic posterior cruciate ligament tibial attachments. (From Noyes FR, Medvecky MJ, Bhargava M. Arthroscopically assisted quadriceps double-bundle tibial inlay posterior cruciate ligament reconstruction: an analysis of techniques and a safe operative approach to the popliteal fossa. *Arthroscopy.* 2003;19:894-905.)

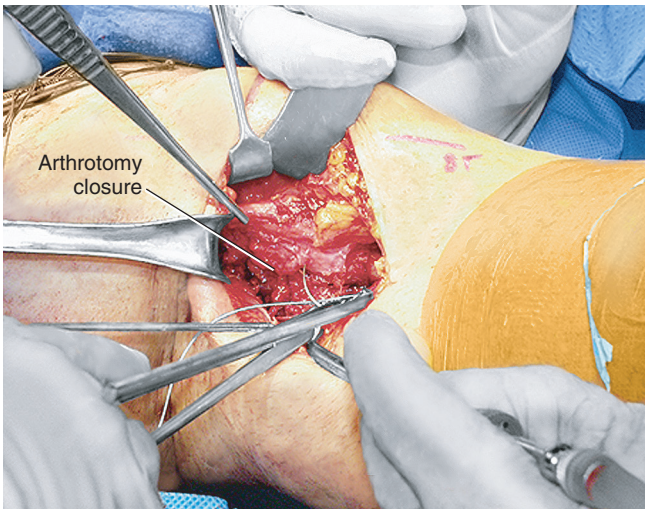


FIG 16-44 Surgical exposure shows the closure of the semimembranosus sheath and posterior arthrotomy. The skin incision is only partially closed at this point to allow for potential fluid extravasation during the final arthroscopic portion of the procedure. (From Noyes FR, Medvecky MJ, Bhargava M. Arthroscopically assisted quadriceps double-bundle tibial inlay posterior cruciate ligament reconstruction: an analysis of techniques and a safe operative approach to the popliteal fossa. *Arthroscopy.* 2003;19:894-905.)

dressing. The lower extremity is placed in a soft hinged knee brace locked at 5 degrees of flexion, with a 3-inch cotton roll placed behind the proximal calf to prevent posterior sagging of the tibia. The neurovascular status is confirmed to be normal before leaving the operating room.

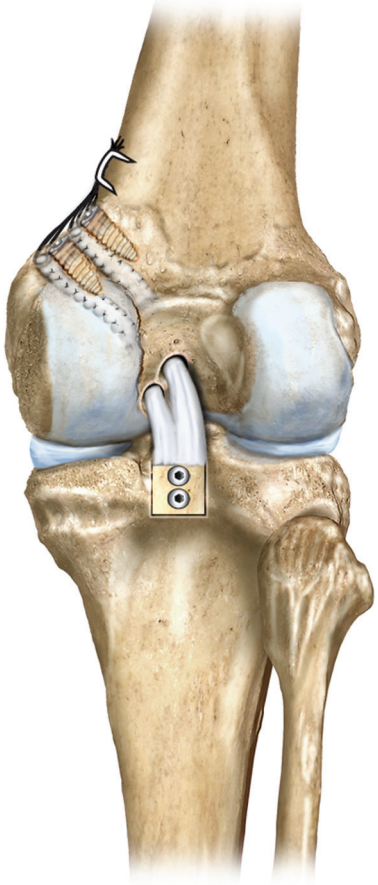


FIG 16-45 The final tibial and femoral fixation of the quadriceps tendon-patellar bone two-strand graft.

Posterior Cruciate Ligament Avulsion Fractures

Avulsion fractures of the PCL are rare, and treatment options depend on the type and size of the fracture, displacement, comminution, and orientation of the fragment.[67,234] These injuries typically occur at the tibial attachment and may involve a small area at the posterior region of the attachment or a large area that extends anteriorly and outside the PCL attachment. Griffith and colleagues[67] reported that the entire insertion area was avulsed in all 19 skeletally mature patients in their series of PCL avulsion fractures. The avulsion fracture is usually obvious on routine radiographs. Occasionally, a computerized tomography scan or MRI is required to define the extent of the facture pattern in major avulsion fractures extending into the joint.[28,67] Avulsion or peel-off PCL injuries at the femoral site have been reported in the literature, but are rare.[62,125,176,186,232]

Patients who have small, partial PCL avulsion fractures, with a negative posterior translation test at 90 degrees of knee flexion, are kept in a brace locked in full extension and remain partial weight bearing for 4 weeks to allow healing. The brace is removed for gentle range of motion (avoiding posterior tibial translation) and quadriceps exercises as described in Chapter 18. Overall, the prognosis for healing and PCL function is good to excellent in these cases.[246]

Complete avulsion of the PCL attachment at the tibia, and less frequently, at the femoral attachment (peel-off avulsion) with posterior tibial subluxation, is an indication for surgical repair. Authors have reported favorable clinical results with the open reduction and internal fixation of PCL avulsion fractures at the tibial insertion site.[8,84] For

CRITICAL POINTS Posterior Cruciate Ligament Avulsion Fractures

- Treatment based on type and size of the fracture, displacement, comminution, orientation of fragment.
- Small, partial avulsion fractures, negative posterior translation at 90 degrees of knee flexion: brace locked full extension, protected motion, partial weight bearing for 4 weeks to allow healing.
- Complete avulsion fractures: surgical repair. Use either arthroscopic or open technique based on experience.
- Large and medium avulsion fractures: arthroscopic approach, cannulated screw fixation.
- PCL tibial avulsions with small bony fragments: consider open posterior medial tibial approach.
- Peel-off PCL rupture from femoral attachment: repair PCL attachment with sutures passed through small drill holes, avoid physeal plate when still open.
- Our preferred technique: arthroscopic-assisted approach, repair PCL fibers to approximate broad elliptical femoral attachment.
- Postoperative protocol suture repair maximum protection, early motion by therapist.

instance, Inoue and associates[84] reported on 31 patients followed for 2 to 8 years and noted low side-to-side differences (<5 mm, KT-2000) after surgery. The majority of knees showed a mild residual posterior knee displacement (mean, 3.0 mm). Along with the tibial avulsion, an abnormal MRI signal intensity may be observed within the PCL fibers, indicating partial tearing.

More recently, several authors have described arthroscopic techniques for PCL tibial avulsion fractures.[28,36,70,81,105,201,225,240,246] Gui and associates[70] treated 28 patients using two posteromedial portals and a single tibial tunnel to facilitate suture passage and seating of the bony fragment. The knees were casted for 2 weeks unless a concomitant tibial plateau fracture was present, which necessitated 4 weeks of immobilization. The fractures healed a mean of 2.8 months postoperatively. At 1 year postoperative, four of 20 cases followed had arthrofibrosis, two of whom underwent arthroscopic release. The posterior drawer test was negative in all but one knee. International Knee Documentations Committee (IKDC) rating system[78] results were normal in 20 and nearly normal in four patients.

Zhao and colleagues[246] treated 29 patients with PCL tibial avulsion fractures. The PCL and bony fragment were arthroscopically fixed with sutures that were pulled out through Y-shaped bone tunnels and fixed on a titanium button. Immediate knee motion and partial weight bearing were allowed in a brace that was used for the first 4 weeks. Four patients required a manipulation 3 months after surgery for flexion limitations. At follow-up (>2 years postoperatively), all patients except one had a negative posterior drawer test, and all regained full knee motion except for two patients who had 5 degrees of flexion limitations. IKDC results were normal in 28 patients and nearly normal in one patient.

Zhang and associates[245] treated isolated PCL tibial avulsion fractures in 16 patients (mean age, 43 years) with a minimally invasive posteromedial approach and suture anchors. The patients all had displaced fractures that exceeded 1 cm and fracture fragments less than 2 cm in diameter. Plaster splints were used for 4 to 6 weeks. At a mean of 18 months postoperatively, all cases showed satisfactory reduction and bony healing and all but one patient had returned to their former occupation.

Chen and coworkers[36] treated 36 patients with displaced PCL tibial avulsion fractures (>3 mm of upward displacement of the bony fragment) and posterior knee instability of grade II or higher. Arthroscopic reduction and suture fixation of the bone fragments was accomplished through two tibial tunnels. The knees were immobilized in a brace the first postoperative week, followed by 0 to 60 degrees of motion during weeks 2 to 4 and 120 degrees by week 8. All fractures demonstrated union within 3 months. At a mean of 3 years postoperatively, all but three patients were participating in strenuous or moderate activities, 92% rated their knee function as normal or nearly normal, and three patients (8%) were rated as abnormal because of limitations in knee flexion.

The concept of immediate postoperative knee motion is addressed in detail in Chapter 18. The therapist initiates early and protected knee motion within the first postoperative week, applying an anteriorly directed load to protect the relatively weak suture fixation. The use of a posterior calf pad and careful positioning in the brace is required for the first 4 postoperative weeks until suitable healing has occurred. Knees with suture or pin fixation have relatively low tensile strength repairs and require expert postoperative rehabilitation.

The surgeon should select either an arthroscopic or open technique for tibial avulsion fractures based on experience. In general, it is relatively straightforward to use an arthroscopic approach for cannulated screw fixation for large and medium avulsion fractures. For PCL tibial avulsions with small bony fragments that require a combination of sutures and bone fixation, an open posterior tibial approach is favored by the senior author because it provides good exposure and allows for secure fixation.

A peel-off type of PCL rupture from the femoral attachment has been described as a hyperextension knee injury, such as that reported by Mayer and Micheli[142] in a child while jumping on a trampoline or in patients suffering from trauma from motor vehicle accidents.[37,176] This type of PCL rupture directly at the femoral attachment may occur at the fibrocartilaginous junction, with minor associated damage to the bulk of the PCL fibers. The PCL attachment is easily repaired with sutures passed through small drill holes, avoiding the proximal physeal growth plate. Arthroscopic approaches to PCL femoral soft tissues avulsions have been described by several authors,[62,176,186,232] although clinical data remain scarce. Ross and associates[186] described an arthroscopic approach for repair of acute femoral peel-off tears. Three No. 2 nonabsorbable sutures were passed through the PCL substance, through a femoral tunnel at the PCL footprint, and tied over the medial cortex. Park and Kim[176] reported an arthroscopic technique that used two transfemoral tunnels for the anterior strand and two posterior tunnels for suture repair of the posterior strand. These authors noted that femoral avulsion injuries were exceedingly rare.

The senior author's preferred technique for femoral peel-off or proximal PCL repairs is to use an arthroscopic-assisted approach in which two to three guide pin tunnels (small-diameter for sutures) are placed at the anterior and posterior aspects of the PCL footprint, distal to the physis, to fan out the PCL fiber attachment. A VMO-sparing approach is used and respective suture passers are brought into the knee joint. Through a limited medial arthrotomy and under direct visualization using a headlight, multiple nonabsorbable baseball looped sutures are placed at appropriate sites in the PCL fibers to approximate the broad elliptical femoral PCL attachment. The miniarthrotomy has limited morbidity and allows the surgeon to carefully place multiple sutures into the broad PCL fibers. Secure fixation is achieved along with anatomic placement of disrupted PCL fibers.

In PCL injuries that extend away from the femoral attachment and involve the proximal third of the PCL fibers, an augmentation is favored (assuming the growth plate is closed). The postoperative protocol for a direct suture repair should take into account the low repair tensile strength, requiring maximum protection. The knee is

maintained in full extension and the therapist assists in gentle range of knee motion for the first 4 weeks postoperatively. Only toe-touch weight bearing is permitted during this time period. Then, the patient may progress to 50% weight bearing with the brace locked at full extension. At 6 weeks postoperative, weight bearing is progressed in the brace. Knee motion is advanced to 0 to 90 degrees. The brace is removed at 8 weeks.

Posterior Cruciate Ligament Augmentation Approaches and Techniques

In select knees, an acute tear of the PCL may occur at the proximal third femoral attachment (and not through the midsubstance). A considerable bulk of the PCL attachment still exists and may be repaired to the femoral attachment, as discussed for the "peel-off" type of tear. In these cases, it is worthwhile to add a graft augmentation to the attachment site, which may be performed in an arthroscopic-assisted manner (assuming the growth plate is closed). An 8-mm femoral tunnel is placed at the desired site where the PCL fibers require a graft augmentation, usually in the more proximal aspect of the femoral attachment.

Sutures are used to repair the more distal fibers to the femoral attachment as already described. The placement of an 8-mm tibial tunnel must be well chosen and not interfere with the PCL attachment site. The tunnel is placed just medial to the tibial PCL attachment, carefully avoiding the medial and lateral meniscal attachments. A lateral tibial tunnel is not used because PCL fibers attach, in part, to the posterolateral meniscus tibial attachment. We prefer a three- or four-strand semitendinosus-gracilis (STG) autogenous graft, although an allograft may also be considered.[6,44,93,115,226] Suture fixation to a femoral or tibial post, or absorbable interference tibial and femoral screws in adults, is required.

In skeletally immature knees, Kocher and associates[107] reported the use of a small-diameter graft placed through the distal femoral and proximal epiphysis, avoiding the physeal plate. An augmentation graft has the advantage of maintaining tibiofemoral reduction and preventing posterior tibial subluxation in the early postoperative healing period.

In very select knees with a prior PCL rupture and abnormal posterior tibial subluxation, the remaining PCL fibers may appear healed and intact, although with a residual elongation. Rarely, the senior author has performed a distal advancement of the tibial PCL attachment; this is only considered when the MRI shows a normal signal to the PCL fibers and arthroscopic examination shows also a normal-appearing PCL. The operative approach is similar to a tibial inlay procedure, except the native PCL tibial bone attachment is advanced distally the required amount to restore posterior stability. A proximal advancement (recession) at the femoral insertion is avoided owing to the marked influence of the PCL femoral attachment on PCL fiber function previously described.

CRITICAL POINTS Posterior Cruciate Ligament Augmentation Approaches and Techniques

- Indications: acute PCL tear at proximal third femoral attachment. Considerable bulk of PCL attachment still exists, may be repaired.
- 8-mm femoral tunnel placed, usually in proximal aspect of femoral attachment. 8-mm tibial tunnel placed just medial to tibial PCL attachment (closed physis).
- Prefer 3- or 4-strand STG, allograft may be considered.
- Rare cases of chronic PCL with normal-appearing PCL on MRI, residual PCL elongation: distal advancement similar to tibial inlay.

OUR CLINICAL STUDIES

In this section, the analysis of 130 knees with PCL deficiency that were placed into clinical investigations is reported. All of the studies involved a prospective consecutive patient enrollment, the minimum follow-up of each study was 2 years, and the results were evaluated by clinical research staff and not the surgeon. All patients were entered into the studies and then tracked with sequential follow-up appointments. The results were determined with posterior stress radiography and/or knee arthrometer testing, and two validated knee rating instruments (CKRS[13] and IKDC rating system[78]). More specific clinical outcome details are provided in the References section; this section provides a brief summary of the results and conclusions.

Posterior Cruciate Ligament Two-Strand Quadriceps Tendon-Patellar Bone Autograft Tibial Inlay

We[153] followed 20 consecutive patients that underwent a two-strand PCL QT-PB autograft reconstruction with a tibial inlay technique. All patients were included in the investigation except for one who lived outside the United States and who could not return for follow-up. Therefore the study group consisted of 19 patients who were followed a mean of 2.9 years (range, 2-7 years) postoperatively. The PCL

CRITICAL POINTS Our Clinical Studies: Posterior Cruciate Ligament Two-Strand Quadriceps Tendon-Patellar Bone Autograft Tibial Inlay Technique

- $n = 19$ consecutive knees followed mean 2.9 years (range, 2-7 years) postoperatively.
- PCL reconstructions mean 3.6 years (range, 0.3-18 years) after original knee injury.
- Prior PCL procedures done elsewhere had failed in 9 knees.
- Associated procedures: 5 posterolateral procedures, 2 ACL reconstructions, 2 MCL reconstructions, 1 meniscus transplant.
- Outcome assessment: stress radiography, KT-2000 testing, Cincinnati Knee Rating System, IKDC rating system.
- Stress radiographs: mean preoperative, 11.6 ± 2.9 mm; follow-up, 5.0 ± 2.6 mm ($P < .0001$).
- KT-2000 (70 degrees): mean preoperative, 10.4 ± 2.9 mm; follow-up, 2.3 ± 2.2 mm ($P = .004$).
- Preoperatively, all knees graded C or D on IKDC rating. At follow-up, 2 knees (10%) graded A; 12 knees (63%), B; 3 knees (16%), C; 2 knees (10%), D.
- Pain with ADL: preoperative, 58%; follow-up, 5%.
- 58% returned to mostly low-impact sports.
- Abnormal articular cartilage surfaces in 42%.
- Difference between patients with normal cartilage and those with abnormal cartilage in mean scores for patient rating of the overall knee condition, squatting, running.
- No infections, permanent limitations of knee motion, donor site problems, patellar fractures.
- 74% compounding problems articular cartilage damage, prior meniscectomy, additional ligament procedures, or osteotomy. Recommend early operative treatment be considered for PCL ruptures.
- Objective assessment of posterior stability demonstrated superior results compared with the single-bundle PCL allografts.

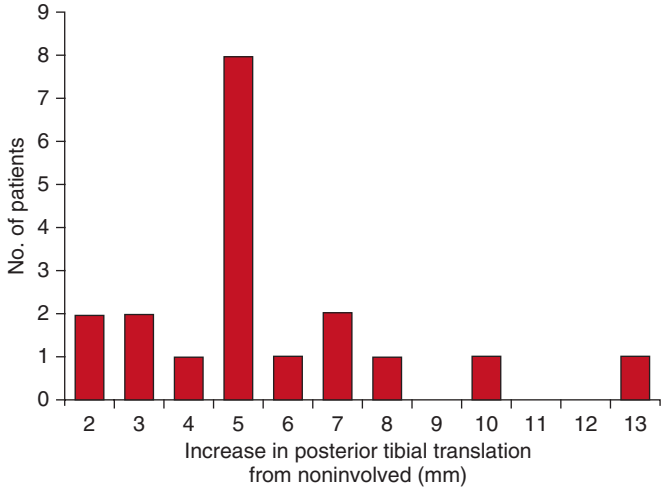


FIG 16-46 Distribution of residual posterior tibial translation at 90 degrees of knee flexion on stress radiography a mean of 2.9 years after posterior cruciate ligament quadriceps tendon-patellar bone two-strand autograft reconstruction with a tibial inlay technique. (From Noyes FR, Barber-Westin SD. Posterior cruciate ligament replacement with a two-strand quadriceps tendon-patellar bone autograft and a tibial inlay technique. *J Bone Joint Surg Am.* 2005;87:1241-1262.)

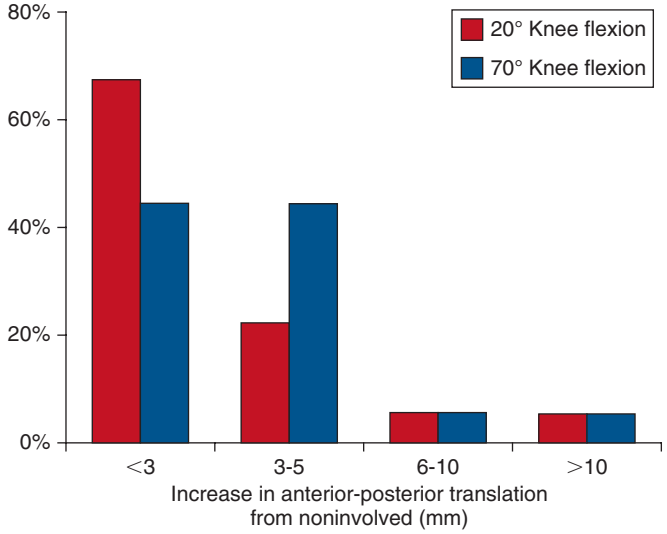


FIG 16-47 Distribution of residual total anterior-posterior translation on KT-2000 testing a mean of 2.9 years after posterior cruciate ligament quadriceps tendon-patellar bone two-strand autograft reconstruction with a tibial inlay technique. (From Noyes FR, Barber-Westin SD. Posterior cruciate ligament replacement with a two-strand quadriceps tendon-patellar bone autograft and a tibial inlay technique. *J Bone Joint Surg Am.* 2005;87:1241-1262.)

reconstructions were done a mean of 3.6 years (range, 0.3-18 years) after the original knee injury. In nine knees, prior PCL procedures had been done elsewhere and failed. The tibial inlay method was advantageous in these revision knees because prior tibial tunnels were avoided and bone grafting was not required. Associated procedures included posterolateral procedures in five knees, ACL reconstruction in two knees, MCL STG reconstruction in two knees, and meniscus transplantation[162] in one knee.

For all 19 knees, the mean increase in posterior tibial translation (compared with the contralateral knee) on stress radiography improved from 11.6 ± 2.9 mm preoperatively to 5.0 ± 2.6 mm at follow-up (mean ± standard deviation; $P < .0001$; Fig. 16-46). The mean increase in AP displacement on arthrometer testing improved from 10.8 ± 3.0 mm preoperatively to 2.0 ± 2.2 mm at follow-up ($P = .005$) at 20 degrees of flexion; and from 10.4 ± 2.9 mm preoperatively to 2.3 ± 2.2 mm at follow-up ($P = .004$) at 70 degrees of flexion (Fig. 16-47). All of the associated knee ligament procedures received an IKDC rating of A or B at follow-up.

Before surgery, 11 patients (58%) had pain with daily activities, but only one (5%) had such pain at follow-up. Eighteen patients (95%) rated the condition of the knee as improved. Significant improvements were noted for symptoms and limitations with daily and sports activities (Table 16-14). Eleven patients (58%) were participating in low-impact sports at follow-up without problems, and two were participating in more strenuous sports without problems. Two patients were participating with symptoms against advice. Three patients did not return to sports because of the knee condition, and one patient did not return to sports because of reasons not related to the knee condition.

Abnormal articular cartilage surfaces were found during the operation in eight knees; in the patellofemoral compartment in two knees, the medial tibiofemoral compartment in seven knees, and the lateral tibiofemoral compartment in one knee. A difference was noted between patients with normal cartilage and those with abnormal cartilage surfaces in the mean scores in the patient rating of the overall knee condition (7.3 ± 1.5 and 5.4 ± 2.2 points, respectively; $P = .05$), squatting (29 ± 11 and 10 ± 14 points, respectively; $P = .005$), and running (82 ± 21 and 57 ± 25 points, respectively; $P < .05$).

Eleven patients had an isolated PCL replacement, and eight had an additional knee ligament reconstruction. There was no difference in the mean millimeters of posterior tibial translation measured on stress radiography among these subgroups. There also appeared to be no difference in the mean pain or patient perception scores at follow-up among the subgroups.

There were no infections, permanent limitations of knee motion, donor site problems, or patellar fractures. One patient required an arthroscopic lysis of adhesions to resolve a limitation of knee motion.

All patients except one rated their knee condition as improved. Still, the residual symptoms prevented the majority from returning to strenuous sports. Fourteen knees (74%) had compounding problems of articular cartilage damage, prior meniscectomy, additional ligament procedures, or osteotomy. The results affirmed the recommendation that early operative treatment be considered for PCL ruptures, because by the time surgical reconstruction is necessary for symptoms with daily activities, knee symptoms may not be improved by reconstruction owing to the arthritic joint damage.

The objective assessment of posterior stability at 70 degrees of knee flexion in this study demonstrated superior results compared with the authors' single-strand PCL allograft study.[154] Stress radiography revealed that 68% of the knees had no more than a 5-mm increase in posterior tibial displacement, compared with 37% of the knees in the allograft population (who had chronic PCL ruptures). Still, in acute injury situations or in dislocated knees that require multiple ligament reconstructive procedures, allografts may be more suitable as previously discussed.

Posterior Cruciate Ligament Two-Strand Quadriceps Tendon-Patellar Bone Autograft Tibial Tunnel

We[159] followed 29 patients who underwent a two-strand PCL QT-PB autograft reconstruction with an all-inside tibial tunnel technique. All

patients were prospectively followed a mean of 3.6 years (range, 2-7 years) postoperatively. Eighteen patients had the PCL reconstruction for chronic ruptures, and 11 for acute injuries. Six patients had prior PCL reconstructions that had failed. Fifteen knees required an associated ligament reconstruction, including ACL reconstruction in nine knees, MCL repair or reconstruction in six, posterolateral procedures in five, and meniscus allograft, in one.

The mean increase in posterior tibial translation measured with stress radiography improved from 10.5 ± 2.9 mm preoperatively to 6.5 ± 4.3 mm at follow-up ($P = .06$). Preoperatively, all knees received an IKDC rating of C or D according to the stress radiographic data. At follow up, three knees (10%) were rated A; seven knees (24%), as B; 17 knees (59%), as C; and two knees (7%), as D.

Preoperatively, the KT-2000 total AP displacement values were 9.6 ± 3.9 mm at 20 degrees of flexion and 9.8 ± 3.1 at 70 degrees of flexion. At follow-up, the total AP displacement at 20 degrees of flexion was 2.2 ± 2.0 mm ($P < .0001$) and at 70 degrees of flexion, 3.3 ± 2.9 ($P = .0001$). All of the associated ligament reconstructions were rated as A or B, except one ACL reconstructions that was rated C.

Before surgery, 87% of the patients with chronic PCL ruptures had pain with daily activities, but only 11% had such pain at follow-up. Statistically significant improvements were noted for pain, swelling, giving-way, walking, stairs, running, jumping, and twisting/turning ($P < .01$). Ninety-four percent rated the knee condition as improved. For all 29 patients, 15 (52%) returned to low-impact sports and seven (24%) were participating in strenuous sports without problems. One patient was participating with symptoms against advice, and six patients did not return because of their knee condition. There were no infections or patellar fractures. Two patients reported residual pain at the patellar donor site.

TABLE 16-14 Symptoms and Functional Limitations Before and After PCL QT-PB Two-Strand Reconstruction With a Tibial Inlay Technique in 19 Knees

Factor	Point Scale	Preoperative*	Follow-up*	*P* Value
Pain	0-10	3.4 ± 1.8	6.6 ± 2.6	<.0001
Swelling	0-10	4.3 ± 2.3	7.4 ± 2.4	<.001
Full giving-way	0-10	5.6 ± 3.1	8.3 ± 2.6	<.001
Patient perception	1-10	3.2 ± 1.2	6.5 ± 2.1	.0001
Walking	0-40	29 ± 8	37 ± 9	<.01
Stair-climbing	0-40	29 ± 7	34 ± 10	<.05
Kneeling, squatting	0-40	10 ± 14	21 ± 16	.05
Running	40-100	44 ± 11	72 ± 25	<.001
Jumping	40-100	43 ± 10	62 ± 25	<.01
Twisting, turning	40-100	44 ± 11	64 ± 26	<.01

From Noyes FR, Barber-Westin SD. Posterior cruciate ligament replacement with a two-strand quadriceps tendon-patellar bone autograft and a tibial inlay technique. *J Bone Joint Surg Am.* 2005;87:1241-1262.
*Mean ± standard deviation.
PCL, Posterior cruciate ligament; *QT-PB*, quadriceps tendon-patellar bone.

Causes of Failure of Posterior Cruciate Ligament Reconstructions

A study was conducted to analyze the potential factors that contributed to the failure of PCL operations.[157] Between June 1989 and July 2003, 41 knees in 40 patients were referred to our center for treatment after 52 failed PCL operative procedures. The patients were evaluated a mean of 3.4 years (range, 1 month to 23.7 years) after the failed PCL procedures. There were 24 males and 16 females whose mean age at the initial PCL procedure was 30 years (range, 11-51 years). The initial PCL procedures were done for an acute knee injury in 15 knees and for chronic deficiency in 26 knees.

A total of 155 operative procedures had been done in the 41 knees. PCL graft reconstructions had been done in 31 cases; primary repairs, in 14; synthetic replacements, in four; and thermoplasties, in three. A single PCL procedure had been done in 32 knees; two procedures, in seven knees; three procedures, in one knee; and four procedures, in one knee. Only four knees (10%) had an isolated PCL reconstruction with no associated or further surgery performed.

Reconstruction of other knee ligaments had been done in 27 knees (66%). These involved 21 FCL or posterolateral complex procedures in 14 knees, 19 ACL reconstructions in 16 knees, and nine MCL procedures in nine knees.

CRITICAL POINTS Our Clinical Studies: Posterior Cruciate Ligament Two-Strand Quadriceps Tendon-Patellar Bone Autograft Tibial Tunnel Technique

- $n = 29$ followed mean 3.6 years (range, 2-7 years) postoperatively.
- PCL chronic 18, acute 11.
- Associated procedures: 9 ACL reconstructions, 6 MCL repairs, reconstructions, 5 posterolateral procedures, 1 meniscus transplant.
- Stress radiographs: mean preoperative, 10.5 ± 2.9 mm; follow-up, 6.5 ± 4.3 mm ($P = .06$).
- Preoperatively, all knees rated C or D on IKDC scale. At follow-up, 3 knees (10%) graded A; 7 knees (24%) graded B; 17 knees (59%) graded C; 2 knees (7%) graded D.
- KT-2000 (70 degrees): mean preoperative, 9.8 ± 3.1 mm; follow-up, 3.3 ± 2.9 mm ($P = .0001$).
- Pain ADL: preoperative, 87%; follow-up, 11%.
- 94% rated knee improved.
- 52% returned to low-impact sports, 24% returned to strenuous sports.

CRITICAL POINTS Our Clincal Studies: Analysis of the Causes of Failure of Posterior Cruciate Ligament Reconstruction

- $n = 40$ patients with 52 failed PCL operations.
- Patients evaluated mean 3.4 years (range, 1 month to 23.7 years) after failed PCL procedures.
- Total 155 prior PCL operative procedures: 31 graft reconstructions, 14 primary repairs, 4 synthetic replacements, and 3 thermoplasties.
- Other ligament procedures: 21 posterolateral (16 failed), 19 ACL (9 failed), 9 MCL.
- Most common probable causes of failure: associated posterolateral deficiency (40%), improper graft tunnel placement (33%), associated varus malalignment (31%), primary suture repair (25%).
- 71% pain with ADL.
- 75% no sports possible.

Medical records, operative notes, radiographs, and MRI scans were reviewed and a comprehensive knee examination performed. A single factor that caused the operations to fail was identified in 23 (44%) of the 52 operations and multiple factors were identified in 29 (56%, Table 16-15). The most common probable causes of failure were associated posterolateral deficiency (40%), improper graft tunnel placement (33%), associated varus malalignment (31%), and primary suture repair (25%).

Sixteen of 21 (76%) prior posterolateral procedures had failed, as had nine of 19 (47%) prior ACL reconstructions. Twenty-nine knees (71%) presented with pain with activities of daily living. Thirty-four knees (83%) had compounding problems of joint arthritis, prior meniscectomy, associated ligament deficiencies, or varus malalignment.

In the patients' rating of their own knee condition, 20 (49%) rated the knee as poor; 12 (29%), as fair; and nine (22%), as good. Thirty-one (75%) patients had given up sports activities completely and 10 were participating with significant limitations and symptoms. Significant functional limitations were found with walking in 19 (46%) patients and during squatting in 37 (90%) patients.

TABLE 16-15 Factors Contributing to Failure of 52 Posterior Cruciate Ligament Operations Referred to Our Center for Treatment

	Single Factor (23/52 Procedures)	Multiple Factors (29/52 Procedures)	Total
Deficiency of other knee ligaments:			
Fibular collateral, posterolateral	1	20	21
Anterior cruciate	0	12	12
Medial collateral	0	3	3
Misplaced tunnels:			
Posterior femoral tunnel	1	6	7
Anterior tibial tunnel	2	4	6
Proximal femoral and anterior tibial	0	4	4
Varus osseous malalignment	1	15	16
Primary repair	7	6	13
Synthetic graft, thermoplasty	1	6	7
Obesity	0	7	7
Traumatic reinjury	1	4	5
Tunnel osteolysis (allograft)	0	4	4
Postoperative infection	0	3	3
Fixation failure, tibial osteopenia	0	2	2
Failure revascularization, allograft removed	0	1	1
Unknown			1

From Noyes FR, Barber-Westin SD. Posterior cruciate ligament revision reconstruction. Part 1: causes of surgical failure in 52 consecutive operations. *Am J Sports Med.* 2005;33:646-654.

In 22 knees (54%), a PCL revision reconstruction was performed. In 19 knees (46%), revision was not performed. Eleven of these 19 knees had developed advanced knee joint arthritis with significant loss of joint space on radiographs (with only a few millimeters remaining in tibiofemoral compartments) that contraindicated PCL revision. Eight patients declined further operative treatment.

Failure to restore associated ligament instabilities and incorrect tunnel placement were major factors contributing to surgical failure of PCL operative procedures. The results suggest the need for greater emphasis on the initial reconstruction in graft tunnel placement, correction of associated ligament instabilities, and correction of varus osseous malalignment. Failure of concurrent posterolateral complex reconstructions was frequently encountered, suggesting the need for higher-strength augmentation procedures or anatomic graft replacement as discussed in Chapter 17. The results of this study were verified in 2012 by Lee and coworkers,[116] who found in a cohort of 28 failed PCL-reconstructed knees that the most common causes of failure were posterolateral deficiency and improper graft tunnel placement. Kim and associates[100] reported that patients with generalized joint laxity (Beighton and Horan criteria) had an increased risk of failure of single-strand PCL reconstruction compared with those without such laxity (nine of 24 patients [37.5%] and six of 29 patients [20.7%], respectively).

Posterior Cruciate Ligament Revision Two-Strand Quadriceps Tendon-Patellar Bone Autograft Reconstruction

From June 1995 until January 2002, a PCL revision reconstruction with a two-strand QT-PB autograft was performed in 15 knees referred after prior failed procedures.[158] There were 10 males and five females whose mean age at the time of PCL revision was 29 years (range, 17-49 years). All patients were followed a mean of 3.7 years (range, 2-7 years) postoperatively.

A total of 21 prior failed PCL operations had been done in these 15 knees, including 12 graft reconstructions, five primary repairs, two synthetic graft replacements, and two thermoplasties. A single PCL

CRITICAL POINTS Our Clinical Studies: Revision Posterior Cruciate Ligament Two-Strand Quadriceps Tendon-Patellar Bone Autograft Reconstruction

- $n = 15$ followed mean 3.7 years (range, 2-7 years) postoperatively.
- Mean 3.8 years (range, 0.3-15.6 years) between failed PCL procedures and revision.
- Staged HTO required in 3 knees, autogenous bone grafting of prior graft tunnels in 1 knee before PCL revision.
- Tibial inlay 9 knees, tibial tunnel 6 knees.
- Concomitant procedures: 4 ACL reconstruction, 4 posterolateral, 1 MCL reconstruction.
- Stress radiographs: mean preoperative, 11.7 ± 3.0 mm; follow-up, 5.1 ± 2.4 mm ($P < .001$).
- KT-2000 (70 degrees): mean preoperative 8.9 ± 2.5 mm; follow-up, 3.3 ± 3.9 mm ($P < .01$).
- Before revision, all knees rated C or D according to IKDC system. At follow-up, 1 knee rated A; 9 knees, B; 4 knees, C; 1 knee, D.
- 87% rated knee condition improved.
- 53% returned to low-impact sports.
- 80% improved pain, 87% improved patient perception scores.
- Results inferior to primary PCL reconstructions, majority salvage knees.

procedure had been done in 11 knees and two or more PCL procedures had been done in four knees. A mean of 3.8 years (range, 0.3-15.6 years) had elapsed between the failed PCL procedures and the revision. The possible causes of failure of PCL reconstructions were previously presented in a larger series of knees described above; these 15 knees were a subgroup of that study.

Reconstruction of other knee ligaments had been done in nine knees: ACL procedures, in seven knees; FCL or posterolateral complex procedures, in three knees; and MCL procedures, in three knees. Before the PCL revision reconstruction, a staged HTO was required in three knees, and an autogenous bone grafting of prior graft tunnels was done in one knee.

The tibial inlay technique was used in nine knees, and the tibial tunnel technique was done in six knees. Six knees had one or more concomitant ligament reconstructive procedures with the PCL revision. In four knees, a concomitant ACL allograft reconstruction was done. One knee had an associated MCL autograft reconstruction for chronic instability. Four knees had a posterolateral reconstruction: three had a proximal advancement of the posterolateral complex[156] and one had an autograft reconstruction of the FCL, popliteus, and popliteofibular ligament.[160]

Stress radiograph posterior tibial translation values improved from 11.7 ± 3.0 mm preoperatively to 5.1 ± 2.4 mm at follow-up ($P < .001$). The KT-2000 total AP displacement values at 20 degrees improved from 9.1 ± 3.3 mm preoperatively to 2.7 ± 3.1 mm at follow-up (mean ± standard deviation, $P < .001$). At 70 degrees, the displacement values improved from 8.9 ± 2.5 mm preoperatively to 3.3 ± 3.9 mm at follow-up ($P < .01$). Before the revision, all knees were rated as C or D according to stress radiographic data. At follow-up, one knee was rated A; nine knees as B, four knees as C, and one knee as D. Two of the 15 revisions failed. Associated knee ligament reconstructive procedures restored anterior, medial, and posterolateral stability.

Significant improvements occurred in pain, function, and patient's perception scores (Table 16-16). Eighty-seven percent felt the overall knee condition was better postoperatively. However, the subjective and functional results were inferior to those reported after primary acute PCL reconstruction. Only 53% returned to light sports without problems.

The QT-PB two-strand revision provided reasonable results in this group of complex knees; however, this is a small series of PCL revision cases and definitive conclusions cannot be reached. Thirteen of 15 knees (87%) had compounding problems of articular cartilage damage, prior meniscectomy, need for associated ligament procedures, or varus malalignment with medial tibiofemoral compartment damage. Improvements were noted in 80% of the patients for pain and in 87% for the patient perception of the knee condition. However, the results were inferior to those obtainable from primary PCL reconstructions because the majority of patients were in a salvage knee situation. The goals in a revision population are to reduce symptoms with daily activities and expect that approximately 50% will be able to resume light recreational activities.

TABLE 16-16 Symptoms and Functional Limitations Before and After Revision PCL QT-PB Two-Strand Reconstruction in 15 Knees

Factor	Point Scale	Preoperative*	Follow-up*	*P* Value
Pain	0-10	2.7 ± 1.8	5.3 ± 2.4	.0001
Swelling	0-10	3.2 ± 2.5	6.4 ± 2.8	.002
Full giving-way	0-10	4.7 ± 3.3	7.3 ± 2.7	.01
Patient perception	1-10	2.8 ± 1.4	5.2 ± 1.9	.05
Walking	0-40	25 ± 12	35 ± 7	.0002
Stair climbing	0-40	23 ± 13	32 ± 11	.004
Kneeling, squatting	0-40	5 ± 12	17 ± 15	.009
Running	40-100	44 ± 11	59 ± 26	.04
Jumping	40-100	44 ± 11	53 ± 22	NS
Twisting, turning	40-100	44 ± 11	55 ± 23	NS

From Noyes FR, Barber-Westin SD. Posterior cruciate ligament revision reconstruction. Part 2: results of revision using a 2-strand quadriceps tendon-patellar bone autograft. *Am J Sports Med.* 2005;33:655-665.
*Mean ± standard deviation.
NS, Not significant; *PCL*, posterior cruciate ligament; *QT-PB*, quadriceps tendon-patellar bone.

CRITICAL POINTS Our Clincal Studies: Posterior Cruciate Ligament Single-Strand Allograft Reconstruction

- *n* = 25 patients followed mean 3.7 years (range, 2-6.1 years) postoperatively.
- PCL acute 10, chronic 15.
- 11 associated posterolateral proximal advancement.
- KT-2000 (70 degrees) at follow-up: >5.5 mm detected 40% acute, 63% chronic cases.
- Acute cases significantly higher scores for all symptom and function scores.
- Majority of patients with chronic PCL rupture advised to avoid strenuous athletics after surgery owing to preexisting articular cartilage damage.
- No infections, evidence of rejection of the allografts, or cases of disease transmission.

Posterior Cruciate Ligament Single-Strand Allograft Reconstruction

Historically, the outcome of arthroscopic-assisted, single-strand PCL allograft reconstructions was determined in 25 patients.[154] All patients were followed a mean of 3.7 years postoperatively (range, 2-6.1 years). In 10 patients, an allograft reconstruction (B-PT-B or AT) was done alone and in 15 patients, the allograft was augmented with a ligament augmentation device (LAD). Ten patients received the operation for acute PCL ruptures, and 15 for chronic ruptures. Additional operative procedures were done in 12 knees; one required a repair of an MCL rupture, and 11 had a proximal advancement of the posterolateral complex.[155]

KT-1000 (MEDmetric) testing at follow-up revealed no difference between patients who had an allograft alone and those who had an allograft-LAD composite in total AP displacement at 20 and 70 degrees of knee flexion. The mean AP displacement value at 20 degrees of flexion for patients who had acute PCL ruptures was not significantly different from that of patients who had chronic ruptures (0.6 ± 1 mm and 1.4 ± 2.3 mm, respectively). Posterior stability was restored at this knee flexion angle in all knees (Fig. 16-48). At 70 degrees of knee flexion, an increase in AP displacement of more than 5.5 mm was detected in 40% of acute and 63% of chronic knees; the mean values were not significantly different among these subgroups (5.8 ± 2 mm and 6.5 ± 4 mm, respectively).

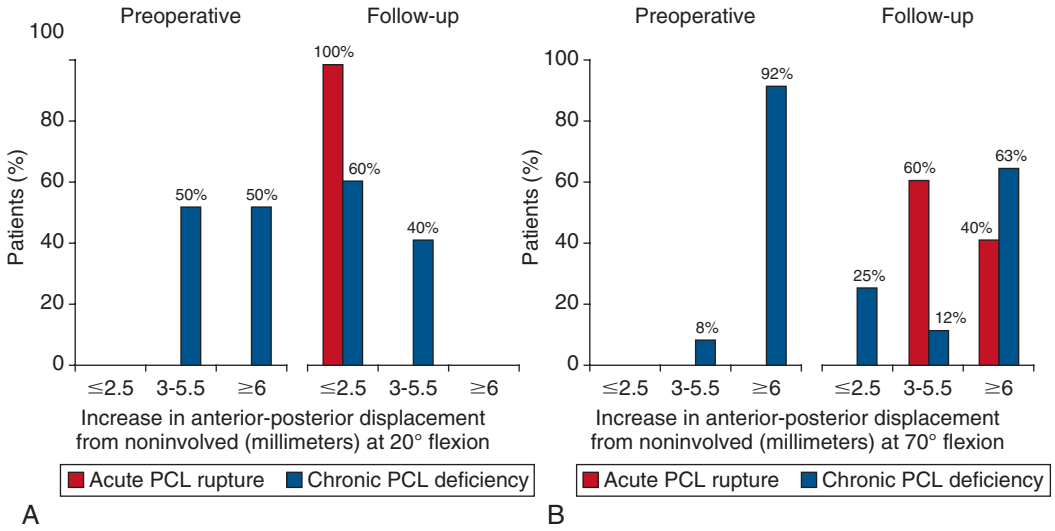


FIG 16-48 Follow-up results of KT-1000 arthrometer testing at 20 degrees (**A**) and 70 degrees (**B**) of knee flexion following PCL single-strand allograft reconstruction. (From Noyes FR, Barber-Westin S.D. Posterior cruciate ligament allograft reconstruction with and without a ligament augmentation device. *Arthroscopy*. 1994;10:371-382.)

Patients who had the operation for chronic PCL ruptures had significant improvements at follow-up in the mean scores for pain, swelling, and giving-way ($P < .001$) and for walking, stair climbing, and squatting/kneeling ($P < .05$). However, patients who had acute PCL ruptures had significantly higher scores in all of the symptom and function analyses (Table 16-17). All but one of the patients with acute PCL ruptures returned to sports activities without problems, whereas only two of the 15 patients with chronic PCL ruptures returned to athletics. The majority of patients with chronic PCL ruptures were advised to avoid strenuous athletics after surgery owing to the preexisting articular cartilage damage.

There was no benefit of the LAD in regard to posterior knee stability or the functional outcome. The single-strand allograft reconstruction restored posterior stability at 20 degrees of knee flexion, but not uniformly at 70 degrees of flexion. From a historical standpoint, the increased posterior subluxation at high flexion angles led us to a biomechanical and clinical analysis of two-strand PCL reconstructions with the goal of achieving improved stability.

TABLE 16-17 Symptom and Function Scores After Single-Bundle PCL Allograft Reconstruction for Acute and Chronic PCL Ruptures in 25 Knees

Factor	Point Scale	Chronic PCL Ruptures ($n = 15$)	Acute PCL Ruptures ($n = 10$)	*t* Test *P* Value
Pain	0-10	6 ± 2	9 ± 1	.001
Swelling	0-10	7 ± 2	9 ± 1	.01
Partial giving-way	0-10	7 ± 3	10	.01
Full giving-way	0-10	8 ± 2	10	.01
Walking	0-40	32 ± 7	40	.001
Stair climbing	0-40	28 ± 11	39 ± 3	.005
Kneeling, squatting	0-40	15 ± 15	33 ± 5	.001
Running	40-100	55 ± 19	94 ± 10	.0001
Jumping	40-100	52 ± 20	92 ± 10	.0001
Twisting, turning	40-100	51 ± 21	90 ± 11	.0001

From Noyes FR, Barber-Westin SD. Posterior cruciate ligament allograft reconstruction with and without a ligament augmentation device. *Arthroscopy*. 1994;10:371-382.
PCL, Posterior cruciate ligament.

RESULTS FROM OTHER CLINICAL STUDIES

Isolated Posterior Cruciate Ligament Single-Strand Reconstruction

Inconsistent results have been reported following single-strand isolated PCL reconstructions in restoration of normal posterior tibial displacement and knee function (Tables 16-18 and 16-19). Generally, improved knee symptoms and activity levels have been reported in the majority of studies, even though normal stability was not always restored.[122,150,223,224] It is not possible at present to scientifically analyze the effects of various graft materials or surgical techniques on the outcome of isolated single-strand PCL reconstructions. Kim and associates[106] conducted a systematic review of isolated PCL single-bundle transtibial reconstruction studies, of which 10 met the inclusion criteria. Autografts were used in 78% of the knees and allografts were selected in 22%. Stress radiographs were done in only one investigation. The IKDC objective knee evaluation form, completed in six studies, reported 75% of the knees were rated as normal or nearly normal at follow-up. The authors concluded that the procedure improved posterior drawer testing by an average of 1 grade, but did not reliably restore normal knee stability.

At the time of writing, only two studies had directly compared the outcomes of a single-strand transtibial tunnel method with a single-strand tibial inlay method.[129,196] Both investigations found no significant differences in knee rating scores and stability. Unfortunately, neither of these studies was randomized and both involved small cohorts. Historically, many studies used the KT-2000 to quantify the results of the PCL reconstructions. Although the knee arthrometer is a valid tool for the measurement of total AP translation at 20 degrees of knee flexion, it underestimates the true amount of posterior tibial

TABLE 16-18 Stability Results of Isolated Single-Strand Posterior Cruciate Ligament Reconstructions

Study	N	Acute, Chronic	Follow-up (yr)	Graft	Type PCL Reconstruction	Knee Arthrometer Results (mm)	Stress X-Ray Results (mm)
Boutefnouchet et al[18] (2013)	15	Acute and chronic	1-9	STG autograft	Transtibial	<3: 73% 3-5: 27%	Not done
Lin et al[124] (2013)	59	Chronic	3-6.2	B-PT-B autograft (25), hamstring autograft (34)	Transtibial	Quadriceps neutral angle; mean B-PT-B 2.8 ± 1.6 (range, 1-6.5); hamstring 2.6 ± 1.5 (range, 1-7.5)	Not done
Yoon et al[243] (2013)	37	Chronic	2	AT allograft	Transtibial	Not done	Postoperative brace group 4.8 ± 2.4; cast group 2.5 ± 1.9 ($P = .007$)
Lahner et al[111] (2012)	33	Chronic	2 (range, 1-2.8)	STG autograft	AL bundle reconstructed	Not done	Mean 5.0 ± 2.5, 76% ≤5 mm
Zayni et al[244] (2011)	21	Acute and chronic	2.4 (range, 1-4)	QT-PB autograft	AL bundle reconstructed	Not done	Mean preoperative 11.9 ± 3.3 (range, 8-15), F/U 3.6 ± 2.2 (range, 0-7)
Hermans et al[79] (2009)	22	Acute and chronic	9 (range, 6.5-12.6)	B-PT-B or STG autograft	AL bundle reconstructed	30 degrees, quadriceps neutral angle 89 N, mean 1.6 ± 1.4; quadriceps neutral angle, mean 2.1 ± 1.6	Mean 4.7 ± 2.8
Wong et al[236] (2009)	55	Chronic	3-7.1	STG autograft	AL transtibial (27), anteromedial transtibial (28)	Mean anterolateral 3.3 ± 2.8 (range, 1-10); anteromedial 2.8 ± 1.6 (range, 1-6)	Not done
Jackson et al[86] (2008)	26	Chronic	10-11.7	STG autograft	Endoscopically assisted	30 degrees, quadriceps neutral angle 89 N, mean 1.1 ± 1.9 <3: 17/20 patients tested	Not done
Adachi et al[2] (2007)	29	Chronic	3.5 (range, 2-6.5)	STG autograft		89 N, mean preoperative 9.3 ± 2.2, F/U 3.7 ± 2.4	Mean preoperative 9.8 ± 2.3, F/U 3.5 ± 2.7
Wu et al[238] (2007)	22	Chronic	5.5 (range, 4.9-6.3)	QT-PB autograft		70 degrees, manual maximum <3: 10 (45%) 3-5: 8 (36%) >5: 4 (18%)	Not done
MacGillivray et al[129] (2006)	20	Chronic	5.7 (range, 2-15)	Tibial tunnel: B-PT-B autograft (9) B-PT-B allograft (2) AT allograft (2) Tibial inlay: B-PT-B allograft (5) B-PT-B autograft (2)		Transtibial: <3: 33% 3-5: 25% >5: 42% Tibial inlay: <3: 14% 3-5: 43% >5: 43%	Not done
Seon & Song[196] (2006)	43	Chronic	2-6.7	Tibial tunnel: STG autograft (21) Tibial inlay: B-PT-B autograft (22)		Not done	90 degrees, 89 N, tunnel mean 3.7 ± 2.1 <3: 9% 3-5: 67% 6-10: 24% Inlay mean 3.3 ± 1.6 <3: 14% 3-5: 68% 6-10: 18%

Continued

TABLE 16-18 Stability Results of Isolated Single-Strand Posterior Cruciate Ligament Reconstructions—cont'd

Study	N	Acute, Chronic	Follow-up (yr)	Graft	Type PCL Reconstruction	Knee Arthrometer Results (mm)	Stress X-Ray Results (mm)
Sekiya et al[194] (2005)	21	Acute and chronic	5.9 (range, 2.6-11)	AT allograft	AL bundle reconstructed	30 degrees, quadriceps neutral angle; done in 14 patients; mean corrected 4.5 (range, 2-10); mean side-side 1.96 (range, –1 to 6)	Not done
Ahn et al[7] (2005)	36	Chronic	2-4.6	STG autograft (18), AT allograft (18)		Not done	Mean preoperative 14 (range, 10-20), F/U 2.6 (range, 0-7)
Jung et al[94] (2004)	11	Acute and chronic	4.3 (range, 2-6.7)	B-PT-B autograft	Tibial inlay	70 degrees, manual maximum <3: 64% 3-5: 36%	70 degrees, 150 N <3: 36% 3-5: 45% >5: 18% Mean 3.4 ± 2.4

AT, Achilles tendon; *AL*, anterolateral; *B-PT-B*, bone-patellar tendon-bone; *F/U*, follow-up; *PCL*, posterior cruciate ligament; *QT-PB*, quadriceps tendon-patellar bone; *STG*, semitendinosus and gracilis tendons.

TABLE 16-19 Subjective and Functional Results of Isolated Single-Strand Posterior Cruciate Ligament Reconstructions

Reference	Rating Systems	IKDC Subjective, Function	Symptoms/Sports	Overall IKDC	Results for Other Scales
Boutefnouchet et al[18] (2013)	IKDC, Lysholm, Tegner	Not given	Tegner levels: 1-4: 3 5-6: 2 7-8: 10	A: 10 (67%) B: 4 (27%) C: 1 (6%)	Lysholm mean 95 (range, 15-100)
Lin et al[124] (2013)	IKDC, Lysholm	No instability, swelling	*Kneeling pain:* 32% B-PT-B group, 3% hamstring group *Squatting pain:* 24% B-PT-B group, 3% hamstring group *Anterior knee pain:* 36% B-PT-B group, 3% hamstring group	*B-PT-B group:* A: 4 (16%) B: 17 (68%) C: 4 (16%) *Hamstring group:* A: 12 (35%) B: 20 (59%) C: 2 (6%)	Lysholm mean B-PT-B group preoperative 63 ± 9, F/U 92 ± 4 Hamstring group preoperative 60 ± 11, F/U 93 ± 4
Yoon et al[243] (2013)	IKDC, Lysholm, Tegner	Mean F/U brace group 73, cast group 75	Tegner mean score, 6 for both groups	A: 14 (38%) B: 13 (35%) C: 10 (27%)	Lysholm mean preoperative 52, F/U 88-92
Lahner et al[111] (2012)	IKDC, Tegner	Mean preoperative 41 ± 11, F/U 69 ± 11	Tegner mean preoperative 2.8 ± 0.8, F/U 5.9 ± 1.2	A: 15% B: 57% C: 24% D: 3% 27% no improvement	None
Zayni et al[244] (2011)	IKDC, Lysholm, Tegner	Mean preoperative 39 ± 21, F/U 74 ± 18	33% anterior knee pain during activities; 81% moderate or strenuous level sports, 71% pivot, contact sports	A: 8 (38%) B: 9 (43%) C: 4 (19%)	Lysholm mean preoperative 41 ± 18, F/U 82 ± 10

TABLE 16-19 Subjective and Functional Results of Isolated Single-Strand Posterior Cruciate Ligament Reconstructions—cont'd

Reference	Rating Systems	IKDC Subjective, Function	Symptoms/Sports	Overall IKDC	Results for Other Scales
Hermans et al[79] (2009)	IKDC, Lysholm, VAS, Tegner	Mean preoperative 38 ± 17, F/U 65 ± 24	Tegner mean preoperative 7.2 ± 1.8, F/U 5.7 ± 2	A: 1 (4%) B: 8 (36%) C: 13 (59%)	Lysholm mean preoperative 50 ± 23, F/U 75 ± 20
Wong et al[236] (2009)	IKDC, Lysholm, Tegner	Mean F/U anterolateral 74 ± 12, anteromedial 73 ± 11	Tegner mean anterolateral 5 (range, 3-9), anteromedial 4.4 (range, 2-8)	Anterolateral/anteromedial: A: 6 (22%)/4 (14%) B: 12 (44%)/15 (54%) C: 4 (15%)/4 (14%) D: 5 (19%)/5 (18%)	Lysholm mean anterolateral 91 (range, 71-100), anteromedial 88 (range, 60-100)
Jackson et al[86] (2008)	IKDC, Lysholm	Mean F/U 87 ± 14; 92% rated normal/ nearly normal, 8%, abnormal	96% no pain or giving-way with moderate or strenuous activities, 100% no swelling; 88% strenuous or moderate IKDC activity levels	Not given	Lysholm mean preoperative 64 ± 15, F/U 90 ± 14
Adachi et al[2] (2007)	Lysholm	Not given	Not given	Not given	Lysholm mean preoperative 69 ± 6, F/U 95 ± 4
Wu et al[238] (2007)	IKDC, Lysholm, Tegner	82% rated normal or nearly normal	82% no pain with moderate or strenuous activities; 82% strenuous or moderate IKDC activity levels	A and B: 82% C and D: 18%	Lysholm mean preoperative 67, F/U 89
Chan et al[31] (2006)	IKDC, Lysholm, Tegner	85% rated normal or nearly normal	95% no pain with moderate or strenuous activities; 90% strenuous or moderate IKDC activity levels	A: 5 (25%) B: 12 (60%) C: 2 (10%) D: 1 (5%)	Lysholm mean preoperative 63, F/U 93
MacGillivray et al[129] (2006)	AAOS, Lysholm, Tegner	92% transtibial group satisfied, 86% tibial inlay group satisfied	54% transtibial group no giving-way, 43% tibial inlay group no giving-way, Tegner mean score 6 for both groups	Not given	Lysholm mean F/U 81 for transtibial group, 76 for tibial inlay group; AAOS mean F/U 90 for transtibial group, 77 for tibial inlay group
Seon & Song[196] (2006)	Lysholm, Tegner	Not given	Tegner mean F/U tunnel group 5.6, inlay group 6.1	Not given	Lysholm mean F/U tunnel group 91, inlay group 93
Sekiya et al[194] (2005)	IKDC, SF-36, KOS	57% rated normal/ nearly normal, 33% abnormal, 10% severely abnormal	71% no pain with daily activities, 62% normal or nearly normal activity level	Not given	Activities of daily living mean score 79, sports activity mean score 72
Ahn et al[7] (2005)	IKDC, Lysholm	Not given	Not given	A: 25% B: 58% C: 14% D: 3%	Lysholm mean preoperative 68, F/U 89
Jung et al[94] (2004)	IKDC, OAK	Not given	Not given	A: 4 (36%) B: 7 (64%) C: 0 D: 0	OAK mean preoperative 72, F/U 92.5 ($P < .01$)

AAOS, American Academy of Orthopaedic Surgeons; *B-PT-B*, bone-patellar tendon-bone; *F/U*, follow-up; *IKDC*, International Knee Documentations Committee; *KOS*, Knee Outcome Survey; *OAK*, Orthopadische Arbeitsgruppe Knie; *VAS*, visual analog scale.

translation in PCL-deficient and reconstructed knees at 70 degrees of knee flexion. Stress radiography is the preferred device for measuring posterior tibial translation.

Few authors have described results of isolated two-strand PCL reconstructions.[33,58,146] Min and associates[146] performed a transtibial two-strand reconstruction with a tibialis anterior allograft in 21 patients who were followed a mean of 4.1 years postoperatively. The graft was passed through two femoral tunnels into one tibial tunnel, which the authors referred to as a single-sling method. At follow-up, a mean KT-2000 90 degrees of flexion value of 3.4 ± 0.8 mm (range, 1.6-6.3 mm) was reported. Three knees had grade II posterior instability. Overall IKDC grades were normal in 38%, nearly normal in 38%, abnormal in 19%, and severely abnormal in 5%. Chen and Gao[33] performed a two-strand PCL reconstruction in 19 patients in whom a quadruple semitendinosus graft was used to replace the ALB of the PCL and a quadruple gracilis tendon graft was used to reconstruct the PMB. A suture suspension technique was used for fixation. Mean posterior stress radiographs improved from 10.6 ± 2.0 mm preoperatively to 2.0 ± 1.2 mm postoperatively ($P < .001$). The IKDC subjective score increased from 65.6 ± 5.1 preoperatively to 92.1 ± 3.7 ($P < .001$). One knee had a grade II posterior drawer test.

Posterior Cruciate Ligament Single-Strand Versus Two-Strand Reconstruction

Comparisons have been made between one- and two-strand PCL procedures, with little to no difference in stability and knee function reported in recent studies (Tables 16-20 and 16-21).[49,101,104,122,202] The few studies available at the time of writing typically had low evidence levels and were not randomized.[49,82,101,104,202,227] One prospective randomized study was conducted by Li and colleagues[122] in which 50 patients were randomized to receive either a single-strand or two-strand tibialis anterior allograft. At a mean of 2.4 years postoperatively, the two-strand group had a significantly lower mean amount of posterior translation on KT-1000 testing compared with the single-strand group (2.2 ± 1.3 and 4.1 ± 1.3 mm, respectively; $P < .05$). The difference in the mean posterior translation of 1.9 mm has questionable clinical

TABLE 16-20 Studies Comparing Stability Results of Single-Strand With Two-Strand Posterior Cruciate Ligament Reconstructions

Study	*N*	Acute, Chronic	Follow-up (yr)	Type PCL Reconstruction, Graft	Knee Arthrometer Results (mm)	Stress X-Ray Results (mm)
Li et al[122] (2014)	25 single-strand, 25 two-strand	Acute	2-3	Tibialis anterior allograft	Single-strand mean preoperative 9.6 ± 0.9, F/U 4.1 ± 1.3; two-strand mean preoperative 9.6 ± 1.5, F/U 2.2 ± 1.3	Not done
Fanelli et al[49] (2012)	45 single-strand, 45 two-strand	Acute and chronic	2-6	AT allograft, tibialis anterior allograft, transtibial, all associated ligament reconstructions	Single-strand mean F/U 1.91 PCL screen, 2.11 corrected posterior, 0.23 corrected anterior Two-strand mean F/U 2.46 PCL screen, 2.94 corrected posterior, 0.15 corrected anterior	142 N, mean F/U single-strand 2.56 (range, 0-8), two-strand 2.36 (range, 0-10.6)
Kim et al[101] (2011)	23 single-strand, 19 two-strand	Chronic	2-5.8	Single-strand: AT allograft; Two-strand: tibialis posterior tendon allograft PLC tibialis posterior tendon allograft in all	Not done	Single-strand mean preoperative 12.4, F/U 4.2; 22% >5 Two-strand mean preoperative 12.7, F/U 3.9; 21% > 5
Shon et al[202] (2010)	14 single-strand, 16 two-strand	Acute and chronic	5.3-7.5	B-PT-B allograft (10), AT allograft (20), tibial inlay	Not done	20 N, mean F/U single-strand 3.0 ± 1.1, two-strand 2.6 ± 0.5
Kim et al[104] (2009)	8 single-strand transtibial,11 single-strand tibial inlay, 10 two-strand tibial inlay	Chronic	2.4-3.9	AT allograft	Not done	155 N, mean F/U single-strand transtibial 5.6 ± 2.0, single-strand inlay 4.7 ± 1.6, two-strand inlay 3.6 ± 1.4

AT, Achilles tendon; *B-PT-B*, bone-patellar tendon-bone; *F/U*, follow-up; *PLC*, posterolateral complex; *STG*, semitendinosus-gracilis tendons.

TABLE 16-21 Studies Comparing Subjective and Functional Results of Single-Strand With Two-Strand Posterior Cruciate Ligament Reconstructions

Study	Rating Systems	Lysholm	Sports Levels	Overall IKDC	Results for Other Scales
Li et al[122] (2014)	IKDC, Lysholm, Tegner	Single-strand preoperative 63 ± 4, F/U 88 ± 4 Two-strand preoperative 65 ± 4, F/U 90 ± 4	Tegner levels F/U: single-strand 5-8, two-strand 5-9	*Single-strand:* A: 10 (45%) B: 8 (36%) C: 3 (14%) D: 1 (5%) *Two-strand:* A: 13 (54%) B: 9 (38%) C: 2 (8%)	Mean IKDC subjective F/U single-strand 65 ± 8, two-strand 72 ± 7 ($P <$ .05)
Fanelli et al[49] (2012)	Lysholm, Tegner, HSS	Single-strand F/U 90 (range, 72-100); two-strand F/U 88 (range, 68-97)	Tegner F/U single-strand 5.0 (range, 2-9), two-strand 4.6 (range, 2-8)	Not done	HSS F/U single-strand 86 (range, 52-99); two-strand 83 (range, 60-92)
Kim et al[101] (2011)	IKDC, Lysholm	Single-strand preoperative 60 ± 11, F/U 85 ± 7 Two-strand preoperative 58 ± 12, F/U 88 ± 7	*IKDC sports F/U:* Single-strand: 6 (26%) level I, 4 (17%) level II, 9 (40%) level III, 4 (17%) level IV; 59% returned to preinjury level Two-strand: 5 (26%) level I, 4 (21%) level II, 7 (37%) level III, 3 (16%) level IV; 60% returned to preinjury level	*Single-strand:* A: 7 (17%) B: 23 (55%) C: 9 (21%) D: 3 (7%) *Two-strand:* A: 3 (16%) B: 11 (58%) C: 4 (21%) D: 1(5%)	None
Shon et al[202] (2010)	Lysholm, Tegner	Single-strand preoperative 43 ± 7, F/U 88 ± 7 Two-strand preoperative 45 ± 5, F/U 89 ± 9	Tegner levels F/U: single-strand 5-9, two-strand 6-10	Not done	None
Kim et al[104] (2009)	Lysholm	*F/U means:* Single-strand transtibial 87 ± 7, single-strand tibial inlay 80 ± 12, two-strand tibial inlay 84 ± 10	Not done	Not done	None

F/U, Follow-up; *IKDC*, International Knee Documentation Committee.

application. The authors did not provide ranges of this test, or the number of knees with a grade II or III posterior drawer. There was a significantly greater percentage of patients in the two-strand group with overall IKDC knee examination scores of normal/nearly normal compared with the one-strand group (92 and 82%, respectively; $P <$ .05). In addition, the mean IKDC subjective knee score was higher in the two-strand group compared with the single-strand group (72 ± 7 and 65 ± 8, respectively; $P <$ .05).

Posterior Cruciate Ligament Reconstruction With Associated Ligament Instabilities

Because isolated, complete PCL ruptures are rare, the majority of clinical studies have described cohorts in which all or the majority of patients had associated ligament instabilities (Tables 16-22 and 16-23). STG autografts and a variety of allografts were the most frequently used grafts to replace cruciate and posterolateral structures in these studies. The majority of investigations published to date had short-term follow-up of typically 2 to 4 years and the heterogeneous cohorts make comparisons among investigations not possible. Most authors reported some improvement in posterior tibial translation, although return of normal values varied among studies.

Posterior Cruciate Ligament Augmentation, Preservation of Remnant

Preserving the PCL remnant, in combination with usually a single-strand PCL graft, has been performed by several investigations in an effort to achieve superior results compared with graft reconstructions

TABLE 16-22 Stability Results of Combined Posterior Cruciate Ligament and Other Ligament Reconstructions

Study	N	Acute, Chronic	Follow-up (yr)	Type PCL Reconstruction, Graft	Other Ligament Reconstructions	Knee Arthrometer Results (mm)	Stress X-Ray Results (mm)
Adler et al[3] (2015)	16	Unknown	23 ± 3	Single-strand QT autograft	PL popliteal bypass (7) or refixation (9)	25 degrees: 5.2 ± 4	Mean posterior 90 degrees: 3.7 ± 3.1 bypass, 8 ± 2.4 refixation Mean varus 0.4 ± 2.3 bypass, –0.5 ± 2.6 refixation
Weber et al[230] (2014)	12	Acute and chronic	3 ± 0.8	Two-strand AT allograft or AT autograft, all arthroscopic tibial inlay	ACL + FCL (6), FCL/PLC (3), ACL + MCL + FCL (1), ACL (1), ACL + MCL + LCL/PL (1)	Not done	90 degrees, 89 N: mean F/U 5.1 ± 3.3
Ahn et al[5] (2013)	30	Chronic	3.9 (2.1-5.2)	Single-strand, transtibial, cross-pin tibial back side fixation STG autograft or tibialis allograft	PL reconstruction (8)	Not done	150 N, mean preoperative 13.4 ± 3.1 (range, 10-20), F/U 3.2 ± 1.5 (range, 1-7)
Zorzi et al[249] (2013)	19	Acute and chronic	3.2	Single-strand tibialis anterior allograft	ST allograft, posterior arm for PFL, anterior arm for FCL	90 degrees: <3: 74% 3-5: 26%	Not done
Kim et al[102] (2013)	65	Chronic	34 ± 11 months	Single-strand AT allograft, transtibial	FCL anatomic tibialis posterior tendon allograft	Not done	90 degrees, 150 N <3: 26% 3-5: 65% 6-10: 9%
Fanelli & Edison[51] (2012)	28	Unknown	2-18	Not given	All ACL, MCL, PL	90 degrees PCL screen 2.02 (range, 0-7), 70 degrees corrected posterior 2.48 (range, 0-9)	90 degrees, 142 N, mean 2.35 (range, –2 to 8)
Maruyama et al[138] (2012)	30	Acute and chronic	1-13	Single-strand B-PT-B or STG autograft, transtibial	STG PLC autograft (4), iliotibial band reconstruction (2)	Not done	No difference between B-PT-B and STG; values not given in mm
Jung et al[91] (2011)	64	Acute and chronic	5.2 (2.8-9.2)	Single-strand STG autograft	PL STG reconstruction (42), ACL (4), ACL + PLC (12)	Not done	Women mean preoperative 12.9, F/U 6.0; men preoperative 13.2, F/U 7.8
Spiridonov et al[206] (2011)	31	Acute and chronic	2.5 (2-4.3)	Two-strand AT and STG allografts	MCL (9), PLC (7), ACL (1), ACL + MCL (3), ACL + PLC (10), PLC + MCL (1), ACL, PLC, MCL (1)	Not done	Mean preoperative 15.0 ± 4.1, F/U 0.09 ± 2.0; all ≤5
Kim et al[99] (2009)	60	Acute and chronic	2-7.6	Single-strand AT allograft, tibialis posterior tendon allograft, or B-PT-B autograft; anteromedial tunnel (23), anterolateral tunnel (37)	PLC anatomic (6), biceps rerouting (33), semitendinosus tenodesis (6)	Not done	Mean F/U anteromedial tunnel 3.98 (1.8-7.8), anterolateral tunnel 2.87 (1.4-6.8); 5 patients >5

TABLE 16-22 Stability Results of Combined Posterior Cruciate Ligament and Other Ligament Reconstructions—cont'd

Study	N	Acute, Chronic	Follow-up (yr)	Type PCL Reconstruction, Graft	Other Ligament Reconstructions	Knee Arthrometer Results (mm)	Stress X-Ray Results (mm)
Zhao et al[247] (2008)	21	Acute and chronic	>2	Two-strand STG autograft	ACL STG autograft in all	70 degrees, mean preoperative 17 ± 2.4, F/U 2.1 ± 1.7 <3: 76% 3-5: 19% 6-10: 5%	Not done
Chen, et al[35] (2006)	52	Acute and chronic	4.5 (range, 4-5.9)	Single-strand STG autograft	PL reconstruction (12)	70 degrees, 134 N <3: 62% 3-5: 19% >5: 19%	Not done
Strobel et al[211] (2006)	17	Chronic	3.4 (range, 2-5.5)	Single-strand STG autograft, transtibial	ACL STG, PLC ST	20 degrees, manual maximum, mean F/U 2.0 ± 2.23 (range, –4 to 7)	90 degrees, 147 N, mean preoperative 15.06 ± 4.68 (range, 8-22), F/U 7.12 ± 3.37 (range, 2-14) <5: 29% 6-10: 59% >10: 12%
Fanelli et al[52] (2005)	15	Acute and chronic	2	Single strand AT allograft, transtibial	ACL AT allograft (15), MCL repair or allograft (9), PLC ST allograft (11)	Mean PCL screen: 1.6 Mean posterior: 1.6 Mean anterior: 0.5	90 degrees, 142 N <3: 67% 4: 27% 7: 7%
Yoon et al[242] (2005)	27	Acute and chronic	2.1 (range, 1-4)	Two-strand AT allograft	ACL tibialis anterior allograft (9)	Not done	Mean preoperative 12.7 (range, 10-26), F/U 2.4 (range, 0-8) <3: 67% 3-5: 22% 6-10: 11%
Cooper & Stewart[39] (2004)	41	Acute and chronic	3.2	Single-strand tibial inlay B-PT-B allograft (25), B-PT-B autograft (16), primary (35), revision (6)	ACL (17), MCL (11), PLC (17)	Not done	245 N, mean 4.11 <3: 34% 4-5: 39% 6-8: 15% 10: 12%
Harner et al[75] (2004)	31	Acute and chronic dislocated knees	3.7 (range, 2-6)	Single-strand AT allograft	All multiple-ligament reconstructions	70 degrees, quadriceps neutral angle, corrected posterior tibial translation, 25 tested <3: 60% 3-5: 28% >5: 12%	Not done
Chen et al[34] (2004)	29	Acute and chronic	3.8 (range, 3-5.8)	Single-strand QT-PB autograft	PLC ST autograft (6)	70 degrees, 134 N total AP translation <3: 41% 3-5: 45% >5: 14%	Not done
Fanelli & Edson[50] (2004)	41	Chronic	2-10	Single-strand AT allograft	All biceps tendon tenodesis, PL capsular shift	Mean screen: 1.80 Mean posterior: 2.11	142 N, mean 2.26 (range, –1.0 to 7.0)

ACL, Anterior cruciate ligament; *AP*, anteroposterior; *AT*, Achilles tendon; *B-PT-B*, bone-patellar tendon-bone; *FCL*, fibular collateral ligament; *MCL*, medial collateral ligament; *PCL*, posterior cruciate ligament; *PFL*, popliteofibular ligament; *PL*, posterolateral; *PLC*, posterolateral complex; *QT*, quadriceps tendon; *QT-PB*, quadriceps tendon-patellar bone; *ST*, semitendinosus tendon; *STG*, semitendinosus and gracilis tendons.

TABLE 16-23 Subjective and Functional Results of Combined Posterior Cruciate Ligament and Other Ligament Reconstructions

Study	Rating Systems	IKDC Subjective, Function	Symptoms, Sports	Overall IKDC	Results for Other Scales
Adler et al[3] (2015)	IKDC, WOMAC, KOOS, Lysholm, Tegner	Mean F/U 42 (range, 12-84)	Mean Tegner preinjury 7 (range, 4-10); F/U 4 (range, 2-10) Mean WOMAC symptoms F/U 40 (range, 14-68) Mean KOOS sports F/U 51 (range, 0-100)	A: 0% B: 31% C: 44% D: 25%	Mean F/U Lysholm 68, WOMAC pain 26, KOOS quality of life 44
Weber et al[230] (2014)	IKDC, Lysholm	Mean F/U 72 ± 19	Not done	A: 0% B: 67% C: 25% D: 8%	Lysholm mean F/U 79 ± 16
Ahn et al[5] (2013)	IKDC, Lysholm	Mean preoperative 63 ± 11, F/U 87 ± 4	Not done	A: 37% B: 57% C: 6%	Lysholm mean preoperative 61, F/U 88
Zorzi et al[249] (2013)	IKDC Subjective	Mean F/U 86 ± 11	Mean F/U Tegner 6 (range, 4-9)	Not done	None
Kim et al[102] (2013)	Lysholm, IKDC	Mean preoperative 57-60, F/U 84-88	Not done	A: 15% B: 63% C: 18% D: 3%	Not done
Fanelli & Edison[51] (2012)	Lysholm, Tegner, HSS	Not done	Mean F/U Tegner 4 (range, 2-9)	Not done	Mean F/U Lysholm 84 (range, 58-100); mean F/U HSS 79 (range, 56-95)
Maruyama et al[138] (2012)	Lysholm	Not done	Not done	Not done	Lysholm mean: PT group preoperative 53, F/U 88; STG group preoperative 55, F/U 87.
Jung et al[91] (2011)	IKDC	Not done	Not done	A: 3 (5%) B: 24 (43%) C: 23 (41%) D: 6 (11%)	None
Spiridonov et al[206] (2011)	IKDC Subjective, Modified Cincinnati	Mean preoperative 39 ± 19, F/U 74 ± 23	Cincinnati mean scores: Symptoms preoperative 14 ± 13, F/U 35 ± 15, function preoperative 21 ± 10, F/U 38 ± 13	Not given	None
Kim et al[100] (2009)	IKDC, Lysholm	Not done	Not done	A: 16 (27%) B: 41 (68%) C: 3 (5%)	Lysholm mean preoperative 63-64, F/U 88
Zhao et al[247] (2008)	IKDC Subjective, Lysholm, Tegner	Mean F/U 85 ± 6	19% returned to preinjury activity level	Not done	Lysholm mean 92 ± 4
Chen et al[35] (2006)	IKDC, Lysholm	83% rated normal or nearly normal	13% pain, 10% swelling, 8% full giving-way with moderate or strenuous activities IKDC activity levels: 58% strenuous or moderate, 25% light, 12% sedentary	A: 58% B: 23% C: 15% D: 4%	Lysholm mean preoperative 54, F/U 91

TABLE 16-23 Subjective and Functional Results of Combined Posterior Cruciate Ligament and Other Ligament Reconstructions—cont'd

Study	Rating Systems	IKDC Subjective, Function	Symptoms, Sports	Overall IKDC	Results for Other Scales
Strobel et al[211] (2006)	IKDC	Not done	Pain with sports 41%, pain during daily activities 18%, instability with sports 29%, instability with daily activities 24%, swelling with activity 41%	B: 5 (29%) C: 10 (59%) D: 2 (12%)	None
Fanelli et al[52] (2005)	Lysholm, Tegner, HSS	Not done	Tegner mean F/U 4.5 (range, 2-7)	Not done	Lysholm mean F/U 87 (range, 69-95); HSS mean F/U 85 (range, 65-93)
Yoon et al[242] (2005)	Lysholm	Not done	Not done	Not done	Lysholm mean preoperative 60, F/U 92
Cooper & Stewart[39] (2004)	IKDC Subjective	Mean F/U 75 (range, 22-100)	Not done	Not done	All patients rated knee improved
Harner et al[75] (2004)	IKDC, Lysholm, Myers, Knee Outcome Survey	ADL mean F/U 89 (64-99); acutes mean 91, chronics mean 84	Sports activities mean F/U 82; acutes mean 89, chronics mean 69	A: 0 B: 11 (35%) C: 12 (39%) D: 8 (26%)	Lysholm mean F/U acutes 91, chronics 80; Myers rating: 10 excellent, 13 good, 5 fair, 3 poor
Chen et al[34] (2004)	IKDC, Lysholm	86% rated normal/nearly normal	IKDC normal, nearly normal: pain 83%, swell 86%, full giving-way 90% IKDC sport levels: strenuous 48%, moderate 17%, light 21%, none 14%	A: 10 (34%) B: 14 (48%) C: 3 (10%) D: 2 (7%)	Lysholm mean preoperative 57, F/U 90
Fanelli & Edson[50] (2004)	Lysholm, Tegner, HSS	HSS mean preoperative 50, F/U 88	Tegner mean preoperative 2.7, F/U 4.9. All return to "desired level of activity"	Not done	Lysholm mean preoperative 65, F/U 91

ADL, Activities of daily living; *F/U*, follow-up; *HSS*, Hospital for Special Surgery; *IKDC*, International Knee Documentations Committee; *KOOS*, Knee Injury and Osteoarthritis Outcome; *OAK*, Orthopadishe Arbeitsgruppe Knie; *WOMAC*, Western Ontario and McMaster Universities Osteoarthritis Index.

(Tables 16-24 and 16-25). A systematic review was recently conducted by Del Buono and coworkers[44] to determine whether significant differences existed between PCL augmentation and PCL reconstruction studies regarding functional and stability results. The review included 24 studies that involved 623 PCL reconstructions and 158 PCL augmentation (remnant preservation) procedures. Overall, equivalent outcomes were found between the two operative techniques for IKDC scores, Lysholm scores, and KT-1000 and stress radiographic measurements. For instance, IKDC overall evaluation scores of normal or nearly normal were reported in a mean of 89.8% of patients who underwent PCL augmentation and in 80.1% of those who had PCL reconstruction. Posterior stress radiograph side-to-side differences improved by a mean of 8.6 ± 1.6 mm after PCL augmentation (from 11.1 ± 1.4 mm preoperatively to 2.5 ± 0.4 mm postoperatively) and by a mean of 8.0 ± 5.8 mm after PCL reconstruction (from 11.5 ± 2.2 mm preoperatively to 3.5 ± 1.3 mm postoperatively). The concern was expressed that no long-term data were available and subsequent rates of arthritis remain unknown.

Posterior Cruciate Ligament Revision Reconstruction

Other than our study just described, only one investigation of PCL revision reconstruction had been published at the time of writing. Lee and associates[116] followed 22 patients who underwent a modified two-strand tibial inlay procedure with an AT allograft a mean of 3.3 years postoperatively. Concomitant posterolateral reconstruction was performed in 17 knees; MCL reconstruction, in one knee; and HTO, in one knee. Posterior tibial translation on stress radiographs improved from a mean of 9.9 ± 2.8 mm before surgery to 2.8 ± 1.8 mm postoperatively. Two patients had more than 5 mm of increased displacement. The subjective IKDC score was classified as normal or nearly normal in 73%; abnormal, in 18%, and severely abnormal, in 9%.

Conclusions

To date, there remain too few long-term and high evidence-based data to determine the indications for a two-strand versus a one-strand technique, the most advantageous graft to select for different circumstances, and the failure rate for autografts and allografts.[83,106,108,141,174,175,229] There is an important need for well-designed Phase I multicenter trials, because individual centers seldom have a sufficient number of PCL cases for statistical analysis and definitive recommendations. Studies that have compared results of various techniques have typically been underpowered to provide definitive conclusions.[82,104,202,227,229]

TABLE 16-24 Stability Results of Posterior Cruciate Ligament Reconstructions With Remnant Preservation

Study	N	Acute, Chronic	Follow-up (yr)	Type PCL Reconstruction, Graft	Other Ligament Reconstructions	Knee Arthrometer Results (mm)	Stress X-Ray, Results (mm)
Eguchi et al[48] (2014)	19	Chronic	2-4.7	Single-strand STG autograft	None	30 degrees, mean F/U 1.0 ± 1.8	Preoperative: 6-10: 53% >10: 47% F/U: <3: 63% 3-5: 37%
Lee et al[114] (2014)	92	Chronic	4	Single-strand, tibialis anterior or posterior allograft, transtibial	PL tibialis anterior or posterior allograft (47)	90 degrees, mean preoperative 10.6 ± 1.9, F/U 1.3 ± 1.2	150 N, mean preoperative 12.1 ± 2.5, F/U 2.7 ± 1.3
Lee et al[113] (2013)	20	Chronic	2.6-7.7	Single-strand AT allograft	None	None	90 degrees, mean preoperative 10.8 (range, 9-13); F/U 3.2 (range, 1-5)
Kim et al[103] (2012)	53	Acute and chronic	2-7.9	Single-strand AT allograft, remnant preservation (30), no preservation (23)	All PLC tibialis posterior tendon allograft	Not done	150 N <3: 43% 3-5: 28.5% >5: 28.5%
Yang et al[239] (2012)	58	Chronic	5	Single-strand AT allograft or hamstring autograft + tibialis anterior allograft	None	Not done	20 N, mean preoperative 12.6 ± 1.4, F/U 3.5 ± 2.1 <5: 90% >5: 10%
Lee et al[115] (2011)	70	Chronic	3.3 (range, 2-8)	Single-strand STG autograft for AL bundle, modified tibial inlay	PL STG reconstruction (65), PL tibialis allograft (5)	70 degrees, manual maximum, mean preoperative 8.4 ± 2.2, F/U 2.0 ± 1.4	150 N, mean preoperative 10.3 ± 2.4, F/U 2.2 ± 1.5 <3: 57% 3-5: 37% >5: 6%
Yoon et al[241] (2011)	53	Acute and chronic	2-3.6	Single-strand (25), two-strand (28), AT allograft	None	Not done	150 N, single-strand mean preoperative 12.0 ± 2.0, F/U 4.5 ± 2.3; two-strand mean preoperative 12.2 ± 3.2, F/U 3.1 ± 2.4
Jung et al[92] (2010)	20	Acute	2-4.3	Single-strand STG autograft, transtibial	PL tibialis posterior allograft (4)	70 degrees manual maximum <3: 50% 3-5: 40% >5: 10%	150 N, mean preoperative 10.4 ± 2.1, F/U 3.0 ± 2.6 <3: 45% 3-5: 45% >5: 10%
Zhao et al[248] (2008)	18	Chronic	2	Two-strand, four-strand ST for AL bundle; four-strand gracilis for PM bundle	None	Manual maximum, mean preoperative 9.3 ± 1.4, F/U 0.7 ± 0.9; one knee 5 mm	Not done
Jung et al[93] (2006)	49	Chronic	2-6.5	Single-strand STG autograft, B-PT-B autograft, AT allograft for AL bundle, modified tibial inlay	PL reconstructions, different methods (35)	70 degrees manual maximum, mean preoperative 8.2 ± 1.5, F/U 1.9 ± 1.0 <3: 73% 3-5: 27%	150 N, mean preoperative 10.4 ± 2.1, F/U 2.2 ± 1.0 <3: 70% 3-5: 30%
Ahn et al[6] (2006)	61	Chronic	2-7	Single-strand STG autograft, AT allograft, transtibial	PL AT allograft (17)	70 degrees manual maximum <3: 53% 3-5: 44% 5-10: 3%	Not done

AL, Anterolateral; *AP*, anteroposterior; *AT*, Achilles tendon; *B-PT-B*, bone-patellar tendon-bone; *F/U*, follow-up; *PCL*, posterior cruciate ligament; *PL*, posterolateral; *PLC*, posterolateral complex; *PM*, posteromedial; *ST*, semitendinosus tendon; *STG*, semitendinosus and gracilis tendons.

TABLE 16-25 Subjective and Functional Results of Posterior Cruciate Ligament Reconstructions With Remnant Preservation

Study	Rating Systems	IKDC Subjective	Symptoms/Sports	Overall IKDC	Results for Other Scales
Eguchi et al[48] (2014)	Lysholm	NA	NA	NA	Lysholm mean preoperative 63 ± 13, F/U 94 ± 4
Lee et al[114] (2014)	IKDC, Lysholm, Tegner	Mean preoperative 53 ± 10, F/U 86 ± 6	Tegner F/U 5 ± 1	Not done	Lysholm mean preoperative 57 ± 7, F/U 89 ± 7
Lee et al[113] (2013)	IKDC, Lysholm, Tegner	Mean preoperative 62 (range, 30-73), F/U 85 (range, 65-95)	Tegner F/U 4-8	A: 40% B: 60%	Lysholm mean preoperative 70 (range, 53-81), F/U 89 (range, 85-95)
Kim et al[103] (2012)	IKDC, Lysholm, Tegner	Mean preoperative 41-42, F/U 64-70	Tegner F/U 2-7	A: 14 (26%) B: 28 (53%) C: 9 (17%) D: 2 (4%)	Lysholm mean preoperative 58-60, F/U 82-84
Yang et al[239] (2012)	IKDC, Lysholm, Tegner	85% rated knee function normal or nearly normal	No. patients with symptoms with moderate/strenuous activities: pain (2), swelling (4), giving-way (2); Tegner F/U 6 (range, 4-9)	A: 19 (32%) B: 31 (53%) C: 7 (12%) D: 1 (2%)	Lysholm mean preoperative 47 ± 7, F/U 89 ± 5
Lee et al[115] (2011)	IKDC, OAK	Mean preoperative 50 ± 17, F/U 80 ± 13	Not done	A: 30 (43%) B: 34 (48%) C: 6 (9%)	OAK mean preoperative 63 ± 10, F/U 89 ± 7
Yoon et al[241] (2011)	IKDC, Lysholm, Tegner	Mean F/U single-strand 79, two-strand 82	Tegner F/U 4-7	Single-strand/two-strand A: 6 (24%)/15 (54%) B: 12 (48%)/9 (32%) C: 6 (24%)/4 (14%) D: 1 (4%)/0	Lysholm F/U mean single-strand 89, two-strand 91
Jung et al[92] (2010)	IKDC, OAK	Mean preoperative 46 ± 15, F/U 85 ± 10	Not done	A: 7 (35%) B: 10 (50%) C: 2 (10%) D: 1 (5%)	OAK mean preoperative 62 ± 13, F/U 88 ± 9
Zhao et al[248] (2008)	IKDC, Lysholm, Tegner	Mean preoperative 64 ± 3, F/U 96 ± 3	Tegner F/U 6.0	A: 16 (89%) B: 2 (11%)	Lysholm mean preoperative 59 ± 4, F/U 95 ± 4
Jung et al[93] (2006)	IKDC, OAK	Mean F/U 87 ± 9	Not done	A: 10 (20%) B: 33 (67%) C: 6 (12%)	OAK mean preoperative 63 ± 8, F/U 91 ± 7
Ahn et al[6] (2006)	IKDC, Lysholm	46% rated knee function normal, 54% nearly normal	Not done	A: 33 (54%) B: 26 (43%) C: 2 (3%)	Lysholm mean preoperative 66 ± 11, F/U 93 ± 3

F/U, Follow-up; *IKDC*, International Knee Documentations Committee; *OAK*, Orthopadishe Arbeitsgruppe Knie.

ILLUSTRATIVE CASES

Case 1. A 16-year-old female athlete injured her left knee playing soccer. A PCL thermoplasty had been performed, which failed, and she was referred to our center 9 months later for consideration of reconstruction. The patient complained of functional limitations with all athletics and had not been able to return to soccer. Physical examination revealed 10 mm of increased posterior tibial translation (90 degrees), 7 mm of increased lateral joint opening (30 degrees), and 30 degrees of increased external tibial rotation (30 degrees). Posterior stress radiographs showed 11 mm of increased posterior tibial translation. The patient was a potential collegiate soccer scholarship candidate.

The patient underwent a two-strand quadriceps tendon-patellar bone PCL reconstruction with a tibial inlay technique (Fig. 16-49). The posterolateral deficiency was treated with a proximal advancement of the posterolateral complex. The *arrows* in Figure 16-49, *A* show the location of the two tunnels in the medial femoral condyle.

The patient was able to return to soccer without problems. Two years postoperatively, she had 4 mm of increased posterior tibial translation on stress radiographs at 90 degrees of flexion, no increase on KT-2000 testing at 20 degrees of flexion, and no increase in lateral joint opening or external tibial rotation. She rated the overall condition of her knee as very good.

Our comment: As discussed, the all-inside PCL reconstruction that places the bone plug within an arthroscopically-placed tibial tunnel has replaced the open tibial inlay procedure, with equivalent clinical results.

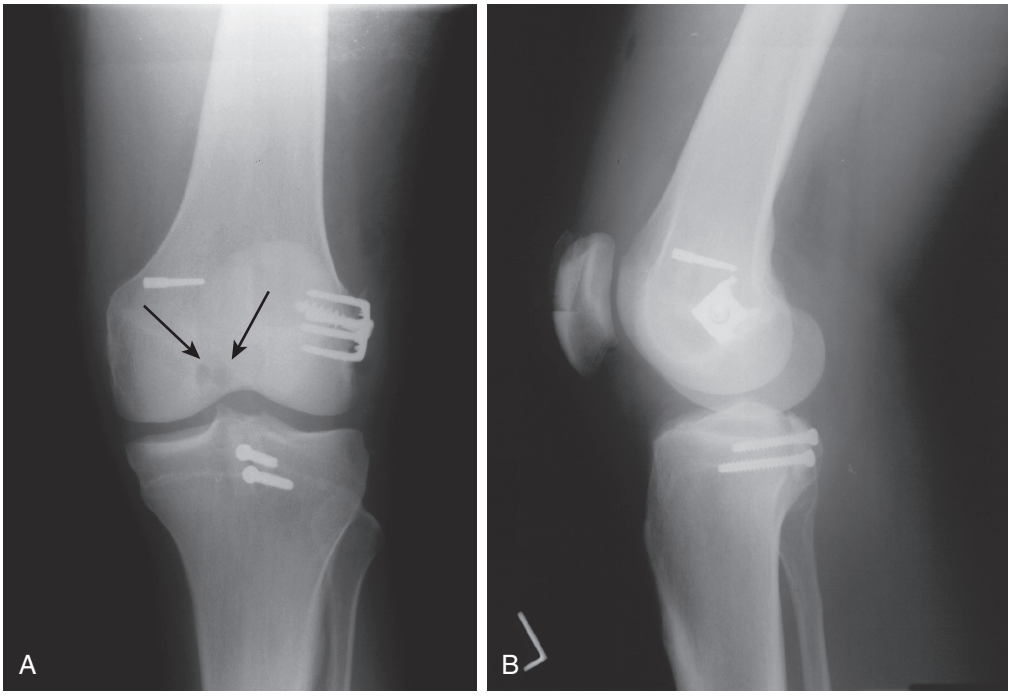


FIG 16-49 Case 1. (From Noyes FR, Barber-Westin SD. Posterior cruciate ligament replacement with a two-strand quadriceps tendon-patellar bone autograft and a tibial inlay technique. *J Bone Joint Surg Am.* 2005;87:1241-1262.)

Case 2. A 45-year-old man sustained a complete PCL rupture during a recreational basketball game and underwent a PCL Achilles tendon-bone allograft reconstruction. He presented to our center 1 year later with complaints of moderate pain with daily activities and severe difficulty with walking, stair-climbing, and squatting. He was disabled from his occupation. Radiographs demonstrated proximal and anterior placement of the tibial tunnel and enlargement of both tunnels with an obvious posterior tibial subluxation (Fig. 16-50). Physical examination showed 10 mm of increased posterior tibial translation (90 degrees), 6 mm of increased lateral joint opening (30 degrees), and moderate patellofemoral crepitus. The patient had a tibial nerve palsy, which was improving. Stress radiographs showed 12 mm of increased posterior tibial translation.

The treatment recommendation was a staged autogenous femoral bone graft procedure followed by a PCL revision posterolateral reconstruction, based on further evaluation at the time of surgery. The patient declined further operative treatment.

Our comment: Inadequate placement of the primary PCL graft represents one of the most common causes of failure, particularly with an anterior tibial placement that produces a vertical PCL graft. In revision PCL reconstructions, approximately 60% of knees have an undiagnosed posterolateral ligament deficiency that requires a concurrent operative procedure.

Case 3. A 36-year-old woman sustained a work-related injury and underwent a single-strand posterior cruciate ligament (PCL) bone-patella tendon-bone allograft reconstruction. The patient's surgical history also included a medial collateral ligament reconstruction with a semitendinosus graft and a proximal patellar realignment. She presented 1 year later at our center with complaints of severe pain and functional limitations with all daily activities. Sagittal, coronal, and axial magnetic resonance imaging scans showed enlarged femoral and tibial tunnels (Fig. 16-51). Physical examination revealed 12 mm of increased posterior tibial translation (90 degrees), 5 mm of increased medial joint opening (30 degrees), and moderate patellofemoral and tibiofemoral crepitus.

The treatment recommendation was a staged autogenous femoral and tibial graft procedure followed by a PCL revision reconstruction. The patient declined and underwent a total knee replacement 3 years later for unresolved pain.

Our comment: This case demonstrates an unfortunate reaction to the allograft with severe tunnel widening, not seen in our experience with autograft tissue.

Case 4. A 28-year-old man sustained complete PCL and posterolateral ligamentous ruptures in a work-related injury and underwent a single-strand PCL allograft and fibular collateral ligament allograft reconstruction. He presented 14 months later with complaints of severe pain and limitations with daily activities. He had not been able to return to work owing to his knee symptoms. Radiographs demonstrated underlying varus osseous malalignment and severe deficiency of the posterolateral structures (Fig. 16-52). Physical examination revealed 10 mm of increased posterior tibial translation (90 degrees), 15 mm of increased lateral joint opening (30 degrees), a grade III pivot shift, and 25 degrees of increased external tibial rotation. There was a varus osseous malalignment (weight-bearing line, 34% on standing hip-knee-ankle radiograph with lateral compartment closure). The patient's body mass index was 32, indicating an obese condition. He also had severe patellofemoral arthritis and compression pain.

Because of the patient's age, the treatment recommendations were a weight loss program (with a targeted amount to be indicated), followed by an opening wedge high tibial osteotomy. Upon recovery from the osteotomy, a combined two-strand PCL revision reconstruction and an anatomic posterolateral reconstruction was performed as described in the text.

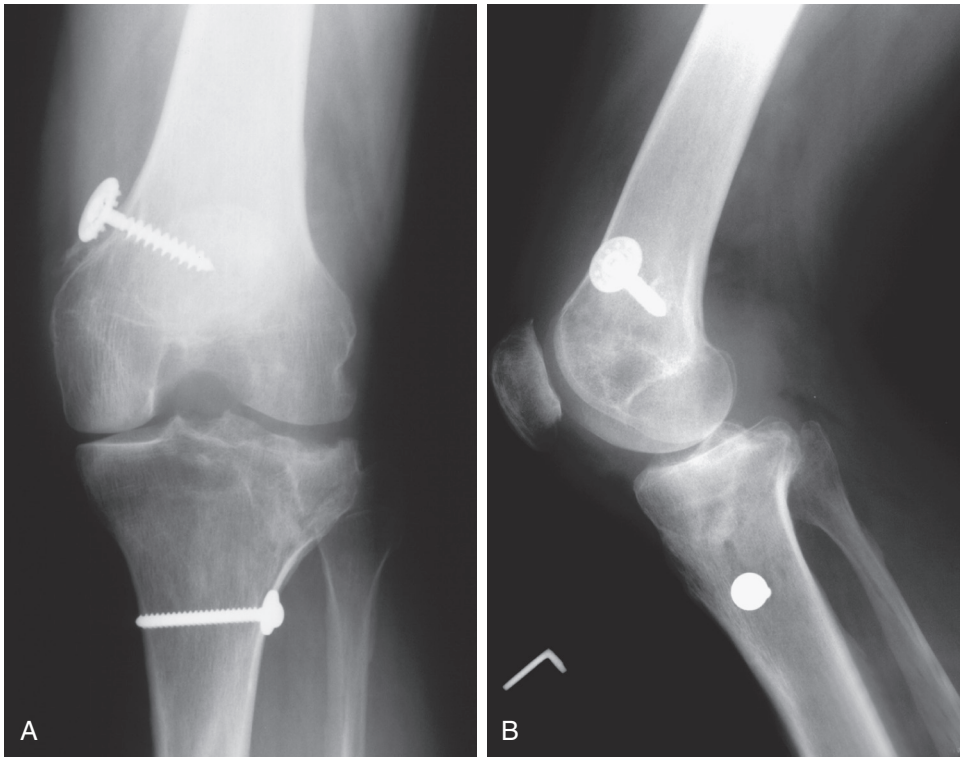


FIG 16-50 Case 2. (From Noyes FR, Barber-Westin SD. Posterior cruciate ligament revision reconstruction, part I. Causes of surgical failure in 52 consecutive operations. *Am J Sports Med.* 2005;33:646-654.)

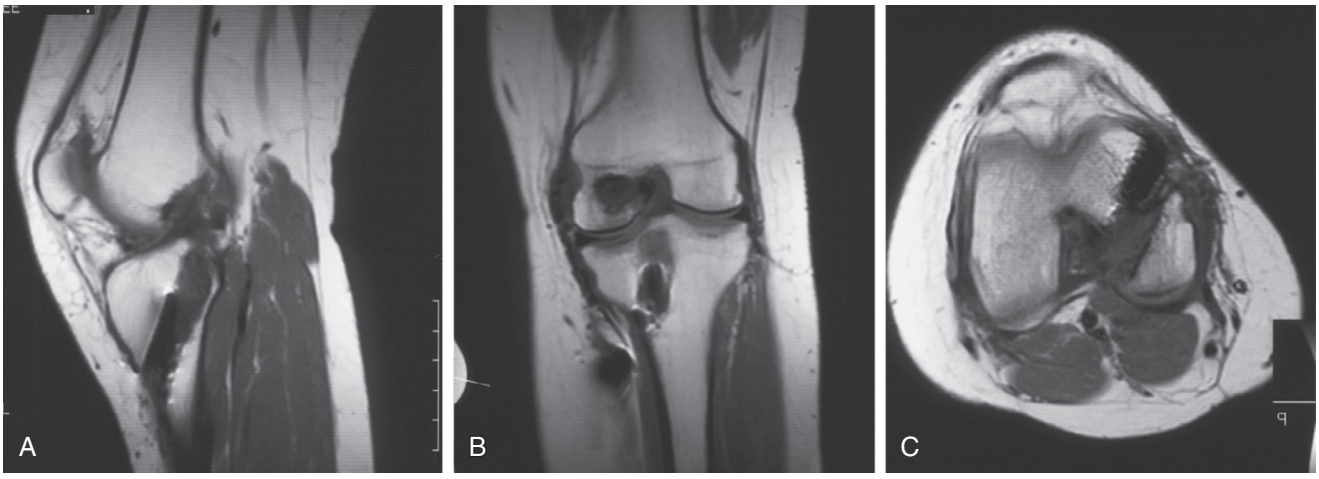


FIG 16-51 Case 3. (From Noyes FR, Barber-Westin SD. Posterior cruciate ligament revision reconstruction. Part 1: causes of surgical failure in 52 consecutive operations. *Am J Sports Med.* 2005;33:646-654.)

Our comment: This case shows the difficulty in achieving a successful posterolateral reconstruction in a varus-angulated knee, particularly in patients with a large body habitus that induces excessive tensile loading of the posterolateral structures. Another option in this patient, although controversial, would have been not to perform an acute operative procedure, allow healing of the posterolateral structures, and accept that a chronic reconstructive procedure would be necessary under more ideal conditions and after corrective tibial osteotomy.

Case 5. A 40-year-old man presented 2 months after an injury sustained to his right knee during a fall in which he suffered a direct blow to the anterior aspect of the tibia. The injury was initially treated conservatively elsewhere, without physical therapy or bracing. The patient presented with complaints of swelling and instability with daily activities and rated the overall condition of his knee as poor. Physical examination revealed a moderate effusion, a limitation of knee flexion of 110 degrees, moderate quadriceps weakness, and 11 mm of increased posterior tibial translation on stress radiographs (Fig. 16-53, *A*).

The patient was treated with rehabilitation to restore knee motion and muscle strength and then underwent an arthroscopic-assisted two-strand quadriceps tendon-patellar bone posterior cruciate ligament reconstruction. He demonstrated noteworthy cartilage damage on the

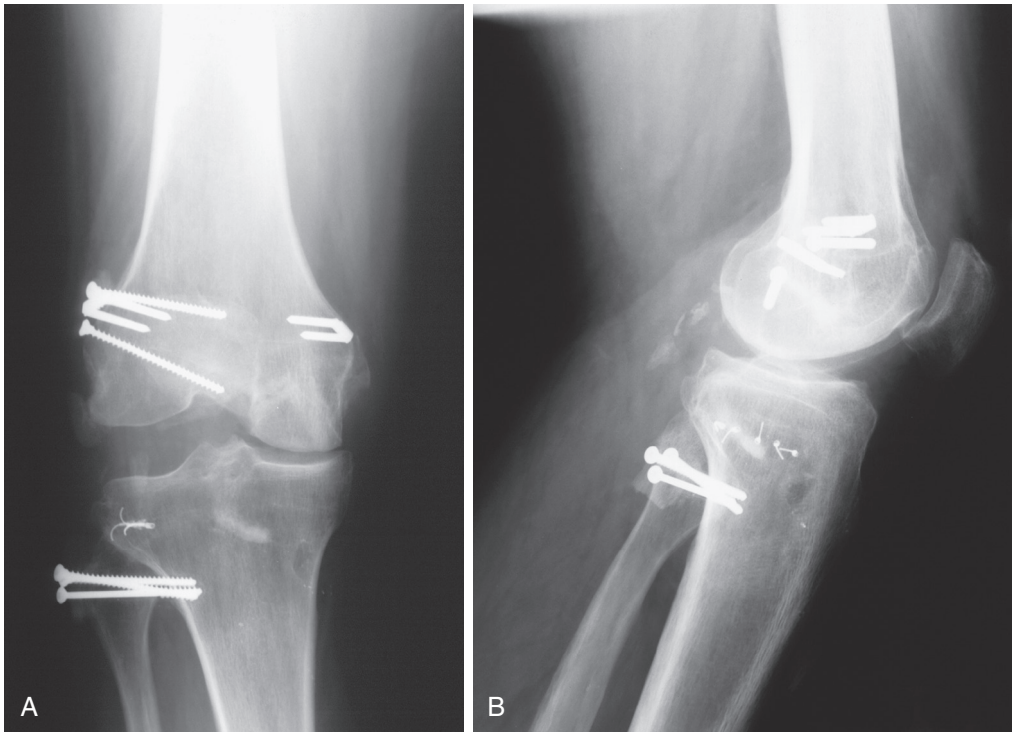


FIG 16-52 Case 4. (From Noyes FR, Barber-Westin SD. Posterior cruciate ligament revision reconstruction. Part 1: causes of surgical failure in 52 consecutive operations. *Am J Sports Med*. 2005;33:646-654.)

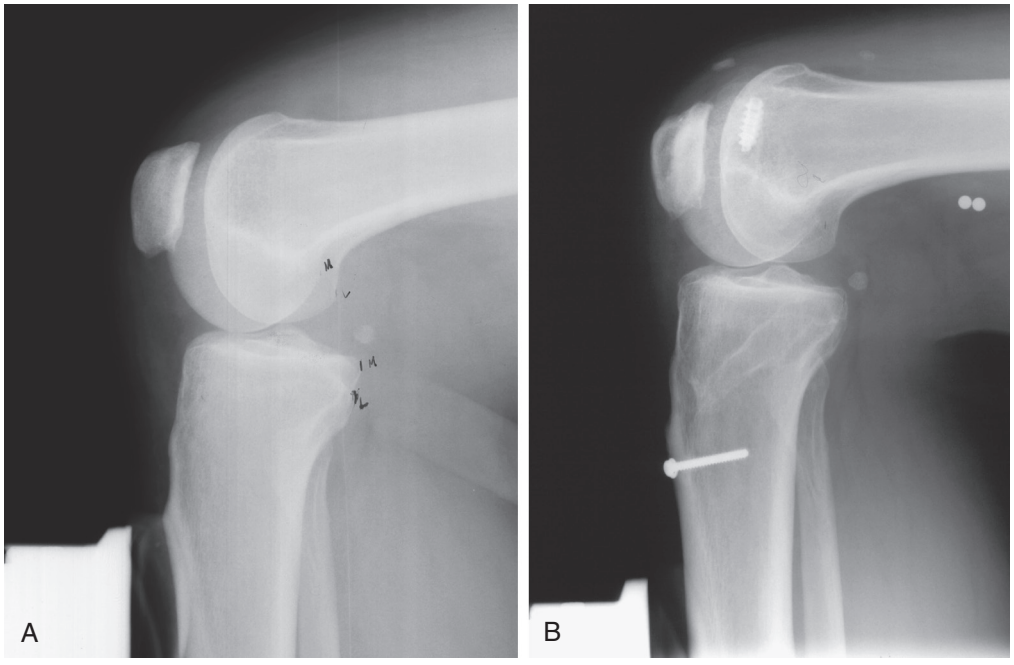


FIG 16-53 Case 5.

undersurface of the patella, femoral sulcus, and medial femoral condyle.

At the most recent follow-up evaluation, 6 years postoperatively, the patient had no effusion, a normal range of knee motion, 4 mm of increased posterior tibial displacement on stress radiographs at 90 degrees of flexion (see Fig. 16-53, *B*), and no increase in posterior tibial displacement on KT-2000 testing at 20 degrees of flexion. He had no symptoms with low-impact athletic activities, hiking, or with his occupation as a machinist. He rated the overall condition of his knee as normal.

Case 6. A 23-year-old man was referred 2 years after a left knee dislocation that was sustained during a motor vehicle accident. He had undergone a PCL B-PT-B allograft reconstruction and an FCL fascia lata autograft reconstruction, both of which had failed. The ACL had been ruptured but not surgically addressed.

Physical examination demonstrated 10 mm of increased posterior tibial translation (90 degrees), a grade III pivot shift test, 9 mm of increased AP displacement on KT-2000 testing, 20 mm of increased lateral joint opening (30 degrees), and 20 degrees of increased external tibial rotation (30 degrees). The patient had a significant peroneal nerve palsy at the time of the injury, which persisted. AP (Fig. 16-54, *A*) and lateral (see Fig. 16-54, *B*) radiographs revealed anterior tibial tunnel placement of the PCL graft. The patient had severe giving-way symptoms with daily activities.

The patient was treated with a PCL two-strand quadriceps tendon-patellar bone autograft reconstruction (tibial inlay approach, graft harvested from contralateral knee), an anatomic FCL semitendinosus autograft reconstruction, an advancement of the PLC, and an ACL B-PT-B allograft.

At follow-up, 4 years postoperative, the patient had no increase in lateral joint opening or external tibial rotation. Stress radiographs at 90 degrees of knee flexion showed restoration of posterior stability (see Fig. 16-54, *C*). He had a grade I pivot shift test and 5 mm of increase in lateral joint opening on stress radiographs. The patient was participating in low-impact activities without symptoms and rated the overall condition of his knee as good.

Case 7. A 42-year-old women presented 3 weeks after a fall complaining of left knee pain, swelling, and an inability to bear weight. The patient had experienced an unusual hyperextension-twisting injury while walking at work. On physical examination, the patient's left knee demonstrated a mild amount of swelling. Although the patient was quite guarded to examination, she appeared to have significant instability in the anterior, posterior, medial, and lateral directions. The neurovascular examination was normal and there was no evidence of localized or focal numbness in the peroneal nerve distribution. Magnetic resonance imaging showed evidence of a complete tear of the ACL, posterior cruciate ligament (PCL), fibular collateral ligament (FCL), and medial collateral ligament (MCL).

The patient underwent an initial course of rehabilitation, protective knee motion, and muscle reeducation. The decision was made 2 weeks later to perform an acute repair and reconstruction of the lateral and posterolateral disrupted structures. She had an arthroscopic-assisted ACL reconstruction with a bone-patella tendon-bone (B-PT-B) allograft, a PCL reconstruction with a single-strand quadriceps tendon-patellar bone allograft, an FCL reconstruction with a B-PT-B allograft, and a repair of the posterolateral capsule and popliteus tendon. Noteworthy articular cartilage damage (grade 2 B) was noted on the undersurface of the patella and trochlea.

At the most recent evaluation, 2 years postoperative, the patient had no complaints with daily activities. Physical examination demonstrated a negative pivot shift, no increase in Lachman, and no increase in medial or lateral joint opening. The neurosensory examination was normal and there was no effusion. Stress radiographs revealed 4 mm of lateral tibiofemoral joint opening, compared with 12 mm on the contralateral knee (Fig. 16-55, *A* and *B*). There was no increase in posterior translation noted on stress radiographs compared with the opposite knee (see Fig. 16-55 *C* and *D*).

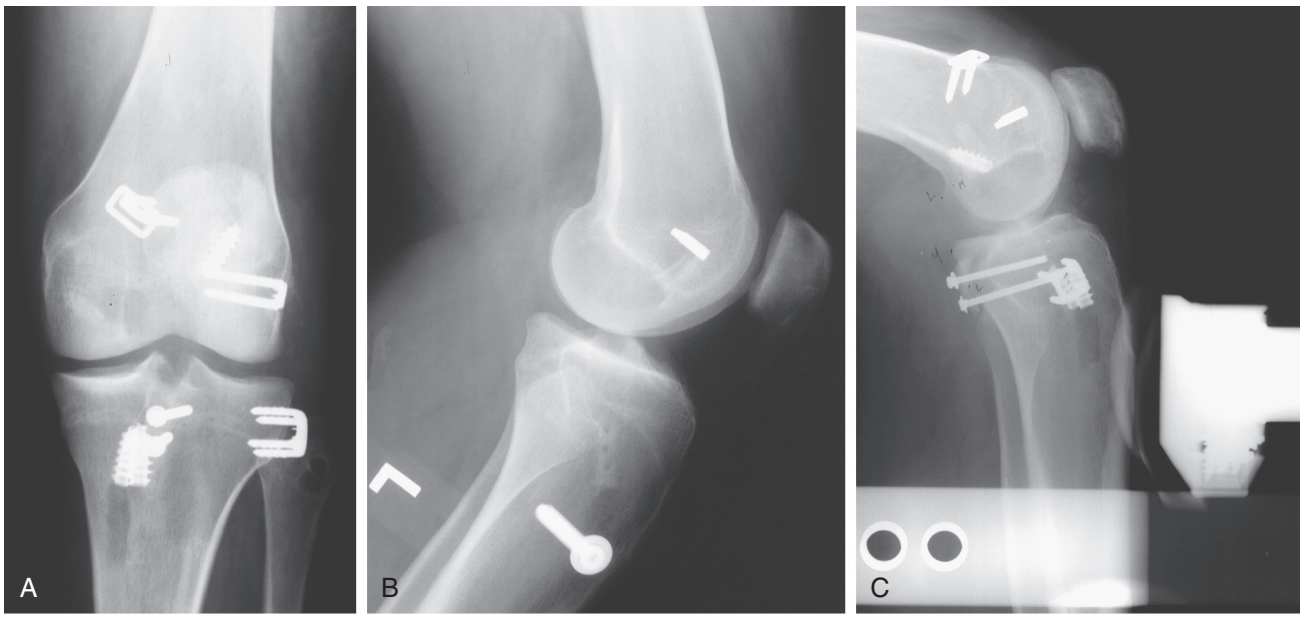


FIG 16-54 Case 6. (From Noyes FR, Barber-Westin SD, Albright JC. An analysis of the causes of failure in 57 consecutive posterolateral operative procedures. *Am J Sports Med.* 2006;34:1419-1430.)

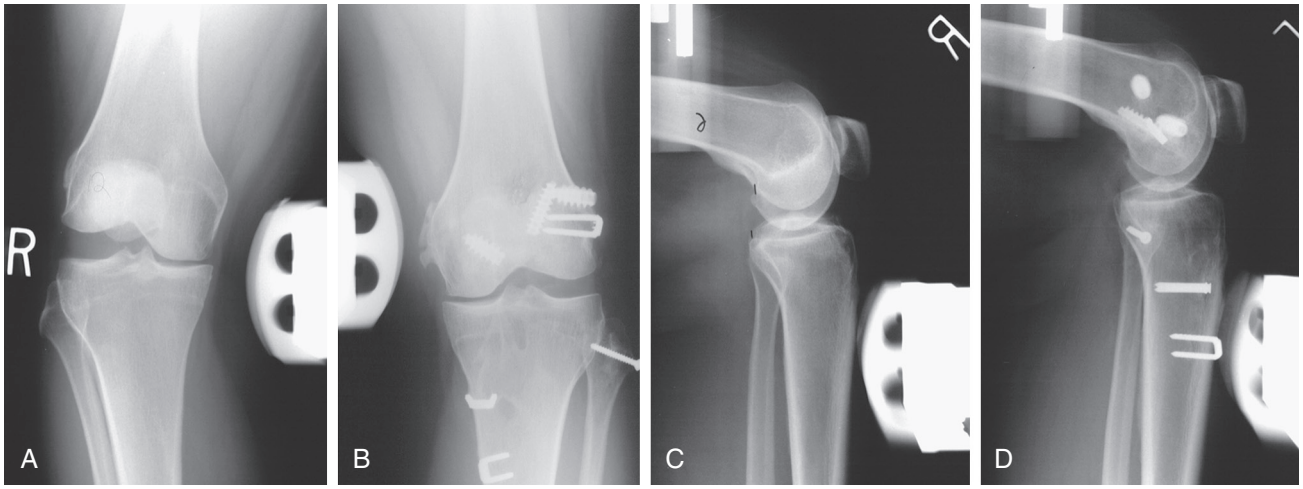


FIG 16-55 Case 7.

Our comment: This patient responded to an initial course of protected rehabilitation that allowed early surgical intervention. Otherwise, a delayed chronic reconstruction would have been performed. The postoperative therapy was done at our center with immediate knee motion to decrease the risk of arthrofibrosis. Only allografts were used not to because of operative time and to decrease postoperative pain and limitation of knee motion. The B-PT-B reconstruction of the FCL provided a strong lateral graft that allowed postoperative knee motion from 0 to 90 degrees. However, a bivalved cylinder cast was still required for 6 weeks to prevent abnormal lateral joint opening and graft disruption.

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Video Content

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17

Posterolateral Ligament Injuries: Diagnosis, Operative Techniques, and Clinical Outcomes

Frank R. Noyes, Sue D. Barber-Westin

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VIDEO CONTENT

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CRITICAL POINTS Indications

- 6- to 10-mm increased lateral tibiofemoral joint opening 20 degrees of flexion.
- ≥15 degrees increased external tibial rotation 30 degrees, 90 degrees of flexion.
- ± Varus recurvatum, standing and supine.
- ± Hyperextension gait abnormality.
- Double or triple varus knee, after osteotomy.
- Acute injuries, bony avulsions amendable to internal fixation.

INDICATIONS

The primary soft tissue–stabilizing structures of the posterolateral (PL) aspect of the knee joint are the fibular collateral ligament (FCL) and popliteus muscle-tendon-ligament unit (PMTL), including the popliteofibular ligament (PFL) and posterolateral capsule (PLC) shown in Figure 17-1. These structures function together to resist lateral joint opening (LJO), posterior subluxation of the lateral tibial plateau with tibial rotation, knee hyperextension, and varus recurvatum.[13,14,38,39,55,64]

The mechanism of injury may be contact or noncontact and usually involves a combined varus and hyperextension joint displacement. The proper management of injuries involving the PL structures requires knowledge of the complex anatomy and potential variations that may exist, the function of the major soft tissue stabilizers, appropriate diagnostic techniques, and surgical options for reconstruction. Isolated PL injuries are rare; however, on occasion an avulsion fracture at the femoral attachment occurs requiring internal fixation.[29] PL injuries are frequently accompanied by anterior cruciate ligament (ACL) or posterior cruciate ligament (PCL) ligament ruptures.[1,3,9,28]

Although the incidence of PL injury is unknown (owing to misdiagnosis or failure to detect the injury), the consequences of untreated PL ruptures are readily apparent. Chronic deficiency of the PL structures may be a factor in the failure of cruciate reconstructions[43,44,49] and

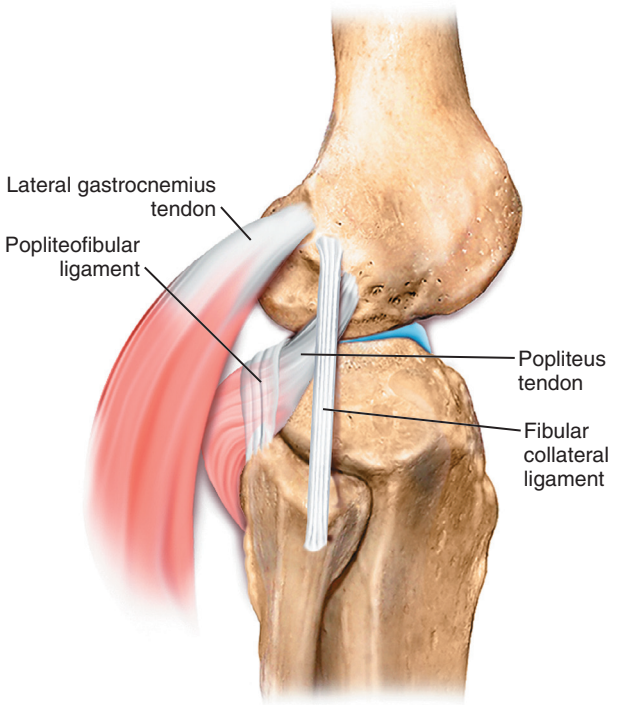


FIG 17-1 The anatomic relationships of the posterolateral structures.

may also play a role in the development of gait abnormalities and giving-way.[50,52,60] The detection and proper treatment of these problems is critical, because failure to properly treat all of the abnormalities may result in a poor outcome. The patient will complain of a varus type of instability with LJO during stance phase and show either a neutral or valgus alignment. The abnormal LJO during stance phase is always greater than that detected on the varus stress test. The patient may demonstrate the abnormal LJO by producing a varus loading at the knee joint while standing.

Knees that fulfill the double or triple varus diagnosis criteria (varus osseous malalignment with increased LJO, external tibial rotation, varus recurvatum, and knee hyperextension [see Chapter 26])[47] require high tibial osteotomy (HTO) first, followed approximately 6 months later, with an appropriate PL reconstruction. In many instances, an ACL or PCL deficiency also exists, which is corrected at the time of the PL reconstruction.

There are different surgical options available for acute knee injuries, dislocated knees with multiple ligament ruptures, chronic knees, and revision knees. The decision-making process for determining the appropriate PL procedure is discussed in detail under "Operative Treatment of Acute Posterolateral Ruptures" and "Operative Treatment of Chronic Posterolateral Ruptures" later in this chapter.

CONTRAINDICATIONS

Contraindications to PL reconstruction are findings of less than 12 mm of absolute increased lateral tibiofemoral joint opening and less than 15 degrees of increased external tibial rotation. These findings are frequently noted in knees with associated varus osseous malalignment (double varus knees) that are candidates for HTO (see Chapter 26).[40]

Patients with varus malalignment who do not undergo HTO and have associated chronic insufficiency of the PL structures are not candidates for a PL procedure. Untreated varus osseous malalignment is a frequent cause of failure of PL reconstructions.[46] In many cases, a knee hyperextension gait abnormality also exists, which must be corrected before surgery with a specific gait retraining program described in Chapter 29.[50] Failure to correct a hyperextension gait abnormality places PL reconstructions at risk for failure owing to the excessively high tensile forces placed on the PL soft tissues with weight bearing after surgery. Gait retraining usually decreases abnormally high knee extension and adduction moments to normal values.[50]

Patients with a history of prior joint infection or who are obese (body mass index > 30) are not candidates for PL reconstruction. Patients with muscle atrophy of the lower extremity undergo preoperative rehabilitation before PL reconstruction.

Knees that demonstrate a loss of lateral tibiofemoral compartment joint space, with less than 2 mm remaining on 45-degree posteroanterior (PA) weight-bearing radiographs, are usually not candidates for PL reconstruction.

CRITICAL POINTS Contraindications

- <5-mm increased lateral tibiofemoral joint opening 20 degrees of flexion.
- <10 degrees increased external tibial rotation 30 degrees, 90 degrees flexion.
- Double varus knee, in which valgus osteotomy and subsequent adaption (decreased laxity) of posterolateral structures eliminate abnormal lateral joint opening and external tibial rotation.
- Triple varus knee without correction of varus malalignment.
- Prior joint infection.
- Patient noncompliant with rehabilitation, bracing, weight-bearing restrictions.
- Hyperextension gait abnormality with no preoperative gait retraining.
- Advanced joint arthritis, <2 mm remaining joint space.

CLINICAL EVALUATION

The PL structures are injured when excessive varus, external tibial rotation, and hyperextension forces are applied to the lower extremity. A blow to the anteromedial tibia during sports participation appears to be one of the most common injury mechanisms. These injuries frequently involve rupture of other knee ligament structures, complicating the diagnosis. An isolated complete PL rupture is rare because, usually, the injury is accompanied by an ACL or PCL rupture. In some cases, the PL structures are only partially disrupted and do not require surgical restoration. It is important to correctly determine the increases in LJO, external tibial rotation, and knee hyperextension of the injured knee (compared with the contralateral knee) preoperatively and intraoperatively. The decision of whether surgical restoration of the PL structures is indicated is based on the abnormal knee motion limits, joint subluxations, and the tissues disrupted.

One frequent patient presentation is a failed ACL or PCL reconstruction owing to untreated PL insufficiency. Another patient presentation is a chronic varus osseous malalignment and underlying ACL insufficiency in which, over time, interstitial stretching and slackening of the PL structures occurred.[40,47] In these cases, HTO unloads the PL soft tissues to the extent where physiologic remodeling and shortening may subsequently occur in some knees and a PL reconstruction is not required.[47]

A comprehensive physical examination is required, including assessment of knee flexion and extension, patellofemoral indices, tibiofemoral crepitus, tibiofemoral joint line pain, and gait abnormalities. Pain in the medial tibiofemoral compartment occurs owing to

CRITICAL POINTS Clinical Evaluation

History
- Common injury mechanism blow to anteromedial tibia causing excessive knee hyperextension, external tibial rotation, lateral tibiofemoral joint opening.
- Most posterolateral injuries occur with anterior cruciate ligament or posterior cruciate ligament ruptures.

Physical Examination
- Knee flexion, extension
- Joint effusion
- Patellofemoral (medial and lateral subluxation, Q-angle, crepitus, compression pain)
- Tibiofemoral crepitus, joint line pain, compression pain
- Recurvatum (standing, supine)
- Gait (severe hyperextension stance phase)
- Muscle strength

Tibiofemoral Rotation Dial Test
- Diagnosis of posterolateral injury is based on final position of the lateral tibial plateau.
- Subluxation of the medial and lateral tibial plateaus separately at 30 degrees, 90 degrees of knee flexion.
- Produce maximal external tibial rotation, determine change in position of medial and lateral tibial plateaus separately.
- Qualitatively determine if anterior or posterior subluxation occurred in each tibial plateau.

Diagnostic Clinical Tests
- External rotation recurvatum
- Lateral and medial tibiofemoral joint opening 5 degrees, 20 degrees of flexion
- Pivot shift, Lachman
- Reverse pivot shift
- Posterior drawer, 90 degrees of flexion
- KT-2000 20 degrees of flexion, 134 N

Radiographs
- Lateral, 30 degrees of flexion
- Posteroanterior, weight-bearing, 45 degrees of flexion
- Patellofemoral axial
- Lateral stress, neutral tibial rotation select knees
- Posterior cruciate ligament ruptures: posterior stress lateral, 90 degrees of flexion, neutral tibial rotation
- Varus malalignment: full standing radiographs, mechanical axis and weight-bearing line

Cincinnati Knee Rating System
- Sports Activity and Function Form
- Occupational Rating Form
- Symptom Rating Form

increased compressive forces related to varus osseous malalignment. Pain in the PL soft tissues may occur from increased soft tissue tensile forces caused by a varus thrusting gait pattern. The abnormal knee hyperextension involves increased extension in the sagittal plane and is often accompanied by a varus alignment in the coronal plane, which has been described as a varus recurvatum alignment. Together with a varus osseous malalignment, this is referred to as a *triple varus knee* (see Chapter 26). Patients with chronic PL insufficiency have varying amounts of altered gait mechanics and knee hyperextension. Some individuals may present with a markedly abnormal gait that is severely disabling and limits ambulation. Other patients may have a less noticeable alteration because the abnormal knee hyperextension occurs only after prolonged walking and muscle fatigue. The abnormal gait pattern is characterized by excessive knee hyperextension during the stance phase, which does respond to gait retraining that initiates normal stance phase flexion (see Chapter 29). Subjective complaints of giving-way during routine daily activities, along with severe quadriceps atrophy, often accompany this gait abnormality.

The surgeon must determine all of the abnormal translations and rotations in the knee joint. The ligament injuries that result in knee hyperextension and varus recurvatum frequently involve not only the PL structures, but also other ligament and capsular structures. The biomechanic and kinematic studies that form the basis for the interpretation and diagnosis of the manual stress tests are described in Chapter 15.

The increases in LJO and external tibial rotation shown in Table 17-1 are only approximations of what would be expected with clinical injury to the PL structures. Importantly, an increase of only a few millimeters (2-5 mm) in LJO occurs with complete rupture of the FCL, whereas an increase of 5 to 9 mm occurs with complete rupture of all the PL structures (FCL, PMTL, and PFL). These values are based on biomechanic studies discussed in Chapter 15. LaPrade and colleagues[24] conducted a cadaveric study in which lateral stress radiography was applied at 12 N-m (on an experimental apparatus) and the increase in LJO over the intact state was compared with that measured during a clinician-applied load after an isolated FCL rupture and a combined FCL, PMTL, and PFL rupture. Compared with the intact state, LJO induced by the clinician-applied load increased by 2.7 mm (isolated FCL rupture) and 4.0 mm (combined PL rupture). However, the mean values showed a wide standard deviation and variation among specimens, making extrapolation to the clinical setting difficult. In addition, the lateral joint space measurement showed wide confidence intervals (CI). For an isolated FCL rupture, the mean lateral gap distance was 10.99 mm (CI, 7.8-14.3 mm) and for the combined PL rupture, the mean distance was 12.2 mm (CI, 9.3-15.2 mm). This amount of overlap indicates that it would not be possible to accurately separate a FCL rupture alone from a combined PL injury. The measurements are important and useful in providing the clinician with a baseline in interpreting lateral stress radiographs. The gap test is based on the joint separation between articular cartilage seen at arthroscopy, and not the tibiofemoral separation on a stress radiograph. Even so, the measurements are somewhat equivalent as to the increase in the amount of millimeters with PL injuries. For example, Figure 17-2 shows an approximate normal lateral gap of 4 mm at the closest point of the lateral compartment at arthroscopy. An increase of only 6 mm results in 10 mm of absolute opening at the closest point or 12 mm at the periphery, which is viewed as a positive gap test and indicative of injury to the PL structures. Fortunately in most knees, these are the lesser values and it is more common that the lateral gap exceeds these measurements, indicating that concurrent PL reconstruction is necessary.

An increase in external tibial rotation may occur with anterior subluxation of the medial tibial plateau, posterior subluxation of the lateral tibial plateau, or a combination of both subluxations. The dial test, which the senior author (F.R.N.) published,[54] allows a diagnosis of tibial rotational subluxations of the medial and lateral tibiofemoral compartments at 30 and 90 degrees of knee flexion (see Table 17-1). Other variations of this test have been described.[7,51,65]

Text continued on p. 534

TABLE 17-1 Comprehensive Knee Examination

Examination	Technique	Illustration	Grading	Significance
Dial test 30 degrees	Supine position, palpate anterior tibial prominence, medial and lateral joint, maximum external rotation, posterior position, lateral tibia (PL) subluxation, anterior position medial tibia (anteromedial subluxation).		Compare external rotation between knees.	External tibial rotation with PL subluxation. Increase 3-5 degrees FCL tear. Increase 6-10 degrees FCL tear, partial PMTL. Increase ≥15 degrees FCL, PMTL, PLC.
Dial test 90 degrees	Maximum external tibial rotation. Determine PL tibial subluxation.		Compare external rotation between knees.	Increase at 30 and 90 degrees means PCL and PLC injury. With PCL tear, degrees of external rotation difficult to estimate owing to posterior tibial position.
PL external rotation test	Knee at 90 degrees, posterior and external rotation loading on tibia, palpate posterior subluxation lateral tibiofemoral joint.		Qualitative PL tibial subluxation 90 degrees (less accurate at 30 degrees of flexion).	Similar to dial test but foot held stationary. Dial test allows tibia to externally rotate fully, providing better estimate of increased tibial rotation. PL subluxation 90 degrees, combined PCL, PLC injury.
Posterior drawer test	Knee at 90 degrees position, posterior load proximal tibia, no tibial rotation. Palpate medial tibiofemoral step-off.		Partial PCL: increase 0-9 mm translation; complete PCL tear: increase >10 mm translation.	Stress radiography more accurate. Increases >10 mm indicate secondary restraints torn or physiologic slack (combined injury).

TABLE 17-1 **Comprehensive Knee Examination—cont'd**

Examination	Technique	Illustration	Grading	Significance
Quadriceps active test	Knee position at 70-90 degrees. Foot stabilized by examiner, patient activates quadriceps by pushing foot against table or attempting to extend knee.		Qualitative. Observe, palpate tibiofemoral position.	Confirms posterior tibial subluxation, PCL injury at resting position. Quadriceps contraction produces anterior translation knee position ≥70 degrees.
Lachman (anterior drawer, 30 degrees of flexion)	Anterior load proximal tibia.		Observe anterior translation tibia; compare with opposite knee.	Estimate increase translation in millimeters. Soft endpoint, ACL not resisting anterior translation, indicates ACL tear. Increase 3- to 5-mm ACL tear. >5 mm ACL plus secondary restraints.
Pivot shift	Knee position 10-30 degrees of flexion. Anterior load tibia, gentle internal tibial rotation (subluxation) followed by posterior load, gentle external rotation (reduction).		Qualitative. Grade: I slipping. II thud, clunk with reduction. III gross anterior subluxation lateral tibiofemoral joint, anterior impingement tibia limits reduction event.	Grade I physiologic laxity, no or partial ACL tear. II ACL tear. Grade III ACL tear plus secondary restraints lax.
Reverse pivot shift test	Similar loading as pivot shift.		PL subluxation with external rotation confused for reduction in pivot shift. No abnormal anterior tibial subluxation.	Observe obvious PL tibial subluxation with posterior and external rotation loading. Dial test more accurate.
Varus stress testing	Thigh supported on examination table. Knee position 0 degree, 30 degrees. Varus load with no external-internal tibial rotation. Palpate lateral joint line opening.		Subtle 30 degrees increase LJO. 2-4 mm complete FCL tear, further increase LJO with PLC injury.	Stress radiography more accurate. 30 degrees of flexion. Increase 2- to 4-mm FCL tear. Increase 5- to 9-mm complete PLC tear (also perform valgus stress test).

Continued

TABLE 17-1 **Comprehensive Knee Examination—cont'd**

Examination	Technique	Illustration	Grading	Significance
External rotation recurvatum test	Grasp and hold both feet above table, allow gravity knee hyperextension.		Qualitative. Tibia externally rotates, varus position caused by PL joint opening, knee.	Hyperextension, indicates PLC injury, >10 degrees frequently associated ligament injury (ACL, PCL).
Standing recurvatum test	Patient stands, feet together pushes knees backward into hyperextension, compare knees.		Qualitative, observe varus hyperextension position (can be measured with goniometer). Increased loading over supine recurvatum test brings out deformity.	10 degrees hyperextension with varus alignment PLC disruption, lateral, PL joint abnormal opening, often combined PLC, ACL tear, confirm with other tests.
Standing frontal alignment	Standing 0-5 degrees of flexion. Avoid hyperextension.		Confirm varus alignment. Hip-knee-ankle radiographs 0-5 degrees of flexion.	Classify primary, double, triple varus based on all tests (see Chapter 26).

TABLE 17-1 Comprehensive Knee Examination—cont'd

Examination	Technique	Illustration	Grading	Significance
Knee hyperextension gait or varus thrust	Observe gait walking to and from examiner.		Qualitative. Knee goes into hyperextension on stance phase. Knee has varus thrust without hyperextension.	Two hyperextension patterns (see Chapter 29). Forward trunk position, loss of quadriceps control, ankle dorsiflexion push-off, requires gait retraining. Varus thrust increases medial compartment loads and tensile forces lateral ligaments, osteotomy may be required.
Range of motion	Perform passive flexion-extension.	 	Normal 3-0-135 degrees. Hyperextension to neutral to flexion	10 degrees hyperextension posterior capsule possible ACL or PCL injury. ≥15 degrees multiple ligament injury.
Effusion, soft tissue swelling, pain	Palpate joint for effusion, tenderness, meniscus, ligament attachments.		Qualitative. Complex examination necessary + meniscus tests.	Partial to complete tears PLC. FCL local tenderness, pain varus, dial tests.
Patellofemoral examination	Comprehensive examination. All tests. Alignment, PF crepitus, medial/ lateral translation, patella height.		See Chapter 35.	Increased external tibial rotation 30 degrees, PLC tear, produces abnormal lateral shifting tibial tubercle, increases Q-angle.

Continued

TABLE 17-1 Comprehensive Knee Examination—cont'd

Examination	Technique	Illustration	Grading	Significance
Neurovascular examination	Complete examination. Both lower extremities, PT, DP pulses, lower extremity muscle function.			Peroneal nerve injuries associated with severe PLC disruption (10%-30%). Arterial studies indicated multiple ligament injuries, dislocations.

ACL, Anterior cruciate ligament; *DP*, dorsalis pedis; *FCL*, fibular collateral ligament; *LJO*, lateral joint opening; *PCL*, posterior cruciate ligament; *PF*, patellofemoral; *PL*, posterolateral; *PLC*, posterolateral capsule; *PMTL*, popliteus muscle-tendon-ligament; *PT*, posterior tibial.

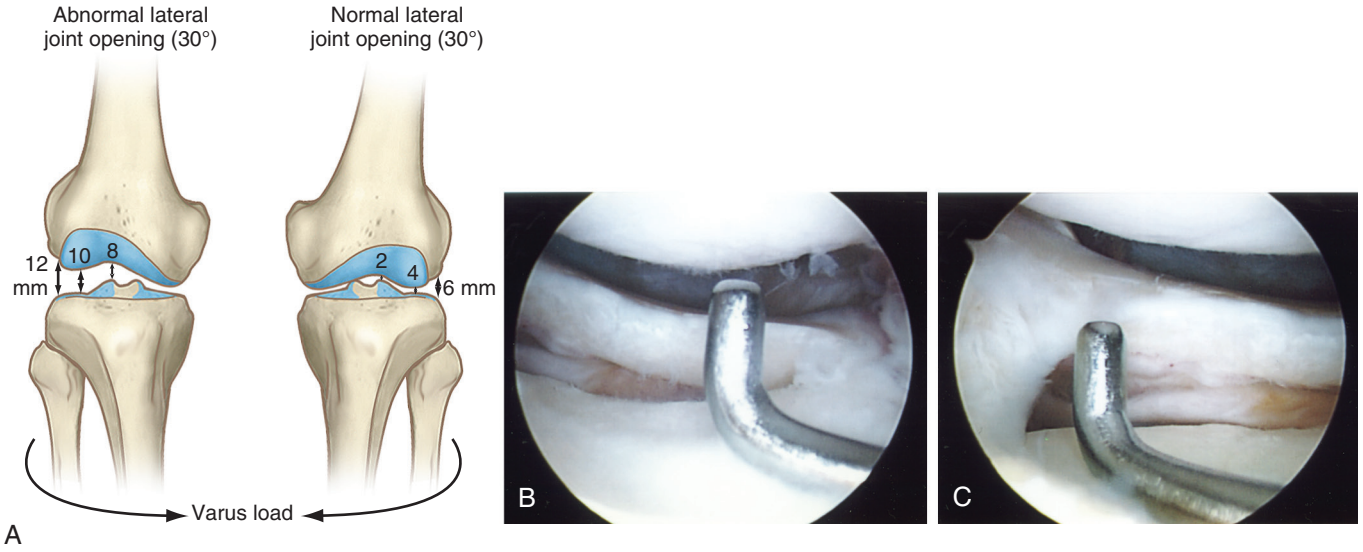


FIG 17-2 The gap test. **A,** The amount of lateral tibiofemoral joint opening is measured with the knee at 25 degrees of flexion. Knees with insufficiency of the posterolateral structures will demonstrate 12 mm of joint opening at the periphery of the lateral tibiofemoral compartment, 10 mm at the midportion of the compartment, and 8 mm at the innermost medial edge. **B,** Normal gap test. **C,** Abnormal gap test.

The position of the medial and lateral tibial plateau is assessed at the starting position (neutral tibial rotation) with the knee flexed to 30 and 90 degrees and at the final position with the tibia in maximal external rotation. The examiner palpates the position of the medial and lateral tibial plateau, which is compared with the normal knee to assess whether a subluxation (anterior or posterior) of the medial or lateral tibial plateau is present. An increase in internal tibial rotation occurs with both lateral ligament, medial ligament, and PCL disruption (see Chapter 15). The axis of tibial rotation is observed in the involved knee and compared with the normal knee to detect a shift in the medial or lateral tibiofemoral compartment during tibial rotation. It is not recommended that the dial test be performed in the prone position because the tibiofemoral joint cannot be accurately palpated to distinguish an anteromedial from a PL tibial subluxation.

It is not possible to clinically determine the actual millimeters of translation of the medial and lateral tibial plateaus in reference to the femoral condyle. A qualitative determination is made of the anterior or posterior subluxation of the medial or lateral tibiofemoral joint.

With PL injuries, there is an abnormal lateral deviation of the tibial tubercle in the dial test compared with the opposite knee.

The use of the dial test in knees with PCL ruptures requires maintenance of a normal anatomic tibiofemoral position. This is accomplished by applying an anterior translation, loading the ACL in both limbs, during the external tibial rotation. It is still necessary to use the supine position so that the examiner can palpate the tibiofemoral position.[61] The dial test is less accurate with a PCL rupture because it is difficult to compare limbs, and other tests to be described (LJO, gap test at arthroscopy, varus recurvatum) for the integrity of the PL structures need to be carefully assessed.

When a posterior subluxation of the lateral tibial plateau is positively identified by the tibiofemoral rotation test, additional tests must be conducted to determine the integrity of other ligament structures. The amount of LJO at 5 and 20 degrees of knee flexion should be determined to further assess the integrity of the FCL and other secondary ligament restraints. The posterior tibial subluxation of the central tibial and medial tibiofemoral joint determines the amount of increased translation because of a PCL injury, which adds to the maximum posterior subluxation to the lateral compartment with external tibial rotation.

The presence of a varus recurvatum in both the supine and standing positions must be carefully assessed. Often, the varus recurvatum reaches its maximum position when the patient is standing and asked to maximally hyperextend both knees.

The appropriate tests to determine the integrity of the ACL and PCL are performed, including KT-2000 (MEDmetric) arthrometer testing at 20 degrees of flexion (134 N) to quantify total anteroposterior (AP) displacement. The pivot shift test is recorded on a scale of 0 to III (grade 0, no pivot shift; grade I, slip or glide; grade II, jerk or clunk; grade III, gross subluxation with impingement of the PL aspect of the tibial plateau against the femoral condyle). A misdiagnosis of a positive pivot shift test may occur with PL injuries as the lateral tibial plateau is brought to a reduced position (starting from a posterior subluxated position) with knee extension and then posteriorly subluxates with knee flexion (reverse pivot shift test). The medial posterior tibiofemoral step-off on the posterior drawer test is done at 90 degrees of flexion.

Radiographs taken during the initial examination include AP, lateral at 30 degrees of knee flexion, weight-bearing PA at 45 degrees of knee flexion, and patellofemoral axial views. Lateral stress radiographs may be required of both knees (20 degrees of flexion, neutral tibial rotation, and 67-N varus force). A comparison is made of the millimeters of lateral tibiofemoral compartment opening between knees.

A lateral radiograph is used to determine the approximate length required for FCL anatomic grafts. The distance from the anatomic femoral insertion site to the anatomic fibular insertion site is measured and adjusted for magnification. A measurement of the patellar tendon length is also made when a bone-patellar tendon-bone (B-PT-B) FCL autograft is planned; however, in most knees, a B-PT-B allograft is used, as will be discussed.

Posterior stress radiographs are obtained in patients with PCL ruptures, especially those in which the distinction of a partial versus complete PCL deficiency is difficult to determine on clinical examination.[15] A lateral PCL stress radiograph is taken of each knee at 90 degrees of flexion. The limb is placed in neutral rotation with the tibia unconstrained and the quadriceps relaxed, and 89-N force applied to the proximal tibia. Measurement is made of the millimeters of posterior tibial translation in both knees. Knees with 10 mm or more of increased posterior tibial translation are considered candidates for PCL reconstruction.

Full standing radiographs of both lower extremities, from the femoral heads to the ankle joints, are done in knees with varus lower extremity alignment. The mechanical axis and weight-bearing line are measured to determine whether HTO is indicated.[11]

Patients complete questionnaires and are interviewed for the assessment of symptoms, functional limitations, sports and occupational activity levels, and patient perception of the overall knee condition according to the Cincinnati Knee Rating System (CKRS; see Chapter 41).[2]

CLASSIFICATION AND TREATMENT OF PARTIAL TO COMPLETE PL INJURIES

The classification and treatment of first-, second-, and third-degree acute PL injuries are detailed in Table 17-2. It is important to diagnose partial tears of the PL structures, with a mild to moderate increase in LJO and external tibial rotation, to allow protection and maintain lateral tibiofemoral joint closure in the initial 3 weeks to allow "stick-down" and healing of lateral soft tissues. This is a program similar to that recommended for medial ligament ruptures (see Chapter 19).

PREOPERATIVE PLANNING: TIMING OF SURGERY

Acute Injuries

There is a distinct advantage for repairing completely disrupted PL structures and meniscal attachments in acute injuries (Fig. 17-3). At the time of surgery, extensive disruption of these structures is observed. Careful dissection is required to identify anatomic tissue planes and maintain an intact vascular and neural supply. The so-called golden period to perform an acute surgical repair is within 7 to 14 days of the injury. After this time, scar tissue will obliterate tissue planes and make the dissection and repair difficult.

A lower extremity venous ultrasound is obtained before surgery in acute multiligament knee injuries that have swelling and soft tissue damage to detect occult venous thrombosis that requires urgent treatment and contraindicates surgery. An initial delay in surgery for 5 to 7 days allows for observation of the neurovascular status, soft tissue swelling, skin integrity, and some clearing of hemorrhage in soft tissues in the injured extremity.

During this time, the lower extremity is supported in a soft-hinged full-leg brace in extension with a well-padded compression dressing. In knees with extensive damage to the PL structures and PCL, a bivalved cylinder cast with a posterior plaster shell and posterior foam calf pad may be required to provide added stability and prevent posterior tibial subluxation. Reduction of the tibiofemoral joint is verified by a lateral radiograph. Lower limb elevation, ice, and compression are important. The physical therapist initiates early protected knee motion, patellar mobilization, active quadriceps function, and electrical muscle stimulation. Dislocated knees scheduled for surgery require vascular consultation, ankle/brachial studies (ankle/brachial index ≥90%), and possible arteriography to exclude arterial injuries, even when intact peripheral pulses are present.

Contraindications to acute surgical repair are excessive soft tissue swelling, hemorrhage, and edema that are frequently present in dislocated knees with multiple ligament ruptures. The operative procedure adds to the injury by increasing edema and soft tissue swelling, risk of infection, vascular problems (including compartment syndromes), and skin flap necrosis. In these cases, it is preferable to treat the acute injury and perform ligament reconstructive procedures later after tissue swelling is resolved and muscle function and knee motion have been restored.

In addition, there is a significant incidence of knee arthrofibrosis after acute surgical treatment of knee dislocations, which is lessened

TABLE 17-2 Diagnosis and Classification of Acute Posterolateral Injuries

	First Degree	Second Degree	Third Degree*		
Anatomic lesion	Minor tearing fibers	Partial tears, one third to two third fibers	FCL tear[†]	FCL tear, partial tear PMTL, PL capsule	FCL tear, PMTL tear, PL capsule tear
Signs	Minor tenderness and swelling	Tenderness and swelling lateral tissues		Tenderness and swelling lateral tissues	
Increase in lateral joint opening[‡]					
30 degrees	None	None	2-3 mm	2-5 mm	5-9 mm
0 degree	None	None	None	None	3-5 mm
Increase in external tibial rotation (dial test, 30 degrees)[‡]	None	None	3-5 degrees	6-10 degrees	15 degrees
Treatment	Progress per symptoms, no crutches	Progress per symptoms, soft support brace	Bivalved cylinder cast 3 wk ROM 0-90 degrees 2 wk Support brace 3-6 week Wean crutches 3-6 wk		Operative repair, reconstruction; usually associated ACL, PCL

*Avulsion FCL, popliteus tendon: surgical indication to reattach.
[†]Even though FCL shows complete tear, adjacent lateral tissues maintain ligament continuity for healing. Bivalved cylinder cast with protected motion, maintain lateral tibiofemoral joint closure.
[‡]See Chapter 15. Increases related to degrees of knee flexion, minor opening may be less under clinical conditions with lower joint loading.
ACL, Anterior cruciate ligament; *FCL*, fibular collateral ligament; *PCL*, posterior cruciate ligament; *PL*, posterolateral; *PMTL*, popliteus muscle-tendon-ligament; *ROM*, range of motion.

CRITICAL POINTS Preoperative Planning

Acute Injuries
- Golden period acute surgical repair: 7-14 days after injury.
- Lower extremity venous ultrasound, vascular consult for multiple ligament ruptures.
- Delay surgery 5-7 days, observe neurovascular status, soft tissue swelling, skin integrity.
- Soft hinged full-leg brace, well-padded compression dressing.
- PCL rupture: bivalved cast with posterior plaster shell, posterior calf pad.
- Verify tibiofemoral reduction with lateral radiograph in multiligament injuries.
- MRI for location of major ligament disruptions.
- Protected knee motion, patellar mobilization, isometrics.
- Contraindications to acute surgery in dislocated knees: excessive soft tissue swelling, hemorrhage, edema. Delay reconstruction until swelling resolved, muscle function and knee motion restored.

Chronic Injuries
- Muscle atrophy requires preoperative rehabilitation.
- Hyperextension gait abnormality requires gait-retraining program before PL reconstruction.
- Varus osseous malalignment requires osteotomy before PL reconstruction.
- Absent lateral meniscus, early tibiofemoral arthritis, consider lateral meniscus transplant.

Cruciate Graft Reconstruction
- Ensure B-PT-B, Achilles tendon allografts available.
- Determine appropriate grafts for ACL or PCL reconstruction.

ACL, Anterior cruciate ligament; *B-PT-B*, bone-patellar tendon-bone; *MRI*, magnetic resonance imaging; *PCL*, posterior cruciate ligament; *PL*, posterolateral.

with a staged approach. In our experience, the majority of multiligament disruptions in dislocated knees are not candidates for acute surgical procedures. A delay in surgical reconstruction results in a decreased incidence of knee arthrofibrosis and markedly improves surgical outcomes. Other obvious contraindications include open wounds and skin abrasions.

Magnetic resonance imaging (MRI) provides important information regarding ligament ruptures, articular cartilage damage, and meniscus tears. Frequently, the sites of rupture to the FCL, popliteus muscle and tendon, PFL, and meniscal attachments may be identified before surgery. One note of caution is the edema and swelling in the PL tissues leads to a conclusion of greater tissue damage and disruption than what is actually encountered at surgery.

Chronic Injuries

Patients with chronic knee injuries often present with severe lower limb muscle atrophy requiring months of preoperative rehabilitation. Patients with a hyperextension gait abnormality must complete a gait retraining program[50] described in detail in Chapter 29. This program is done in addition to lower extremity muscle strengthening exercises. In our experience, patients will convert to a more normal gait pattern after 4 to 6 weeks of training.

Varus osseous malalignment must be corrected before chronic PL reconstruction, as described previously. Failure to address varus malalignment will greatly increase the risk of failure of any PL procedure (Fig. 17-4). In anatomic PL reconstructions, the ligament surgery is staged after healing of the HTO. The indications for the various PL procedures are described in detail under the "Operative Treatment of Acute Posterolateral Ruptures" and "Operative Treatment of Chronic Posterolateral Ruptures" sections.

Patients who have undergone prior lateral meniscectomy and who demonstrate early tibiofemoral arthritis are considered for a staged lateral meniscus transplantation after the PL reconstruction.[48]

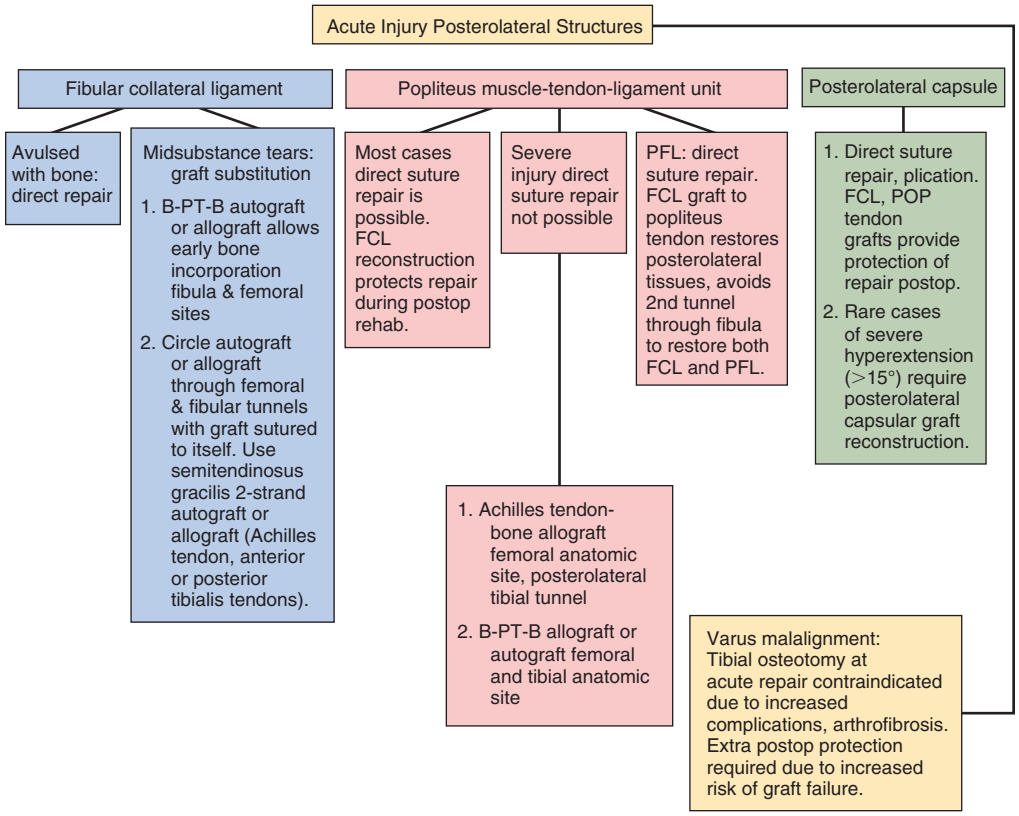


FIG 17-3 Algorithm for treatment of acute injuries to the posterolateral structures. *B-PT-B*, Bone-patellar tendon-bone; *FCL*, fibular collateral ligament; *PFL*, popliteofibular ligament; *POP*, popliteus.

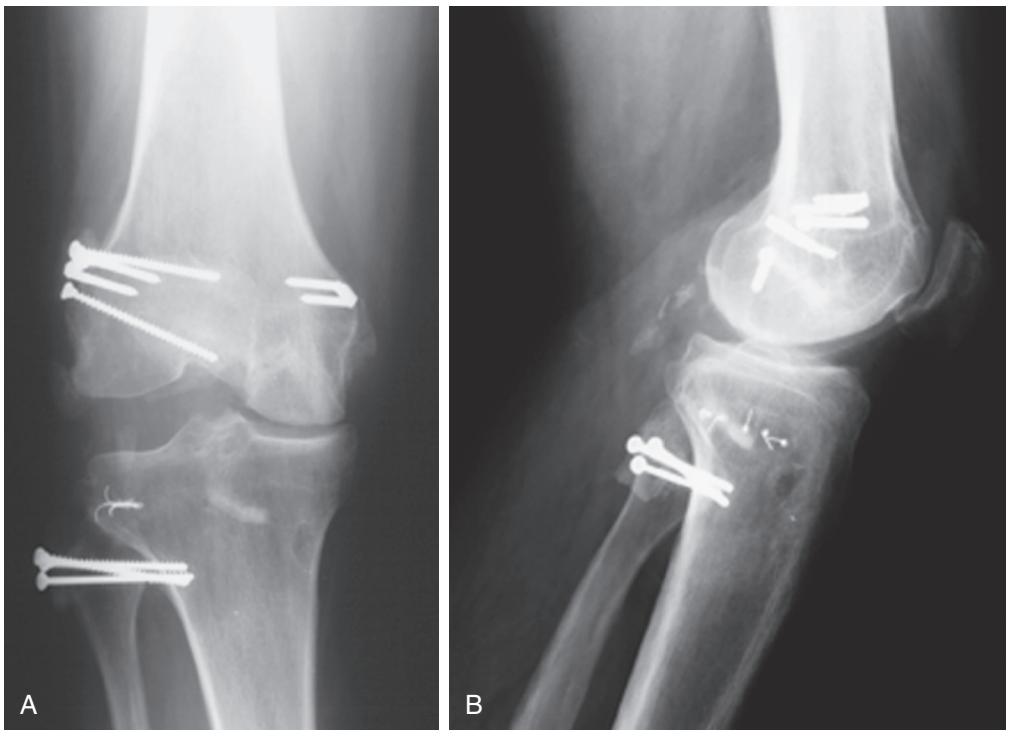


FIG 17-4 Standing anteroposterior; **(A)** and lateral **(B)** radiographs of a 28-year-old man referred to our center 14 months after failure of an acute repair of the posterolateral structures and posterior cruciate ligament allograft reconstruction. The patient had underlying varus osseous malalignment, which likely was a factor in the failure of the ligament reconstructions. This malalignment requires correction before revision surgery. (From Noyes FR, Barber-Westin SD. Posterior cruciate ligament revision reconstruction. Part 1: causes of surgical failure in 52 consecutive operations. *Am J Sports Med.* 2005;33:646-54.)

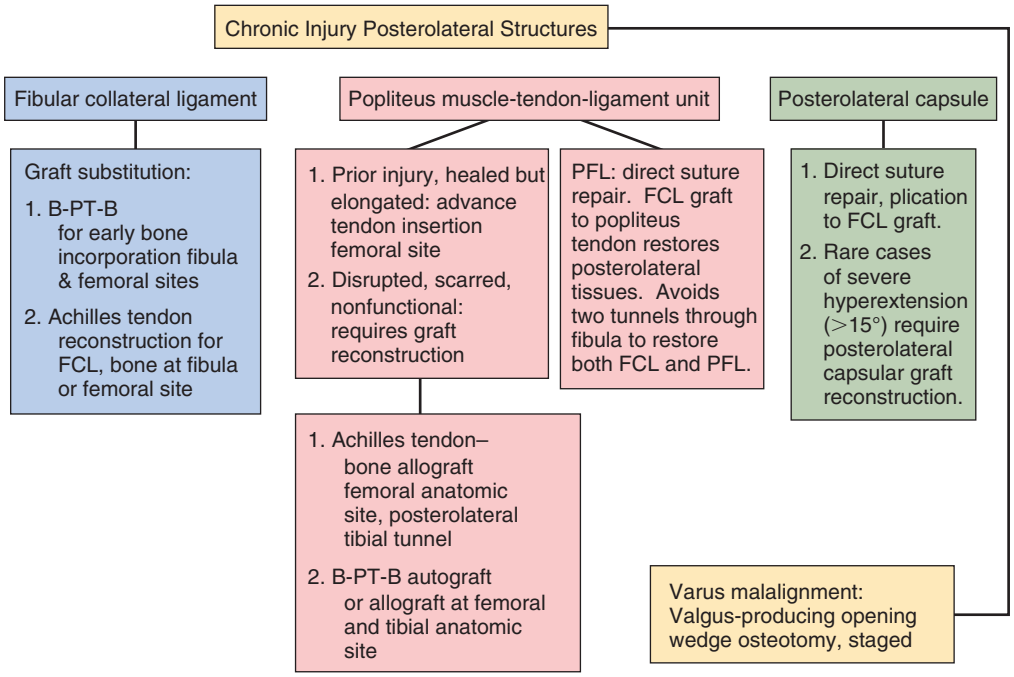


FIG 17-5 Algorithm for treatment of chronic injuries to the posterolateral structures. *B-PT-B*, bone-patellar tendon-bone; *FCL*, fibular collateral ligament; *PFL*, popliteofibular ligament.

Cruciate Graft Reconstruction

The majority of patients who undergo PL reconstruction require a concomitant ACL or PCL reconstruction (Fig. 17-5). The appropriate grafts for the cruciate procedures should be determined; autogenous tissues with bony fixation are preferred. However, the surgeon should ensure that B-PT-B and Achilles tendon-bone (AT-B) allografts are available the day of surgery. These will be required if autogenous tissue is unavailable or not suitable for the PL or cruciate procedures.

INTRAOPERATIVE EVALUATION

All knee ligament tests are performed after the induction of anesthesia in both the injured and contralateral limbs. The amount of increased anterior tibial translation, posterior tibial translation, LJO, and external tibial rotation is documented. A thorough arthroscopic examination is conducted, documenting articular cartilage surface abnormalities (see Chapter 44) and the condition of the menisci.[53]

The gap test is done during the arthroscopic examination.[47] The knee is flexed to 30 degrees and a varus load is applied. A calibrated nerve hook is used to measure the amount of lateral tibiofemoral compartment opening (see Fig. 17-2). Knees with 12 mm or more of joint opening at the periphery of the lateral tibiofemoral compartment require a PL reconstructive procedure.

In knees that undergo ACL reconstruction, the millimeters of joint opening at the intercondylar area at the site of the ACL graft is the critical distance in the gap test. Increases in LJO will occur postoperatively, allowing increases in ACL graft length. This space is normally 3 to 5 mm under varus loading.

Following the surgical exposure, the FCL and its fibular head and femoral attachment sites, the PMTL, PL capsule, and PFL are inspected. The distal popliteal tibia and fibula attachments of the popliteus tendon are identified and inspected to determine the appropriate surgical treatment. All of the lateral and PL structures, including meniscus attachments, are inspected in a stepwise manner, to be described. The peroneal nerve is identified and protected at all times.

CRITICAL POINTS Intraoperative Evaluation

- Repeat all knee ligament tests under anesthesia, both limbs.
- Rate all articular cartilage surfaces for abnormalities, size of lesion
  - Normal
  - Grade 1, softening
  - Grade 2A, fissuring & fragmentation <50% depth of the articular surface
  - Grade 2B, fissuring & fragmentation >50% depth of the articular surface
  - Grade 3, subchondral bone exposed
- Gap test at arthroscopy
  - Knee 30 degrees of flexion
  - Varus load
  - Measure millimeters lateral tibiofemoral opening with calibrated nerve hook
- Surgical exposure inspection
  - Peroneal nerve
  - FCL, fibular and femoral attachments
  - PMTL, PLC, PFL
  - Popliteus muscle, tendon attachments
  - Meniscus attachments

FCL, Fibular collateral ligament; *PFL*, popliteofibular ligament; *PLC*, posterolateral complex; *PMTL*, popliteus muscle-tendon-ligament.

OPERATIVE TREATMENT OF ACUTE PL RUPTURES

Operative Setup and Patient Positioning

The patient is instructed to use a chlorhexidine soap scrub of the operative limb ("toes to groin") three days before and the morning of

surgery. Lower extremity hair is removed by clippers, not a shaver. Antibiotic infusion is begun one hour before surgery. A nonsteroidal antiinflammatory drug (NSAID) is given to the patient with a sip of water upon arriving on the morning of surgery (which is continued until the fifth postoperative day unless there are specific contraindications to the medicine). The use of an NSAID and a postoperative firm double-cotton, double-Ace compression dressing for 72 hours (cotton, Ace, cotton, Ace-layered dressing) has proven very effective in diminishing soft tissue swelling and is used in all knee surgery cases. In complex multiligament surgery, the antibiotic is repeated at 4 hours and continued for 24 hours. A urinary indwelling catheter is not used unless there are specific indications. The patient's urinary output and total fluids are carefully monitored during the procedure and in the recovery room. The knee skin area is initialed by the surgeon before entering the operating room, with a nurse observing the procedure. The identification process is repeated with all operative personnel with a "time out" before surgery to verify the knee undergoing surgery, procedure, allergies, antibiotic infusion, and special precautions that apply. All personnel provide verbal agreement.

The patient is placed supine on the operative table and appropriately padded. The knee portion of the table is flexed 20 degrees, and the table is tilted into a mild Trendelenburg position. A posterior thigh pad is placed behind the proximal thigh to suspend the knee joint at 20 to 30 degrees of knee flexion. There is no pressure exerted on the posterior popliteal space, allowing the posterior neurovascular tissues and popliteal tissues to drop posteriorly away from the operative approach. A common mistake is to place a posterior bolster in the popliteal space that pushes the neurovascular structures into the operative dissection.

In cases of acute dislocation, the entire lower limb is draped free to allow vascular checks of the anterior and posterior tibial pulses at the foot during the operative procedure.

An initial arthroscopic examination is performed under low-pressure conditions with a free or controlled open outflow to prevent fluid extravasation. The arthroscopic examination confirms damage to intraarticular structures and allows photographic documentation of the injury. If a leg holder is used, it is removed for the open surgery.

The tourniquet is placed at the proximal portion of the thigh with appropriate padding. The tourniquet is inflated (275 to 300 mm Hg) during the initial exploration of the ligamentous injury and identification of the common peroneal nerve (CPN). The tourniquet may often be deflated for the remainder of the procedure. The surgeon may elect to be seated, directly facing the lateral aspect of the knee, with a headlight for careful dissection of the lateral soft tissues including the CPN.

CRITICAL POINTS Operative Treatment of Acute Posterolateral Ruptures: Operative Setup and Patient Positioning

- "Time out" before surgery: verify signed knee at surgery, procedure, allergies, antibiotic infusion, and special precautions.
- Complete examination of knee joint under anesthesia, compare with opposite knee.
- Acute dislocation or questionable vascular status: drape entire lower limb free to check anterior and posterior tibial foot pulses during procedure.
- Arthroscopic examination under low pressures with free or controlled open outflow to prevent fluid extravasation. Confirm damage to intraarticular structures, photograph injury.
- Place tourniquet at proximal thigh with appropriate padding. Inflate (275-300 mm Hg) during initial exploration, identify common peroneal nerve. Deflate for surgical repair, reconstruction.

Identification of Ligament and Soft Tissue Rupture Pattern

A 10- to 12-cm skin incision is made in a straight line centered over the joint line and 1 cm posterior to the iliotibial band (ITB) attachment at the tibia (Fig. 17-6, *A*). After careful mobilization of the skin flaps, the ITB, biceps tendon, and lateral structures are encountered.

Before dissection of the lateral aspect of the knee, the location of the CPN must be identified. If the CPN cannot be easily palpated and its course determined, then it is necessary at this point to expose and identify the nerve along the entire lateral aspect of the knee. The CPN does not have to be removed from its anatomic bed but requires protection throughout the subsequent surgery.

In the majority of knees, the ITB will be intact or demonstrate only partial tearing. In select cases, the ITB will be completely disrupted at the joint line or avulsed off its tibial attachment at Gerdy's tubercle. If the ITB is intact, an incision is made along its posterior border and the ITB is elevated proximally to allow visualization of all of the underlying structures (see Fig. 17-6, *B*).

The lateral capsular tissues and meniscal attachments are the next structures visualized. A vertical incision is made into the anterior third of the capsule and extended to the lateral meniscus just anterior to the anterolateral ligament attachment. The popliteus tendon and meniscus attachments at the femoral popliteal recess are identified. Frequently, it is necessary to repair the anterior inferior meniscal fasciculi (Fig. 17-7) and tibial meniscal attachments. Careful varus stress is placed on the knee joint to allow inspection of the lateral meniscus attachments and tibiofemoral articular cartilage. In some knees, an additional anterior ITB incision is required for visualization of underlying anatomy (see Fig. 17-6, *C*).

The fibular head and attachments of the biceps femoris short and long head are the next structures visualized, which have been described in detail in Chapter 2. The two tendinous components (direct and anterior arms) and one of the fascial components (lateral aponeurotic expansion) make up the key portion of the long head anatomy. The other fascial components are the reflected arm and the anterior aponeurotic expansion.

CRITICAL POINTS Operative Treatment of Acute Posterolateral Ruptures: Identification of Ligament and Soft Tissue Rupture Pattern

- Skin incision straight line 10-12 cm in length, centered over joint line, 1 cm posterior to the ITB attachment at tibia.
- Intact ITB: incision along its posterior border to allow anterior displacement, visualize all underlying structures.
- Small bursa located superficial and anterolateral to distal portion of FCL: open to allow better exposure of distal FCL attachment.
- Proximal third of posterior capsule attaches to proximal portion of gastrocnemius muscle and fabellum.
- Interval between posterior capsule and gastrocnemius tendon entered just above fibula.
  - Exposes PL structures, popliteus muscle tibial attachments, popliteus muscle tendon junction, PFL, popliteus tendon attachment at the femur, fabellofibular ligament.

FCL, Fibular collateral ligament; *ITB*, iliotibial band; *PFL*, popliteofibular ligament; *PL*, posterolateral.

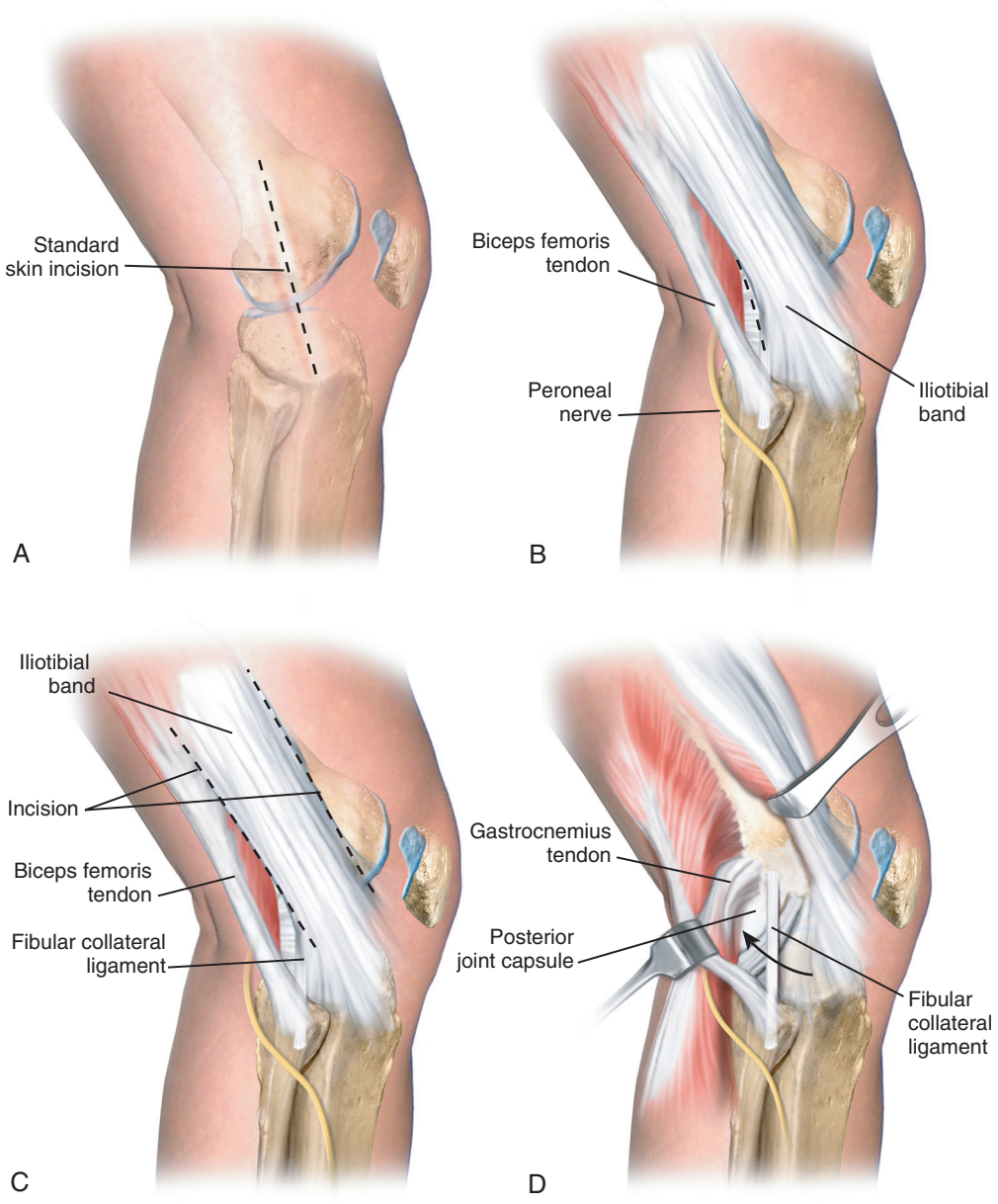


FIG 17-6 Posterolateral (PL) surgical technique. **A**, Site for the skin incision. **B,** Incision site in the interval between the posterior edge of the iliotibial band (ITB) and the anterior edge of the biceps tendon. **C,** In chronic cases with severe scarring, it may be necessary to add an anterior incision and displace the ITB posteriorly during the reconstructive procedure to allow better exposure. **D,** With the ITB retracted anteriorly, the interval between the lateral head of the gastrocnemius and the PL aspect of the capsule is opened bluntly, just proximal to the fibular head, without entering the joint capsule proximally.

The most proximal component is the reflected arm. It originates just proximal to the fibular head and ascends anteriorly to insert on the posterior edge of the ITB. The direct arm inserts onto the PL edge of the fibula just distal to the tip of the styloid. A portion of the anterior arm inserts onto the lateral aspect of the fibular head, and the rest continues distally just lateral to the FCL. Portions of the anterior arm ascend anteriorly, forming the lateral aponeurotic expansion that attach to the posterior and lateral aspect of the FCL. Here, a small bursa separates the anterior arm from the distal fourth of the FCL. The anterior arm forms the lateral wall of this bursa (see Fig. 2-15). This is an important surgical landmark, because a small horizontal incision can be made here, 1 cm proximal to the fibular head, to enter this bursa and locate the insertion of the FCL into the fibular head. The anterior arm then continues distally over the FCL, forming the anterior aponeurosis, which covers the anterior compartment of the leg. The primary areas of injury are tendon avulsions off of the fibula, which often have a major osseous component that can be repaired. In addition, the fascial extensions anteriorly and laterally are repaired.

The short head of the biceps courses just deep (or medial) and anterior to the long head tendon, sending a majority of its proximal muscular fibers to the long head tendon itself.[63] It has six distal attachments described in detail in Chapter 2. The most important attachments are those of the direct arm, the anterior arm, and the capsular arm.

The capsular arm originates just before the short head reaching the fibula and continues deep to the FCL to insert onto the PL knee capsule and fabella. Here the fibers of the capsular arm continue distally as the fabellofibular ligament. Just distal to the capsular arm, a capsulo-osseous layer forms a fascial confluence with the ITB (the biceps-capsulo-osseous iliotibial tract confluent). The direct arm of the short head inserts onto the fibular head just posterior and proximal to the direct arm of the long head tendon. The anterior arm then continues medial or deep to the FCL, partially blends with the anterior tibiofibular ligament, and inserts onto the tibia 1 cm posterior to Gerdy's tubercle. This site is also the attachment of the mid-third lateral knee capsule. The lateral aponeurotic expansion of the short head inserts onto the medial aspect of the FCL. The FCL may be torn at its femoral attachment or within its substance or avulsed along with the biceps attachment at the fibula.

Proceeding posteriorly, the next structure encountered is the lateral gastrocnemius muscle tendinous attachment to the femur. The proximal third of the posterior capsule attaches to the proximal portion of the gastrocnemius muscle and fabellum (osseous or cartilaginous analogue).

The interval between the posterior capsule and the gastrocnemius tendon is entered just above the fibula, similar to the exposure for a lateral meniscus repair. This exposes the popliteus muscle tibial attachments, popliteus muscle-tendon junction, PFL, popliteus tendon attachment at the femur, and fabellofibular ligament (see Fig. 17-6, *D*).

In dissection studies, LaPrade and coworkers[23] described a fabellum (osseous or cartilaginous) present in all specimens. This structure forms an attachment for the oblique popliteal ligament and fabellofibular ligament, which along with the posterior capsule, are important restraints for limiting knee hyperextension. Although individual capsular components and structures are difficult to discern with extensive capsular ruptures, it is important to repair disrupted posterior capsular tissues after completion of the initial dissection.

Common Peroneal Nerve Identification

It is important at the initial stages of the dissection to palpate and determine the location of the CPN. To expose the CPN, it is safest to begin in the proximal aspect of the operative exposure. A large retractor is used to elevate the muscular portion of the biceps femoris, placing the fascial tissues beneath the biceps muscle under gentle tension. This gentle upward displacement of the biceps muscle and vastus lateralis muscle is key to visualize and dissect the CPN, because the normal curviform undulations are removed and the CPN assumes a straighter appearance (Fig. 17-8). The investing crural fascia is incised over the CPN to the fibula.

The CPN and its branches are not removed from their normal anatomic position to avoid damaging the delicate blood supply, particularly in the region where the CPN approaches and then passes around the fibular neck. Kadiyala and associates[18] reported measurements in cadaveric specimens of the blood supply to the CPN in the popliteal fossa and fibular neck region. These investigators hypothesized that the susceptibility of the CPN to injury or lack of a response to operative treatment when injured may be related to deficiencies in intraneural and extraneural vascular supply and anastomoses.

The most common source of blood supply to the proximal portion of the CPN is a direct branch of the popliteal artery. This branch divides into proximal and distal anastomotic vessels that run in the connective tissue sheath of the nerve and anastomoses with the anterior recurrent tibial artery. The vessels, located in the epineurium, give rise to many small vessels of fine caliber, which extend 20 to 30 mm within the substance of CPN. It is important not to disturb this blood supply. Kadiyala and associates[18] noted that the blood supply of the CPN was somewhat sparse with poor vascularization. A connection of

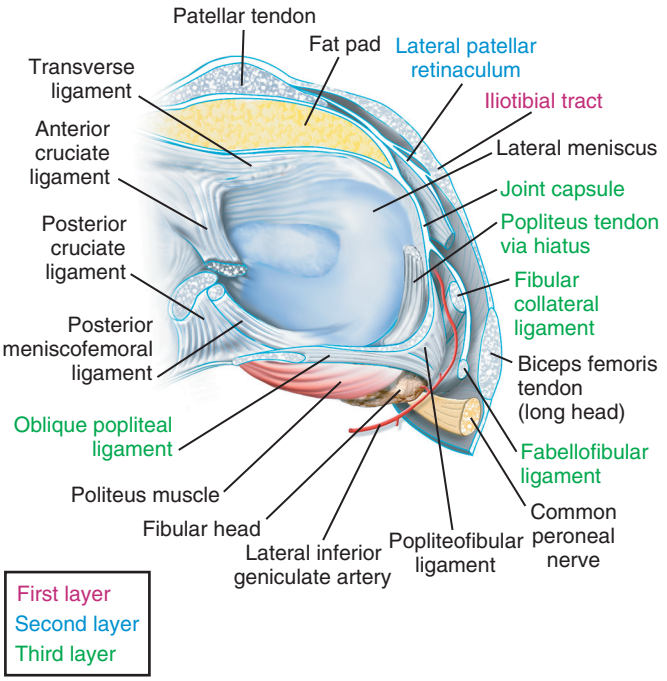


FIG 17-7 Illustration of the popliteus tendon and its surrounding popliteomeniscal fascicles and lateral meniscus attachments that are frequently disrupted, requiring repair.

CRITICAL POINTS Operative Treatment of Acute Posterolateral Ruptures: Common Peroneal Nerve Identification

- Initial dissection: proximal aspect operative exposure, palpate, determine location common peroneal nerve (CPN).
- Gently displace, elevate biceps muscle to visualize, dissect fascial covering over CPN.
- CPN and its branches are not removed from normal anatomic position to avoid damaging delicate blood supply.
- Most common source of blood supply to proximal portion of CPN from direct branch popliteal artery. Branch divides into proximal and distal anastomotic vessels.
- The vessels, located in the epineurium, give rise to many small vessels of fine caliber within CPN. Do not disturb this blood supply.
- Gerdy's safe zone: area where CPN and anterior recurrent branch define an arc with an average radius of 45 mm.
- Region advantageous for surgical exploration, damage to peroneal nerve and its branches avoided.
- In cases of partial to complete peroneal nerve injury, avoid added trauma to neural tissues.
- CPN passage into the lateral and anterolateral compartment at the entrance of the peroneal longus muscle at the fibular neck potential area for nerve compression. Requires identification, division of variant fascial tissue bands. Further CPN dissection avoided.

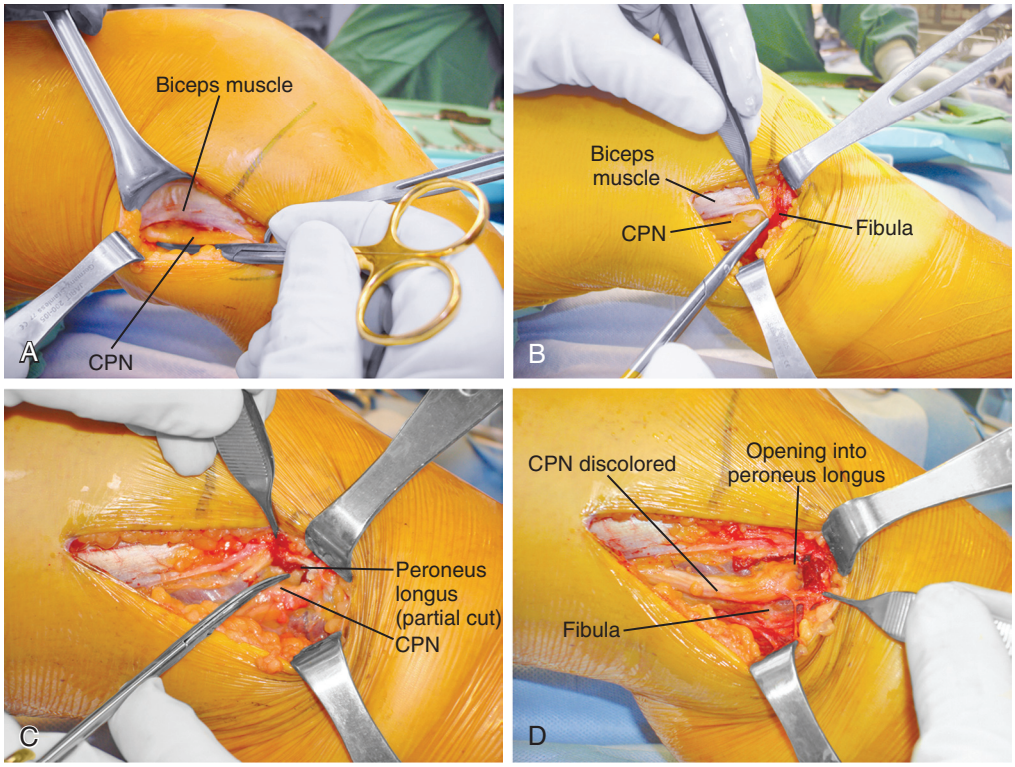


FIG 17-8 Exposure of the common peroneal nerve (CPN). **A,** Proximal exposure of the CPN inferior to the long head of the biceps tendon. **B,** The superficial fascia over the peroneus longus is incised. **C,** The peroneus longus muscle at the fibular neck is partially incised adjacent to the CPN. **D,** Complete exposure of the CPN entering into the anterolateral compartment. In this knee, the CPN is shown to be distinctly abnormal and edematous at this site. The CPN is not displaced from its normal anatomic site to protect the vascular supply.

the vasa nervorum was not found from the geniculate arteries, but occasional contributions from muscular branches were recognized (Fig. 17-9).

Bottomley and colleagues[4] reviewed the anatomic position of the CPN in 54 patients who had extensive traumatic disruption of the PL structures. The CPN was noted to be displaced from its normal position in 16 of 18 patients who had biceps avulsions or associated fibular head fractures. These authors advised that the surgeon should expect an abnormal nerve position on surgical exploration in knees with bone or soft tissue avulsion from the fibular head and the potential for iatrogenic damage.

Rubel and coworkers[58] conducted an anatomic investigation of the CPN in 31 cadaveric limbs by dissecting the CPN to its intramuscular branches. The authors described Gerdy's safe zone as the area where the CPN and anterior recurrent branch defined an arc with an average radius of 45 mm. The distance between the fibular head and Gerdy's tubercle was used to determine the radius of the safe zone. Therefore this region in the proximal aspect of the tibia is advantageous for surgical exploration, because damage to the peroneal nerve and its branches is avoided (Fig. 17-10). The CPN divides into three branches as it enters the anterolateral musculature, with the anterior recurrent branch more proximal to the superficial and deep peroneal branches.

Dellon and associates[10] reported on the anatomic variations of the CPN at the fibular head in 29 cadavers (bilaterally) and 65 patients treated with a CPN decompression for symptoms. Three possible anatomic variants were described that require attention and decompression in chronic neuropathies for a successful outcome. First, the superficial fascia of the superficial head of the peroneus longus muscle is divided by a proximal and distal transection of the fascia (found in 30% of cadavers and 78% of patients, see Fig. 17-8, *B*). Second, when the peroneus longus muscle at the fibular neck is partially incised adjacent and superior to the CPN and the peroneus muscle is lifted anteriorly, a fibrous band may be found that requires release (soft tissue restriction found in 43% of cadavers and 20% of patients, see Fig. 17-8, *C*). Third, there may be a fibrous connection between the peroneus longus and soleus muscle requiring division (found in 9% of cadavers and 6% of patients). These authors advise that after CPN decompression, the surgeon's index finger should be able to gently pass along the CPN and into the anterolateral compartment (see Fig. 17-8, *D*).

In cases of partial to complete peroneal nerve injury, added trauma to neural tissues should be avoided. The goal is to identify the nerve pathway to avoid further damage during the ligament reconstructive procedure. The CPN passage into the lateral and anterolateral compartment at the entrance of the peroneal longus muscle at the fibular neck is a potential area for nerve compression. This area requires identification and division of variant fascial tissue bands, as previously described. Further CPN dissection is avoided.

Surgical Repair and Reconstruction of Acute Injuries

The key to restore function to the disrupted PL structures, muscle attachments, and lateral meniscus attachments is a meticulous dissection, identification of damaged tissues, and repair of all injured structures. There is an unacceptably high risk of failure of primary repairs of disrupted PL structures, particularly the FCL, owing to high lateral tensile forces exerted on these tissues postoperatively.[59] Therefore it is necessary to reconstruct one or more disrupted PL structures with an autograft or allograft. This adds tissue integrity and sufficient repair

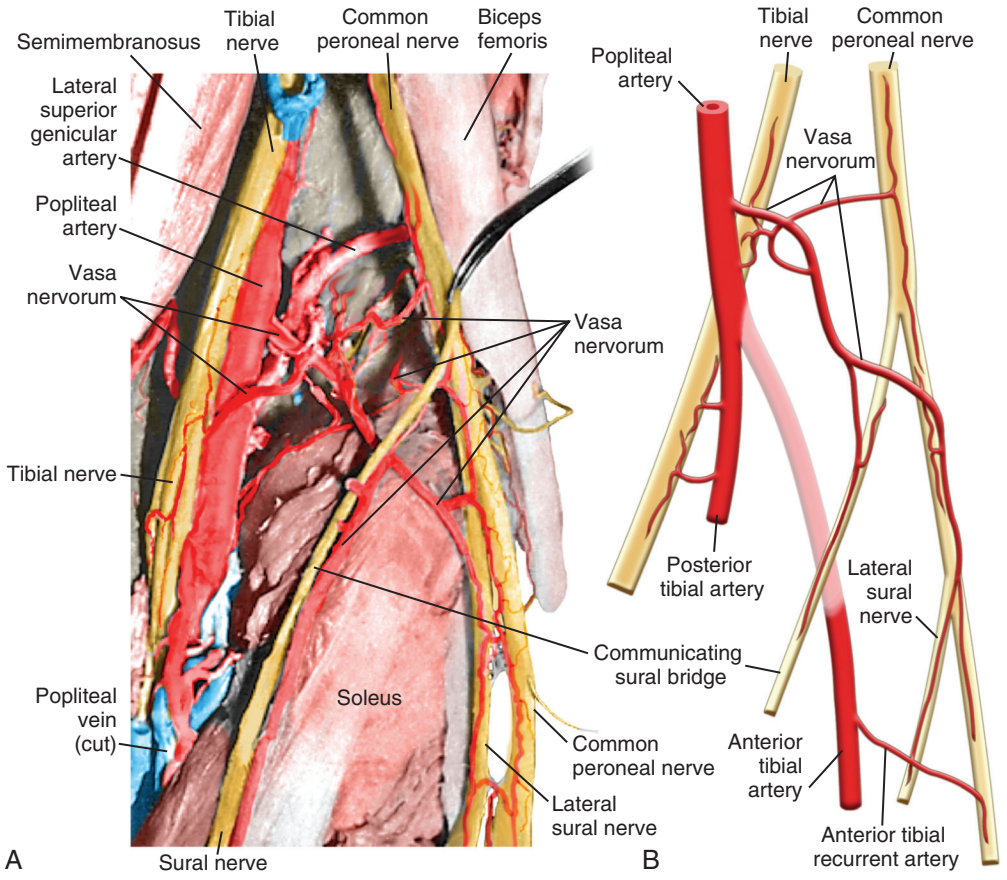


FIG 17-9 **A,** Gross dissection of the popliteal fossa of the right leg. The vessel branching from the popliteal artery gives rise to vasa nervorum to the tibial nerve and common peroneal nerve (CPN) and a branch that bifurcates into a vessel accompanying the sural nerve and the epineurial vessel running with the CPN. **B,** The major vascular arrangements supplying the CPN in the popliteal fossa. (From Kadiyala, RK, Ramirez A, Taylor AE, et al. The blood supply of the common peroneal nerve in the popliteal fossa. *J Bone Joint Surg Br.* 2005;87:337-342.)

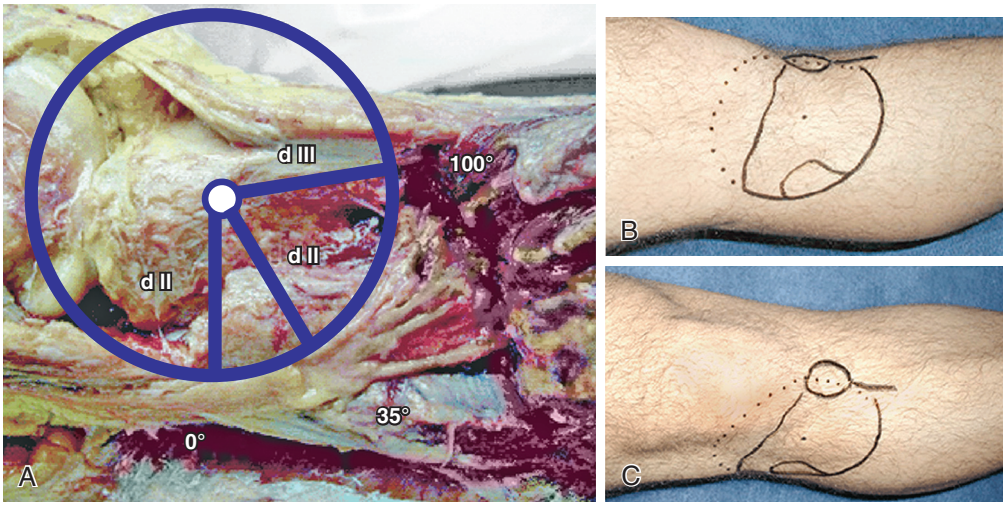


FIG 17-10 **A,** Cadaveric dissection of a fresh tissue specimen shows the circumferential area free of neural structures at the level of the proximal aspect of the tibia. The center of this circumference is located at Gerdy's tubercle with an average radius (and standard deviation) of 45.32 ± 2.6 mm. *d II,* distance from the most prominent aspect of Gerdy's tubercle to the starting point of the superficial branch of the CPN; *d III,* distance from the most prominent aspect of Gerdy's tubercle to the anterior recurrent branch of the nerve. **B,** Gerdy's safe zone marked preoperatively. Note how the marking follows the contour of the surface in a 3-dimensional fashion on the lateral **(B)** and frontal **(C)** photographs. (From Rubel IF, Schwarzbard I, Leonard A, Cece D. Anatomic location of the peroneal nerve at the level of the proximal aspect of the tibia: Gerdy's safe zone. *J Bone Joint Surg Am.* 2004;86:1625-1658.)

strength to resist LJO and external tibial rotation in the initial healing period of 4 to 6 postoperative weeks.

In most acute PL injuries, the FCL is reconstructed and the other PL soft tissues and PMTL are treated by primary repair. The FCL graft reconstruction resists lateral tibiofemoral compartment opening and posterolateral subluxation, protecting the overall repair process during the initial healing stage. In more severe injuries, a graft reconstruction of both the FCL and PMTL may be necessary. The reconstruction procedures are discussed in detail in the "Operative Treatment of Chronic Ruptures" section later in this chapter.

Surgical Approach and Order of Repair

The surgical approach the senior author prefers involves a graft reconstruction of the FCL to stabilize the lateral side of the knee joint using a B-PT-B allograft or an AT-B allograft. A femoral-fibular reconstruction[41] is a second option described later in this chapter. The FCL reconstruction provides for secure fixation, prevents abnormal joint displacements in the immediate postoperative period, and allows for early protected knee motion. These procedures are not difficult because the attachment sites on the femur and fibula are easily identifiable. Importantly, the graft provides the cornerstone about which the remainder of the soft tissue repair of the PL structures is performed. A B-PT-B allograft requires an appropriate tendon graft length of 60 mm, which may not always be available. Alternative graft options are an AT-B or anterior tibialis allograft. The bone portion of the AT-B may be placed at either the FCL fibular attachment (preferred for bone fixation and healing) or femoral attachment. If a soft tissue tendon graft is selected, the graft is passed through a fibular tunnel (anterior-to-posterior), the tendon is sutured back on itself, and a soft tissue interference screw is used at the femoral fixation site and, frequently, at the fibular site.

After all of the anatomic structures and rupture sites are identified and carefully exposed, the order of the operative repair starts with deeper structures and proceeds to superficial structures. Examples of an acute operative repair are shown in Figures 17-11 and 17-12.

1. Meniscofemoral and tibial capsular repairs
   - Meniscus attachment repair.
   - FCL reconstruction with femoral and fibular tunnel placement and graft fixation.
   - Posterior capsule repair with sutures tied with the knee in full extension.
2. PMTL repair options
   - Musculotendinous repair with direct suture (backup by FCL reconstruction).
   - PFL primary repair (tissues often of poor quality; FCL graft provides suitable tissue for additional sutures).
   - Popliteus tendon femoral attachment: avulsion (while rare) may be reattached.
   - Repair of disrupted biceps attachments: ITB repair of distal insertion, posterior femoral attachments, patellar retinaculum.

CRITICAL POINTS Operative Treatment of Acute Posterolateral Ruptures: Surgical Repair and Reconstruction of Acutely Disrupted Ligament and Soft Tissues

- Unacceptably high risk for failure of primary repairs of FCL owing to high lateral tensile forces postoperatively.
- FCL graft reconstruction, other PL soft tissues and PMTL repaired.
- Severe injuries: PMTL graft reconstruction may be necessary.
- Surgical approach, order of repair
  - Prefer B-PT-B autograft or AT-B allograft replacement of FCL.
  - Graft provides secure bone fixation, prevents abnormal joint displacements, and allows early protected knee motion.
  - Graft provides the cornerstone for repair of other PL structures.
  - Operative repair starts with deep structures and proceeds to superficial structures.

AT-B, Achilles tendon-bone; *B-PT-B*, bone-patellar tendon-bone; *FCL*, fibular collateral ligament; *PL*, posterolateral; *PMTL*, popliteus muscle-tendon-ligament unit.

OPERATIVE TREATMENT OF CHRONIC POSTEROLATERAL RUPTURES

Overview of Operative Options

The surgical options in knees with chronic injuries to the PL structures are based on the quality and integrity of these tissues determined at the initial surgical dissection. The surgical approach is similar to that described for acute dissection of the PL structures. The CPN is always identified before any lateral dissection, as previously described. The posterior border of the ITB is incised and elevated to allow complete exposure. In chronic instabilities, the ITB may be lax and nonfunctional. In such knees, the attachment at Gerdy's tubercle is osteotomized, and at the conclusion of the operative procedure, the proximal ITB attachments (lateral intermuscular septum, femoral posterior attachments) are sutured and the ITB osseous attachment is advanced distally by staple fixation to the tibia. The importance of identification of meniscus attachments, PMTL attachment, PL capsular structures, the biceps short and long head attachments, and the peroneal nerve has been previously discussed.

Markolf and colleagues[35-37] reported a series of cadaveric studies on the effect of a nonanatomic PL ligament reconstruction, which has the potential to overconstrain internal tibial rotation and adduction throughout knee flexion. The authors concluded there was no consensus on the graft tensioning routine for PL reconstructions.

The approach advocated in this chapter is an anatomic FCL reconstruction. The FCL may be deficient from prior disruption or replaced with scar tissue in which a well-defined structure cannot be identified. An FCL reconstruction provides a cornerstone for the PL reconstruction.

An anatomic PMTL reconstruction will be described later in this chapter. In the majority of chronic unstable knees, the distal attachments of the PMTL are disrupted or replaced with scar tissue and it is necessary to perform a graft substitution of the PMTL. In rare cases in

CRITICAL POINTS Operative Treatment of Chronic Posterolateral Ruptures: Overview of Operative Options

- Anatomic reconstruction for PL structures
- Unstable, disrupted, or scar tissue replacement of FCL and PMTL requires anatomic graft substitution. If distal PMTL attachments are intact, possible advancement and recession of popliteus tendon at femoral attachment site performed and PFL attachment tissues repaired.
- Nonanatomic femoral-fibular graft reconstruction performed when operative time is limited (dislocated multiligament injuries).
- Proximal advancement PL structures: select knees with chronic stretching and interstitial injury without traumatic ligament disruption.

FCL, Fibular collateral ligament; *PFL*, popliteofibular ligament; *PL*, posterolateral; *PMTL*, popliteus muscle-tendon-ligament unit.

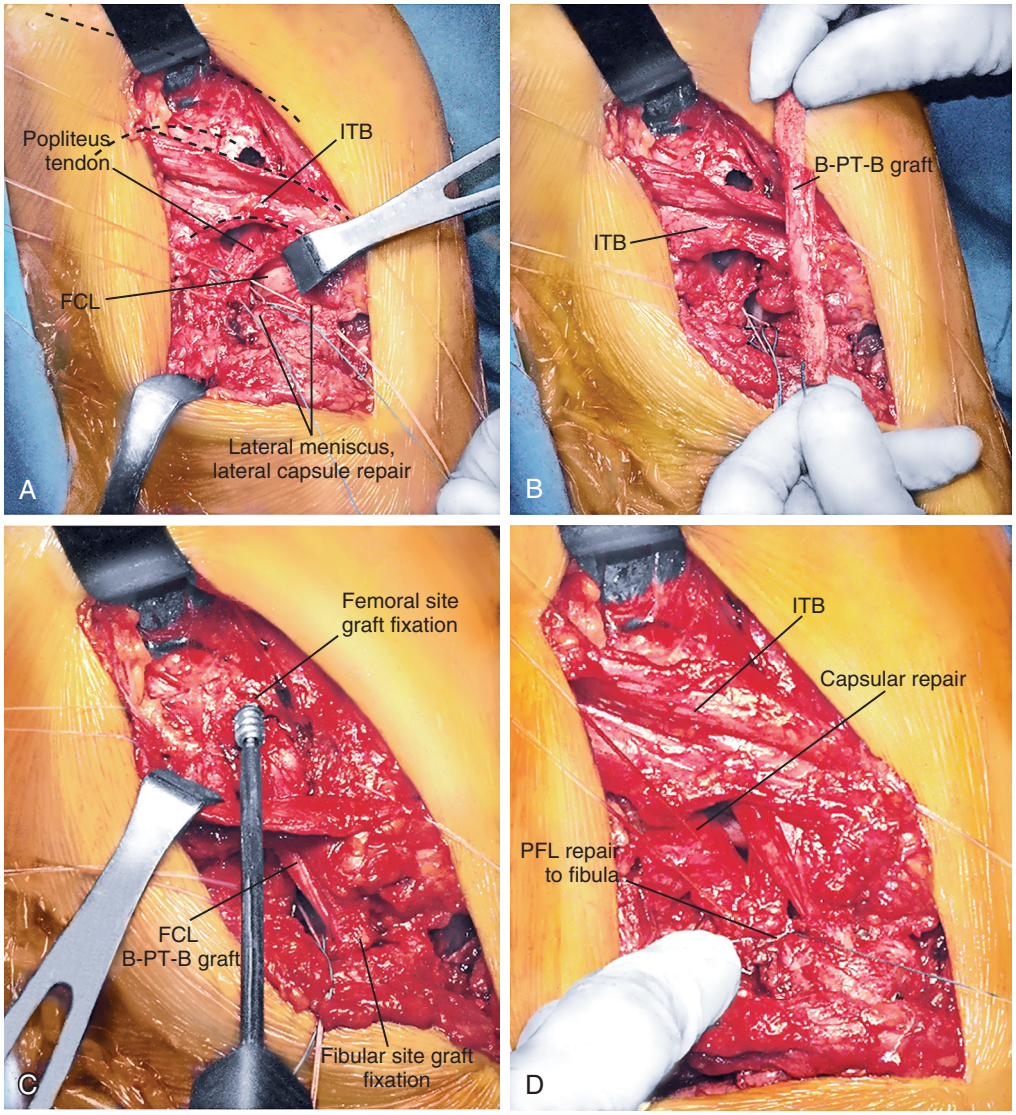


FIG 17-11 Acute repair of rupture to the posterolateral (PL) structures. **A,** Lateral approach; anterior and posterior incisions have been made into the iliotibial band (ITB). Sutures are placed to repair the lateral meniscus tibial attachments. **B,** Fibular collateral ligament (FCL) reconstruction with a bone-patellar tendon-bone (B-PT-B) allograft and suture of the popliteofibular ligament (PFL) to the fibula. The popliteus tendon attachment at the femur was intact. **C,** Fixation of the FCL graft at the femoral and tibial anatomic attachments. **D,** Repair of PL capsule, biceps attachments, and posterior ITB.

which the distal attachments of the PMTL are intact, an advancement and recession of the popliteus tendon at the femoral attachment site may be performed.

A nonanatomic femoral-fibular graft reconstruction is described as an option that is occasionally performed for acute or chronic ruptures of the PL structures. This procedure is indicated when the FCL is elongated or deficient and the PMTL does not require graft substitution. The operative procedure is advantageous when operative time is limited (as in dislocated multiligament knees) or when a relatively rapid stabilizing procedure is required. However, anatomic reconstruction and repair of both the FCL and PMTL are necessary in grossly unstable chronic knee instabilities.

A third operative approach is described using a proximal advancement of the PL structures when chronic insufficiency of the PL structures exists from a minor injury (without traumatic ligament disruption). In knees with varus osseous malalignment and a varus thrust on ambulation, there is frequently an insufficiency of the PL structures because of chronic interstitial tearing. In these situations, a definitive FCL of normal width and integrity (although lax) may be identified at surgery and the PMTL attachments are intact though elongated. A graft reconstruction of the FCL and PMTL is not indicated in these knees. Instead, the PL structures may be advanced proximally in a more simplified operative procedure that avoids the added complexity and morbidity from major graft reconstructive procedures. The PL structures must be carefully inspected at surgery, because this procedure will fail if there is scar tissue replacement, lack of a normal appearance of the structures (although lax), or if the distal attachments of the PL structures are disrupted.

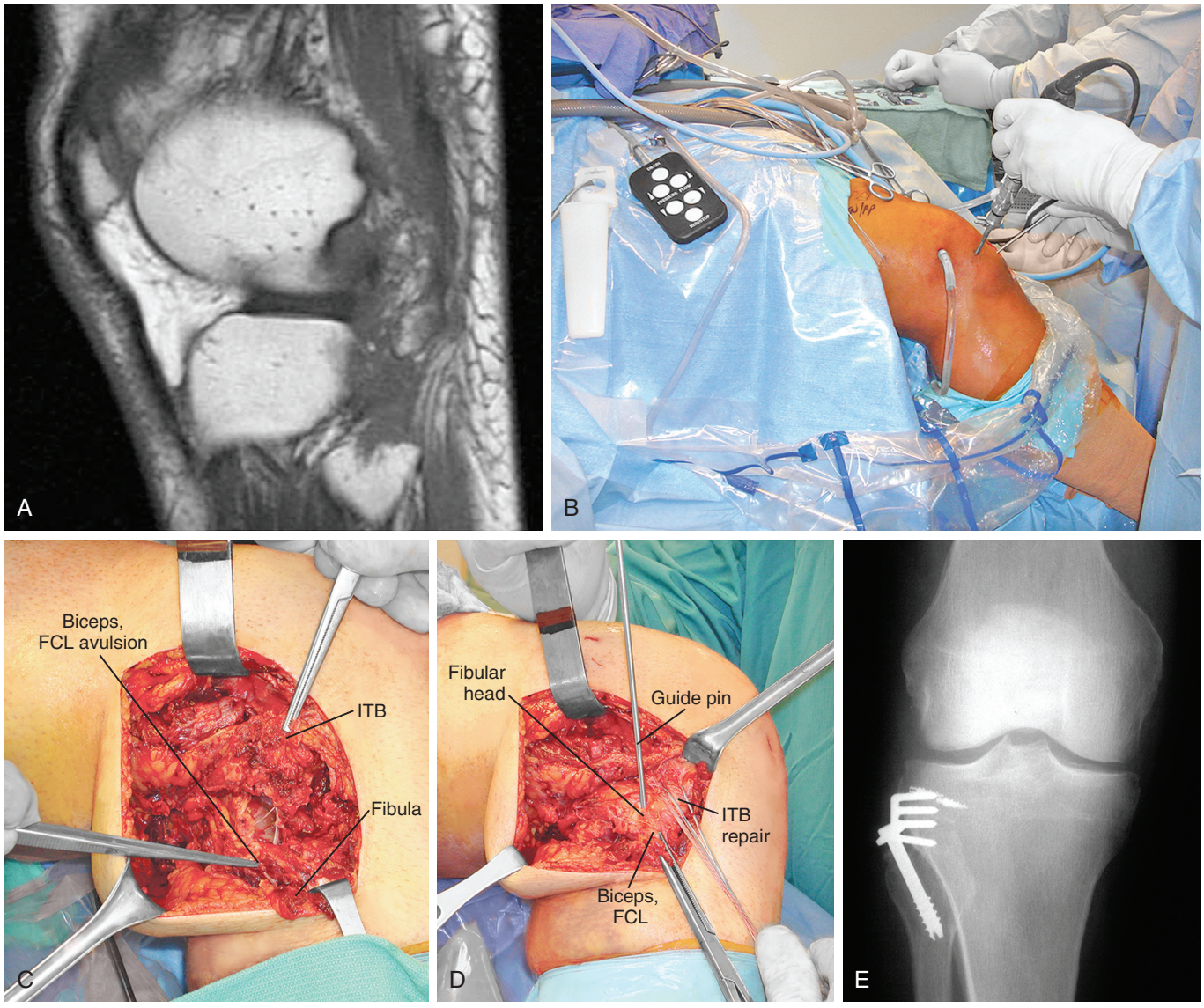


FIG 17-12 Acute disruption of posterolateral structures with avulsion of biceps and fibular collateral ligament (FCL) from fibula. **A,** Magnetic resonance imaging shows avulsion of biceps and FCL from fibular head. **B,** Initial arthroscopic procedure 10 days after injury, performed under low pressure and volume conditions. **C,** Surgical exploration shows avulsion of iliotibial band (ITB) from tibial insertion and biceps, FCL attachment to fibula. The common peroneal nerve was identified to be in a normal anatomic position. **D,** Repair of capsular attachments and ITB (sutures). Guide pin placed in the proximal fibula for screw and washer fixation of biceps and FCL. **E,** Anteroposterior postoperative radiograph shows fixation of biceps and FCL to the proximal fibula, four-prong staple for ITB attachment to tibia, soft tissue anchor for deep capsular attachments.

Anatomic Reconstruction of the Fibular Collateral Ligament and Popliteus Muscle-Tendon-Ligament Unit

Patient Positioning and Surgical Approach

An operative time-out and identification of the operative limb are performed as already described. The patient is positioned on the operative table, with a high thigh tourniquet placed as previously described in the "Acute Injuries" section. A leg holder is only used if a meniscus repair is anticipated to provide for limb control and opening of the medial tibiofemoral compartment. Otherwise, the lower limb is draped free with a bolster placed under the proximal thigh to allow the popliteal neurovascular structures to drop posteriorly away from the dissection plane. The initial arthroscopic evaluation is performed, including meniscus repairs and drilling of tunnels for concurrent cruciate reconstructions for placement of cruciate grafts as described in Chapters 7 and 17. There are two options with cruciate reconstructions. The cruciate grafts may be placed with the distal fixation performed after the lateral dissection. If this approach is selected, the order of final graft tensioning and fixation is (1) PCL, (2) ACL, (3) FCL, and (4) PMTL. The rationale is to restore the tibiofemoral joint in the sagittal plane and then perform the final PL graft fixation and repair of disrupted tissues. The second option is to complete the cruciate reconstruction and then repair and reconstruct the PL structures. If

CRITICAL POINTS Anatomic Reconstruction of the Fibular Collateral Ligament and Popliteus Muscle-Tendon-Ligament: Patient Positioning and Surgical Approach

- Initial arthroscopic evaluation performed.
- Tourniquet inflated during initial operative approach, deflated remainder of procedure.
- Skin incision: straight line 10-12 cm in length, centered over joint line, 1 cm posterior to ITB attachment at the tibia.
- Skin flaps created by undermining the skin in proximal, distal, anterior, posterior directions.
- Skin dissection beneath superficial fascia, not in fatty subcutaneous plane.
- Identify, protect CPN and possible nerve branches as first priority.
- ITB incised along posterior margin at the junction of the band and biceps muscle.
- ITB posterior attachments excised to short head of biceps femoris muscle.
- ITB lifted anteriorly to expose lateral aspect of lateral femoral condyle and attachments of popliteus, FCL, lateral gastrocnemius muscle tendon attachment.
- Interval anterior to lateral gastrocnemius tendon at joint line, directly at top of fibula entered, avoid inferior geniculate artery. Visualize space behind posterior capsule, lateral meniscus attachment, popliteus muscle attachment, posterior gastrocnemius tendon.
- Second anterior ITB incision may be required for exposure.
- VLO lifted gently in anterior direction, S retractor placed beneath muscle fibers.
- Vertical incision 2 cm in length into capsule just anterior to anterolateral capsule ligament and popliteus tendon attachment. Joint entered, lateral meniscus attachments inspected. Similar incision into PL capsule, starting at its femoral attachment, inspect posterior meniscus attachments.

CPN, Common peroneal nerve; *FCL*, fibular collateral ligament; *ITB*, iliotibial band; *PL*, posterolateral; *VLO*, vastus lateralis obliquus.

this sequence is followed, the surgeon must carefully control the limb during the dissection and repair steps to make sure there is no inadvertent opening of the lateral tibiofemoral joint, which would disrupt the cruciate graft fixation. In general, the first option is safest.

The surgeon is seated with a headlight to allow a meticulous dissection of the CPN first, followed by the PL structures. The tourniquet is inflated during the initial dissection and then deflated during the remainder of the surgical procedure. A skin incision 10 to 12 cm in length is made in a straight line, centered over the joint line and 1 cm posterior to the ITB attachment at the tibia, using the same approach as already described (see Fig. 17-6).

Skin flaps are created by undermining the skin in proximal, distal, anterior, and posterior directions. A cosmetic approach is used in which the skin incision is transposed to different portions of the operative field, thereby reducing the skin incision length. The skin dissection is accomplished beneath the superficial fascia and not in the fatty subcutaneous plane to avoid damage to the blood and neural supply to the skin flaps. The surgeon avoids skin necrosis by not placing tension on the skin edges and flaps.

Peroneal Nerve Dissection and Visualization

The CPN is identified, beginning proximally as already described. A retractor is used to elevate the proximal biceps muscle and vastus lateralis to place tension on the lateral fascial tissues and gently elongate the CPN. The fascia is incised directly anterior to the CPN, and care is taken to avoid opening the surrounding neural sheath. At the fibular head, the peroneal longus muscle is partially incised for a few millimeters overlying the CPN at the fibular neck. The area is inspected for fibrous or fascia tissues that may potentially compromise the CPN entrance into the lateral and anterolateral muscular compartments, as described in the previous section. The yellow fatty tissue about the CPN is protected.

The nerve is not displaced from its anatomic bed to protect its blood supply. In cases in which scar tissue is encountered that surrounds the nerve, further dissection of the CPN is avoided because injury may easily occur as the scar tissue prevents a safe dissection plane. The CPN is identified proximally and distally to the scar tissue, so its location can be protected during the ligament reconstruction.

Only in rare cases in which there is near-complete to complete loss of CPN function and a compressive neuropathy exists, is it justified to dissect the CPN from the encased scar tissue, because the risk of nerve damage is high. In either situation, the surgeon must always know where the CPN and its branches are located during the operative procedure.

The ITB is incised at the posterior edge and anterior to the biceps tendon. The ITB attachments are excised to the short head of the biceps femoris muscle, and the ITB is gently lifted anteriorly to expose the entire lateral aspect of lateral femoral condyle and attachments of the popliteus, FCL, and lateral gastrocnemius muscle tendon attachment.

The tissues overlying the FCL and PL structures may have fascia tissues that require dissection to identify the structures. These fascia tissues should be grasped and gently stripped with dissection scissors, protecting the biceps tendon attachment and underlying posterior capsule and FCL. The bursa located anterolateral to the distal fourth of the FCL is used as a landmark. In chronic knee injuries considerable scar tissue may be encountered at this point that prevents clear identification of all the PL structures.

The interval anterior to the lateral gastrocnemius tendon at the joint line, and directly at the top of the fibula, is entered, avoiding the inferior genicular artery. The space behind the posterior capsule, lateral meniscus attachment, popliteus muscle attachment, and posterior gastrocnemius tendon is visualized, as already described in the "Acute Injuries" section.

A second anterior ITB incision may be required when there is extensive scar involving all of the PL structures. The ITB is incised along its anterior margin at the junction of the band and fascia, 10 cm from its tibial attachment. The vastus lateralis obliquus (VLO) is carefully elevated from the lateral intermuscular septum, avoiding any penetrating vessels. The VLO is lifted gently in an anterior direction and an S retractor is placed beneath the muscle fibers. The surgeon should avoid entering the suprapatellar synovial pouch by placing the retractor adjacent to the periosteum. Occasionally, blunt dissection with a Cobb elevator is required to gently displace the suprapatellar synovial pouch to allow placement of the S retractor.

A vertical incision approximately 2 cm in length is made into the capsule just anterior to the anterolateral ligament and popliteus tendon attachment. The joint is entered and the lateral meniscus attachments are inspected. If necessary, a vertical incision into the PL capsule may be required to allow for further inspection and repair of the posterior meniscus attachments. This posterior incision cannot be extended distally, because the popliteus tendon will be observed crossing into the popliteus meniscus recess.

It may be beneficial to place a curved Kelly in the anterolateral capsular incision, with the instrument passed beneath the popliteus tendon and FCL, to place tension into these tissues to facilitate further identification and inspection. The femoral anatomic attachments of all

the PL structures are shown in Figure 2-1, *C* and *D*, and the surgeon should be thoroughly familiar with this anatomy because the goal of the surgical procedure is to restore normal anatomic attachment sites. Note the femoral FCL attachment is just posterior and superior to the lateral epicondyle, and that the insertion of the lateral gastrocnemius tendon is on the lateral aspect of the femoral condyle.

LaPrade and coworkers[27] reported a mean distance of 18.5 mm from the FCL insertion to the popliteus tendon insertion, indicating that two separate grafts are required to anatomically reconstruct the FCL and popliteal tendon femoral attachments. Although some authors recommend a single graft placed at the femoral attachment and split into two strands to reconstruct both the FCL and PMTL, this procedure does not reproduce the anatomic femoral attachment sites. For these reasons, a separate graft and femoral attachment for the FCL and PMTL are recommended.

The PMTL, PFL attachments, and lateral meniscus attachments are identified by careful probing to determine the integrity of these structures and the appropriate procedure required. Disruption of the popliteomeniscal attachments is usually present, requiring suture repair. Chronic cases of rupture to the PL structures usually demonstrate severe deficiency of the FCL and PMTL, which are encased in scar tissue and require a two-graft anatomic reconstruction. The dissection is limited to the respective structures to be reconstructed to avoid soft tissue injury and devascularization.

Fibular Collateral Ligament Bone-Patellar Tendon-Bone Reconstruction

The goal of a FCL reconstruction is to use a strong graft, attached by bone to anatomic insertion sites on the femur and fibula. This construct provides the cornerstone for the remainder of the PL repair and reconstruction. With an FCL graft resisting LJO and external tibial rotation, immediate protected knee motion may be initiated postoperatively to counteract the expected limitation of joint motion and scar tissue that occurs after major ligament reconstructive procedures.

Graft choices for fibular collateral ligament reconstruction. The normal anatomic attachment sites of the FCL to the lateral femur and anterolateral aspect of the fibular head are carefully identified.[27] A suture is placed between the two attachment sites and the length measured to determine the required graft size. The bone portion of each end of the graft is 22 to 25 mm in length. The fibular graft attachment is performed using a proximal fibular tunnel. The femoral graft attachment is performed by placing a femoral tunnel at the anatomic attachment site. A second option is a femoral inlay of the proximal bone portion of the graft, which is only required if there is a 5- to 8-mm discrepancy of graft length that will not allow full coverage of the bone in a femoral tunnel.

The patellar tendon graft must normally be 55 to 60 mm to be suitable for an anatomic FCL reconstruction; the senior author keeps these lengths of allografts available. The average cross-sectional area of the FCL (reported by LaPrade and associates[22]) is 11.9 ± 2.9 mm^2. The FCL graft is 8 to 10 mm × 4 mm, resulting in a 32- to 40-mm^2 graft. If the patient's own tissue is of sufficient length, an autograft harvested from the ipsilateral or contralateral patellar tendon is an added consideration. In select cases in which a prior FCL allograft reconstruction has failed, an autograft approach is favored. The hypothesis is that an autograft will heal at the fibular and femoral tunnels, with minimal remodeling and weakening of the graft in the postoperative phase. The complications of a meticulously performed B-PT-B graft harvest from the contralateral knee are less than 1% in terms of infection, scar formation, and graft site pain.[43]

CRITICAL POINTS Fibular Collateral Ligament Bone-Patellar Tendon-Bone Reconstruction

- Anatomic FCL attachment sites to lateral femur, anterolateral aspect of fibular head identified.
- Femoral graft attached via tunnel at FCL anatomic site. Inlay procedure useful if 5- to 8-mm discrepancy of graft length that does not allow full coverage of bone portion of graft.
- Patellar tendon graft length not counting bone: 55-60 mm.
- B-PT-B allograft favored over soft tissue FCL graft owing to prompt osseous incorporation and healing at femoral and fibular attachment sites.
- Placement of fibular and femoral tunnels
  - Anterior bare area of fibula exposed 20 mm, avoid lateral dissection that may injure CPN.
  - Fibular tunnel drilled using guide pin to depth of 25 mm.
  - Avoid drilling too deep.
  - Femoral tunnel placed eccentric to normal FCL attachment, allows collagen portion of graft to occupy normal FCL anatomic location.
- B-PT-B graft placement
  - Bone portion of graft gently taped into fibular tunnel, bone entirely seated into tunnel and level with proximal fibular head.
  - Ideal graft fixation: one or two small fragment cortical screws.
  - Proximal bone portion of graft placed in femoral tunnel.
  - Graft conditioned by cycling knee 20-30 times.
  - Graft fixed with interference screw, 30 degrees of flexion, neutral tibial rotation, 22 N.

B-PT-B, Bone-patellar tendon-bone; *CPN*, common peroneal nerve; *FCL*, fibular collateral ligament.

If an allograft is chosen, as is the usual case in multiligament reconstructions, a B-PT-B allograft is favored over a soft tissue graft owing to more prompt osseous incorporation and healing at femoral and fibular attachment sites. It is recognized that soft tissue allografts in bone tunnels require added maturation time and may incompletely remodel even under the best of circumstances.[34,57]

Placement of fibular and femoral tunnels. The attachment sites at the fibula and femur are identified. The anterior *bare area* of the fibula is exposed for 20 mm, avoiding lateral dissection that may injure the CPN. The fibular tunnel is drilled first, using a guide pin to a depth of 25 mm. The drills are gradually increased in diameter to create a final 9-mm tunnel (Fig. 17-13). Care should be taken to avoid drilling too deep, because the drill would break out the cortex distally at the fibular neck, close to the location of the CPN. The normal cortical integrity of the fibular head is not disrupted to maintain circumferential cortical fixation strength at the fibular attachment site.

The femoral tunnel is placed 5 mm eccentric to the normal FCL attachment to allow the collagenous portion of the graft to occupy the normal FCL anatomic location. Before drilling the femoral socket, a suture is attached to the fibular graft site and positioned at the desired femoral location to check graft isometry. If the femoral position is too anterior, the graft will be under high tension with knee flexion. The opposite will occur if the graft is too posterior, because it will be under tight tension with knee extension. The goal is to have tension in the graft ideally in the 0 to 70 degrees knee motion limits, which replaces the normal FCL function. A Beath guide pin is passed for the femoral tunnel, which is angulated in an anterior and proximal direction in line with the FCL fibers at 30 degrees of knee flexion.

If an ACL reconstruction is performed, it is necessary to diverge the FCL tunnel in an anterior direction away from the ACL tunnel to

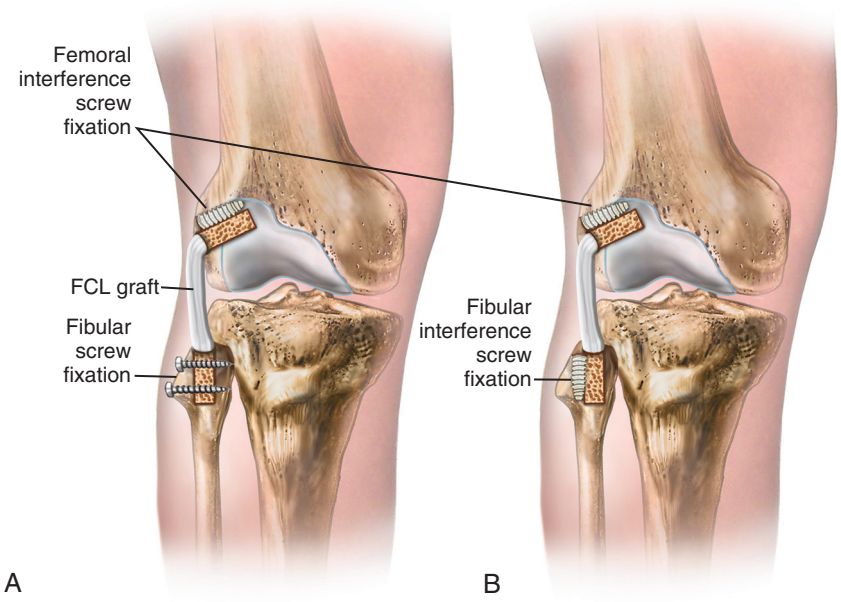


FIG 17-13 Anatomic substitution of the fibular collateral ligament (FCL) with a bone-patellar tendon-bone autograft or allograft shows two methods for fibular graft fixation. **A,** Two small fragment screws are used to fix the bone into a slot created in the proximal fibula (our choice). Interference screw fixation is used at the femoral anatomic site of the FCL. **B,** A fibular tunnel is made, the graft seated, and an interference screw is used for fixation.

maintain integrity of the two tunnels. The edges of the femoral tunnel are smoothed with a rasp to avoid graft abrasion.

The use of a FlipCutter (Arthrex) for the ACL femoral tunnel is ideal because it maintains the integrity of the lateral femoral cortex, particularly if two femoral sockets are required for an FCL and PTML graft reconstruction. Selecting grafts with a bone portion at the femoral site is advantageous because it avoids soft tissue graft tunnels that in the senior author's experience always remain and potentially weaken the lateral femoral condyle. The bone portion of the allograft will incorporate within the femoral condyle.

Bone-patellar tendon-bone graft placement. The bone portion of the graft is gently taped into the fibular tunnel so that the bone is entirely seated into the tunnel and level with the proximal fibular head to preserve graft length. The bone-tendon junction is marked with ink to define the correct depth in the fibular tunnel. The fibular graft fixation is done with one or two small-fragment cortical screws placed at the anterolateral bare area to engage the center bone portion of the graft and both fibular cortices (Fig. 17-14). The angle of the screw is posterior and medial (and never lateral) to protect the CPN. The cortical screws may be 2.7 or 3.5 mm, based on the size of the graft and fibular head. A washer is used anteriorly. Alternative graft fixation methods, rarely required, include an interference screw or sutures tied over the fibular cortex.

The proximal bone of the graft is advanced into the femoral tunnel. The graft is conditioned by cycling the knee 20 to 30 times. The graft is fixed at the femoral site with an interference screw at 30 degrees of knee flexion, in neutral tibial rotation, under an approximate 5-lb tensile load (22-N) on the sutures, which have been advanced by the Beath needle to the medial aspect of the knee joint. The graft is purposely not overtensioned to avoid overconstraining the lateral tibiofemoral joint.

Graft Replacement of Popliteus Muscle-Tendon-Ligament Unit: Acute or Chronic Cases

The graft replacement of the PMTL is shown in Figure 17-15. An AT-B allograft is favored, with the bone portion of the graft placed at the anatomic femoral insertion site and the collagenous portion of the graft passed in the tibial tunnel.

An incision is made just beneath Gerdy's tubercle, extending from the bare area of the anterior fibula to the tibial tubercle and then 3 cm distally along the anterolateral tibia. Careful subperiosteal dissection exposes the anterolateral aspect of the tibia in Gerdy's safe zone, as already described.

The posterolateral dissection is anterior to the lateral gastrocnemius muscle at the same interval as described for a lateral meniscus repair. A retractor is placed anterior to the lateral gastrocnemius muscle directly behind the posterior tibia to expose the popliteus muscle. One mistake is to place the posterior tibial tunnel too proximally because the tibia has a normal posterior convexity. A second mistake is to place the posterior tibial tunnel too far medially. A lateral placement of the tibial tunnel is required to increase the moment arm of the graft to resist external tibial rotation. Distal dissection over the popliteus muscle and distal placement of retractors are avoided as the anterior tibial artery courses laterally to enter the anterolateral compartment.

The final tibial 8- to 9-mm tunnel is at the most lateral aspect of the tibial margin and 15 mm distal to the joint line, passing through the popliteus muscle attachment and just medial to the tibiofibular joint (see Fig. 17-15). A guide pin is placed anterior-to-posterior, with a retractor placed posteriorly and the correct position confirmed with the tunnel drilled protecting the posterior structures. The total length of the graft is measured from the femoral to tibial tunnels, plus the length for the tibial fixation distal to the anterior tibial tunnel.

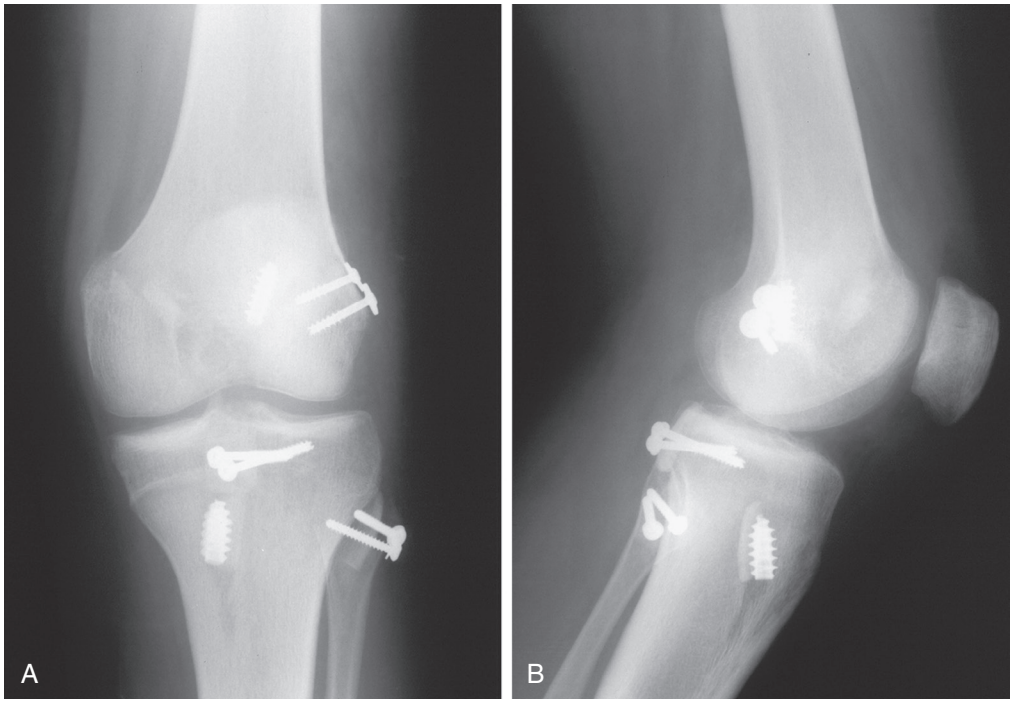


FIG 17-14 Postoperative anteroposterior (**A**) and lateral (**B**) radiographs of a 22-year-old man who underwent a posterior cruciate ligament quadriceps tendon-patellar bone autograft tibial inlay two-strand reconstruction, an anterior cruciate ligament bone-patellar tendon-bone (B-PT-B) allograft reconstruction, and a posterolateral reconstruction. The fibular collateral ligament (FCL) B-PT-B allograft fixation is shown. The method of fixation at the femur was a bone inlay at the anatomic FCL fixation site and at the fibula with two small fragment screws. An advancement of the popliteus tendon at the femur and repair of the popliteofibular ligament were also performed. (From Noyes FR, Barber-Westin SD. Posterolateral knee reconstruction with an anatomical bone-patellar tendon-bone reconstruction of the fibular collateral ligament. *Am J Sports Med.* 2007;35:259-273.)

CRITICAL POINTS Graft Replacement of Popliteus Muscle-Tendon-Ligament Unit

- AT-B allograft preferred, bone portion placed at anatomic femoral insertion site. Collagenous portion of graft passed into tibial tunnel.
- Careful subperiosteal dissection exposes anterolateral aspect of tibia in Gerdy's safe zone.
- Retractor placed anterior to lateral gastrocnemius muscle to expose popliteus muscle.
- Graft brought out though 8-mm tunnel placed at most lateral aspect of tibial margin, 15 mm distal to the joint line, passes through popliteus muscle attachment to tibia.
- Graft passed and fixed femoral tunnel, conditioned by repetitive knee flexion-extension. Fixation interference screw in tibial tunnel, 30 degrees of flexion, neutral tibial rotation, 22-N tension. Additional suture fixation screw post on tibia.
- Final graft assessment determined under adequate tension, resists abnormal external tibial rotation and knee hyperextension.
- Direct suture of PMTL graft to FCL graft at the level of fibular head.

AT-B, Achilles tendon-bone; *FCL*, fibular collateral ligament; *PMTL*, popliteus muscle-tendon-ligament unit.

The graft is passed through the femoral tunnel and then through the tibial tunnel and fixed at the femoral site by an interference screw. The graft is conditioned by repetitive knee flexion and extension, and fixation is performed with a soft tissue interference screw in the tibial tunnel with the leg at 30 degrees of knee flexion, neutral tibial rotation, and approximately 5 lb (22 N) of tension placed on the graft. A backup suture fixation screw post is used on the anterolateral aspect of the tibia.

A final graft assessment is done to determine that it is under adequate tension and resists abnormal external tibial rotation and knee hyperextension. With graft reconstructions of both the FCL and PMTL, it is not necessary to add additional drill holes to the fibula to perform a graft reconstruction of the PMTL. Rather, a direct suture of the PMTL graft to the FCL graft at the level of the fibular head is performed (see Fig. 17-15, *F* and *G*). A plication procedure is performed of the PLC at 10 degrees of flexion, avoiding overtension, which would limit normal extension (see Fig. 17-15, *H* and *I*).

Posterolateral Capsule Reconstruction for Severe Varus Recurvatum

In patients who demonstrate 15 degrees or more of knee varus recurvatum and hyperextension, severe deficiency exists of the entire posterior capsule and oblique popliteal ligament in addition to possible cruciate, FCL, and PMTL damage (Fig. 17-16). In these severe knee injuries, a PMTL reconstruction and posterior capsule plication will

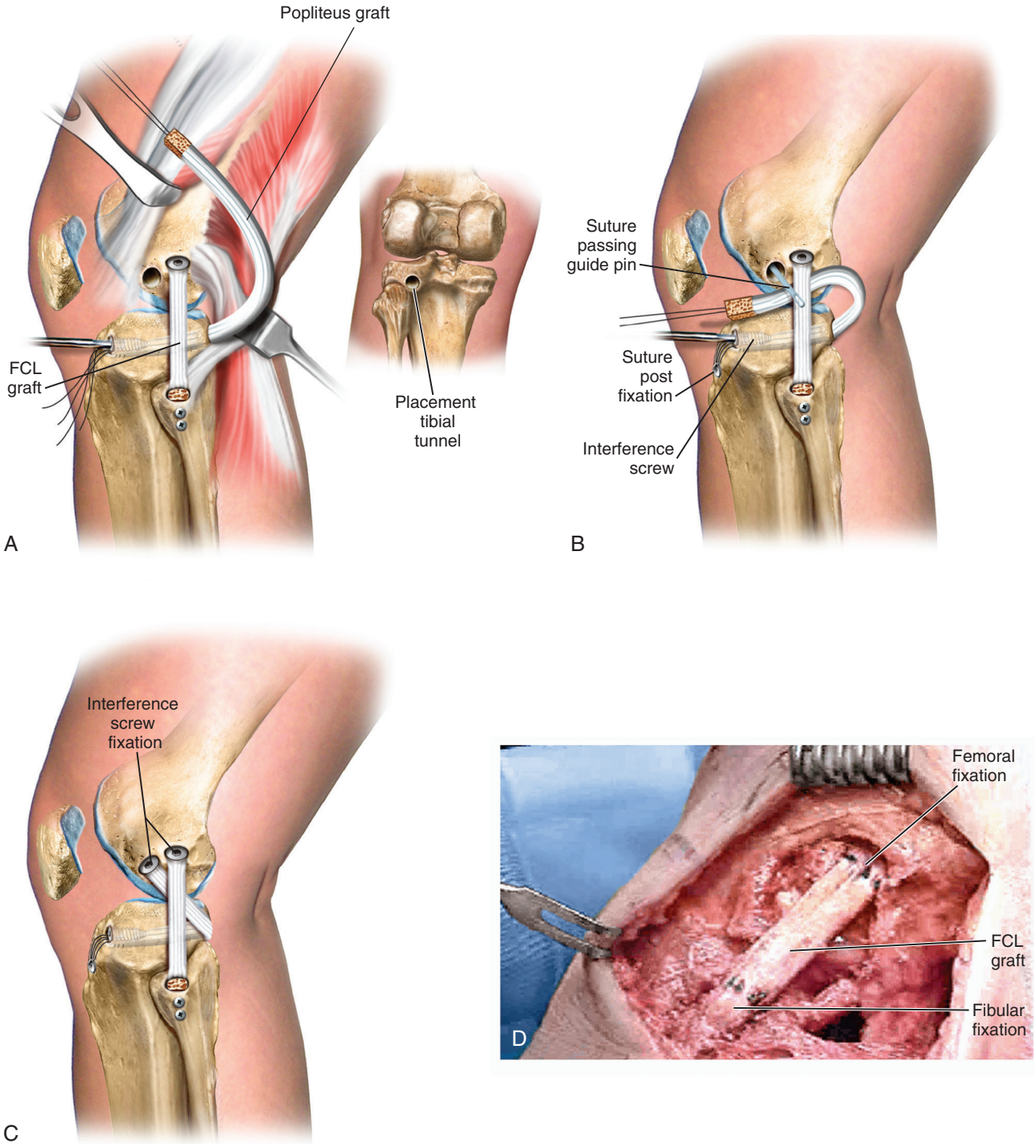


FIG 17-15 Anatomic popliteus muscle-tendon-ligament reconstruction and fibular collateral ligament (FCL) reconstruction with bone-patellar tendon-bone (B-PT-B) autograft or allograft. **A,** Location of posterolateral tibial tunnel and graft passage. A soft tissue interference screw and suture post are used for tibial fixation of the popliteus graft. **B,** Passage of popliteus graft beneath the FCL B-PT-B graft. **C** to **E,** Final fixation of the popliteus and FCL graft reconstructions.

not resist the severe varus recurvatum deformity. A PLC reconstruction is required in addition to a reconstruction of the PMTL and FCL (Fig. 17-17). The operative approach and placement of the tibial tunnel for the capsular reconstruction using an AT-B allograft (8-9 mm in diameter) is the same as described for the PMTL reconstruction. The tibial tunnel is enlarged as required for both graft passage. The bone portion of the graft is located adjacent to the lateral gastrocnemius tendon origin using either a femoral tunnel or a bone inlay technique. The inlay technique is required when a concurrent ACL reconstruction is performed to avoid a second femoral tunnel. The fixation at the femoral attachment requires a portion of the lateral gastrocnemius tendon insertion (which is very broad) to be partially incised to expose

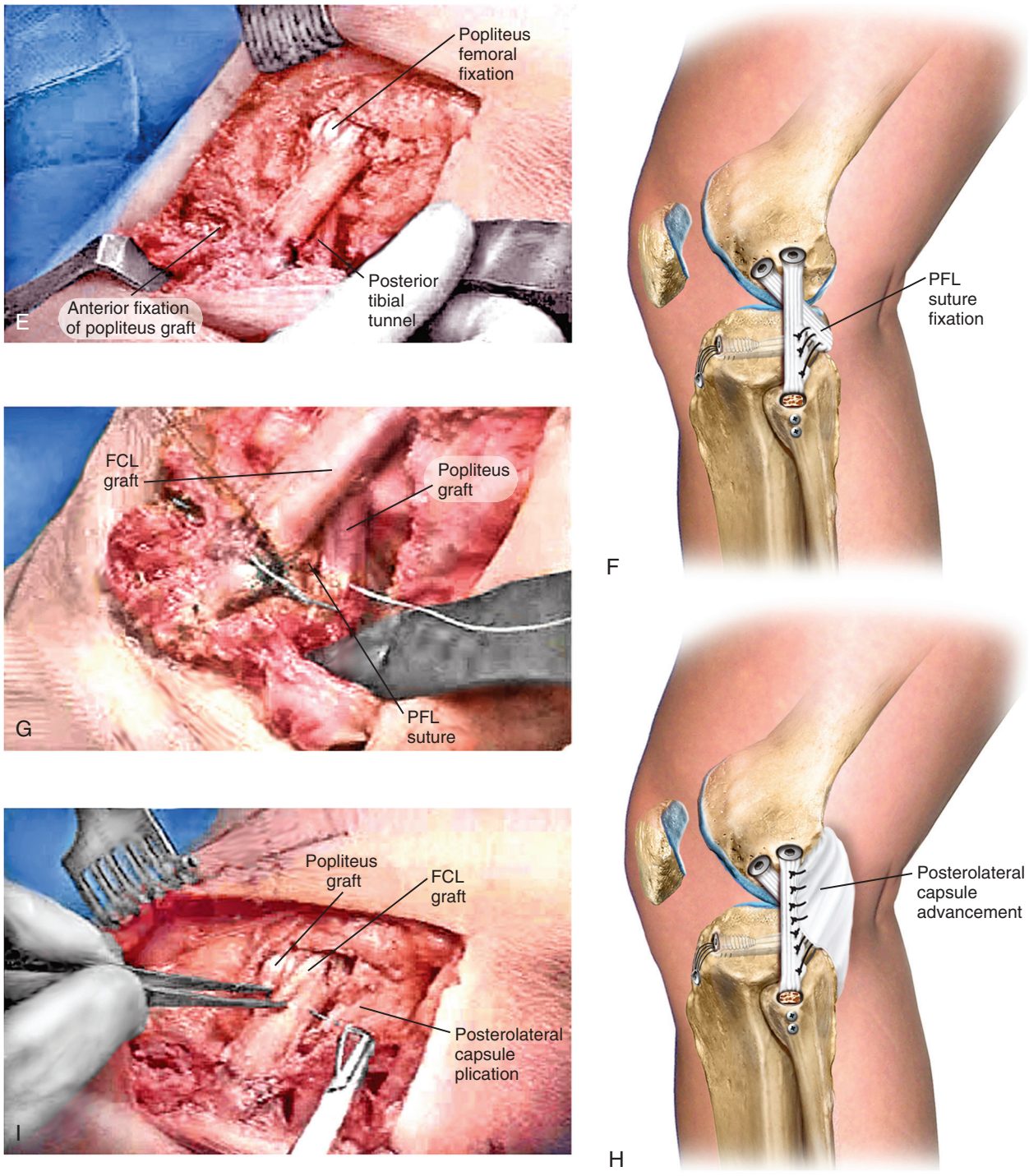


FIG 17-15, cont'd **F** and **G,** Suture of popliteus graft to posterior margin of the FCL graft at the fibular attachment site to restore the popliteofibular ligament (PFL). **H** and **I,** Suture plication of the posterolateral capsule to posterior margin of the FCL graft.

the site for the AT-B graft fixation. The fixation of the bone inlay is accomplished with two small-fragment cancellous screws and washers (Fig. 17-18). This provides a stable bone-to-bone attachment. If a femoral tunnel is used, a 7-mm interference screw is selected. The graft lies along the PLC, which is plicated and the graft is passed through the tibial tunnel.

The tendon portion of the graft is fixated at the tibia after graft conditioning similar to that previously described for the PMTL reconstruction. The knee is placed at 10 degrees of flexion with 5 lb (22 N) of graft tension. The knee joint will passively go to 0 degrees. Ultimately, the graft will stretch a few millimeters; the goal is to allow 0 to −2 degrees of hyperextension, which effectively blocks knee hyperextension and varus recurvatum. Frequently, the ACL is ruptured and the two ligaments grafts (ACL and PLC) work in concert to block varus recurvatum. The same is true when a concomitant PCL reconstruction is performed.



FIG 17-16 **A,** A 20-year-old gymnast with chronic deficiency of the posterolateral structures and complaints of recurrent hyperextension injuries with athletic activities. The anterior cruciate ligament and posterior cruciate ligament were intact, although a prior partial disruption could not be excluded. **B,** Dial test at 30 and 90 degrees demonstrates increased tibial rotation of the right knee.

CRITICAL POINTS Posterolateral Capsule Reconstruction

- Indicated 15 degrees of knee hyperextension, severe deficiency entire posterior capsule, cruciate, FCL, and PMTL damage.
- PMTL reconstruction alone will not block severe varus recurvatum deformity.
- Operative approach, place tibial tunnel using AT-B allograft, same as PMTL reconstruction.
- Bone portion of graft placed adjacent to lateral gastrocnemius tendon origin by tunnel or inlay.
- Inlay technique required with ACL reconstruction to avoid second femoral tunnel.
- Tendon portion of graft lies along posterolateral capsule, which is plicated, graft fixed at tibia with interference screw, suture post after graft conditioning.
- Goal: obtain 0 to –2 degrees of hyperextension, block knee hyperextension, varus recurvatum.
- Highly unstable knees with severe disruption of all PL structures may require PMTL and PL capsular grafts. Both grafts brought out through tibial tunnel drilled to appropriate diameter. Soft tissue interference screw used at tibial tunnel after graft suture post fixation.

AT-B, Achilles tendon-bone; *FCL*, fibular collateral ligament; *PL*, posterolateral; *PMTL*, popliteus muscle-tendon-ligament unit.

Femoral-Fibular Reconstruction

The nonanatomic femoral-fibular graft reconstruction is indicated primarily in acute knee repairs to provide the stable graft cornerstone about which other soft tissues are repaired. This technique is contraindicated when a combined PMTL graft reconstruction is required. In these knees, an anatomic FCL and PMTL reconstruction is performed.

The femoral-fibular reconstruction provides a large graft reconstruction of the FCL and a posterior graft arm to augment the PL structures. The PLC reconstruction is performed by a plication procedure. The popliteus tendon is plicated to the fibular FCL reconstruction to restore the PFL. The procedure is termed a *nonanatomic reconstruction* because the femoral-fibular graft is placed adjacent but not directly at the FCL femoral and fibular anatomic attachment sites.

The FCL femoral-fibular reconstruction does have some advantages. The graft placement (by drilling a tunnel anterior and posterior to the FCL femoral and fibular attachment sites) is relatively simple and allows a large doubled graft to be placed at the lateral side of the knee joint. Direct suture of the graft to itself provides lateral stability in acute operative repairs to initiate immediate protected knee motion postoperatively. The double-strand FCL graft provides a cornerstone for plication or repair of the other disrupted PL structures.

A femoral-fibular reconstruction has disadvantages. In cadaver studies, a femoral-fibular graft was found not to unload a concurrent PCL graft reconstruction in the same manner as a combined FCL and PMTL graft reconstruction.[36] In addition, although a single femoral-fibular graft stabilizes the knee at time zero, this graft may stretch out in the long term when there is loss of the PMTL, which does not participate in load sharing. Therefore all of the load is transferred to the single graft. The goal of PL repairs and reconstruction is to restore the function of all of the soft tissue structures and not just the femoral-fibular component. A modification of a femoral-fibular technique is to cross the graft, placing the anterior femoral portion to the posterior fibula to restore PFL function. However, whether this option is superior to two parallel femoral-fibular graft arms is not known.

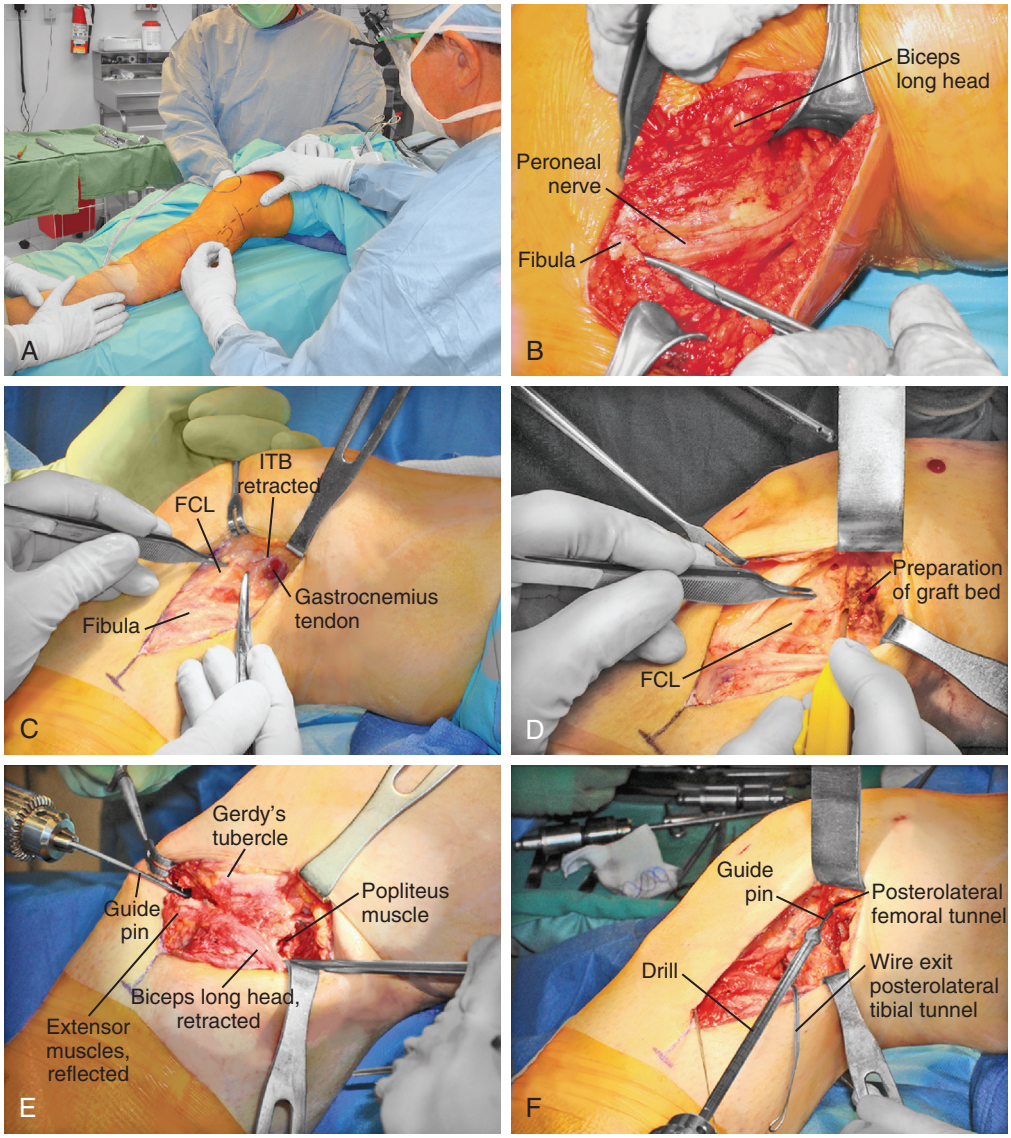


FIG 17-17 Posterolateral capsular reconstruction for severe knee varus recurvatum and hyperextension using an Achilles tendon-bone (AT-B) allograft. **A,** Patient positioning. **B,** Identification of the peroneal nerve at fibular neck. **C,** Identification of fibular collateral ligament (FCL) and popliteus muscle-tendon-ligament, functionally intact. **D,** Exposure of femoral graft site at lateral gastrocnemius tendon attachment. **E,** Placement of the tibial drill hole lateral and distal to the joint line. **F,** Placement of the femoral drill hole.

A straight lateral incision, approximately 12 cm in length, is used centered over the lateral joint line. The surgical approach already described is followed. The incision is extended distally to allow exposure of the fibular head and peroneal nerve and proximally to allow exposure of the attachment of the FCL to the femur. The skin flaps are mobilized beneath the subcutaneous tissue and fascia to protect the vascular and neural supply to the skin. The attachment of the ITB is identified.

An inferior incision is made along the posterior aspect of the ITB and the attachments overlying the biceps muscle. This allows the ITB to be reflected anteriorly so that the anatomy of the PL aspect of the knee is easily visualized.

The CPN is carefully protected throughout the surgical procedure for the drill hole made through the proximal fibula for placement of the FCL graft. It is usually not necessary to dissect the peroneal nerve when its course can be identified; however, if there is any question, it is prudent to dissect the sheath over the nerve around the fibular neck for complete identification.

The fibular head is exposed anteriorly and posteriorly by subperiosteal dissection. Only 12 to 15 mm of the proximal fibula is exposed. A 6-mm drill hole is carefully made anteriorly and posteriorly in the center of the fibular head; a drill guide is used to ensure that soft tissues are protected. A straight curette is used to dilate the 6-mm cortical hole from anterior to posterior, compressing the cancellous bone. Care is taken not to disturb the tibiofibular joint capsule, thereby preserving joint stability.

At the femoral attachment of the FCL, one of two approaches may be selected. In the first approach, the femoral tunnel is made just posterior and superior to the FCL attachment for a single tunnel, with the graft passed into the tunnel by use of a Beath needle. A second approach

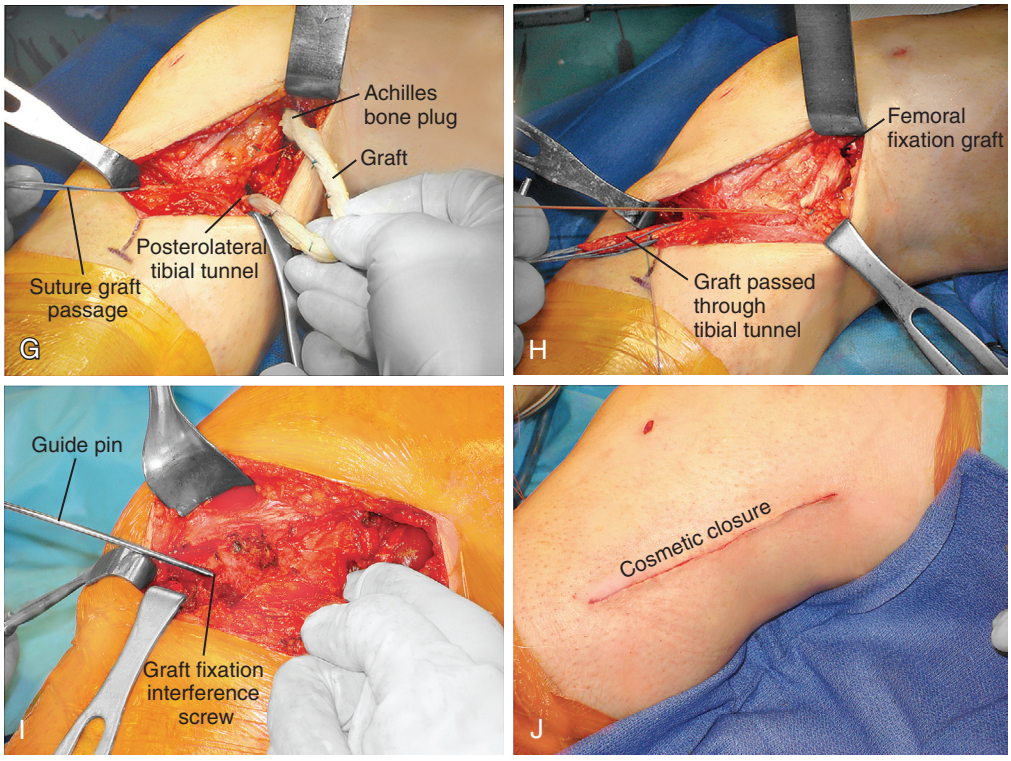


FIG 17-17, cont'd **G,** Placement of the AT-B allograft with bone plug at femoral site. **H,** Fixation at the femoral site and graft conditioning with tension of distal graft. **I,** Graft fixation at the tibia with interference screw and suture post. **J,** Cosmetic closure. *ITB,* Iliotibial band.

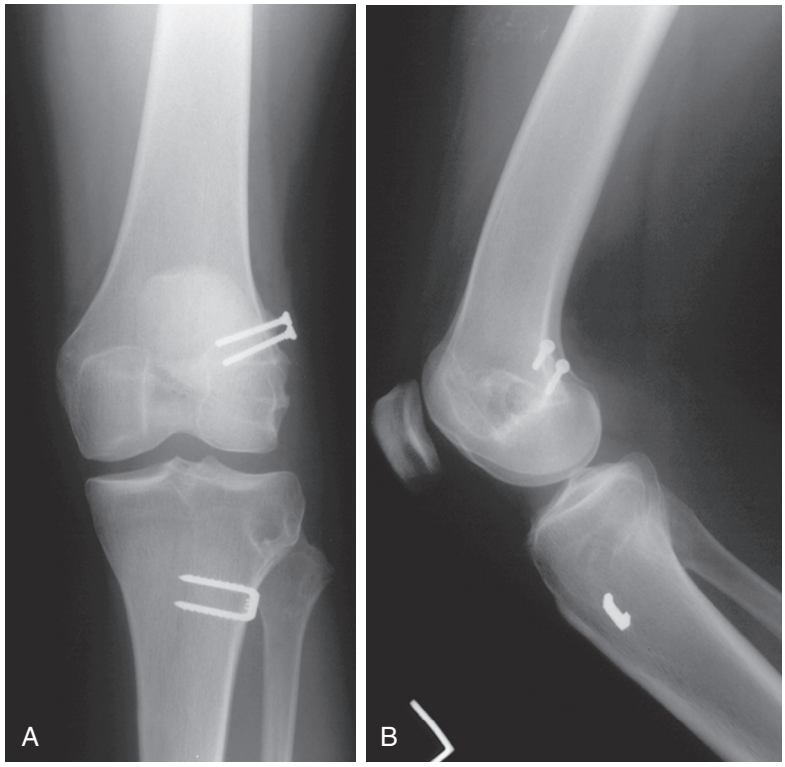


FIG 17-18 Anteroposterior **(A)** and lateral **(B)** radiographs show fixation of posterolateral capsular reconstruction with two 4.0-mm cancellous screws at the femoral site and an absorbable interference tibial screw and suture post. At the femoral site, either a bone inlay or tunnel may be selected.

CRITICAL POINTS Femoral-Fibular Reconstruction

- Indicated when FCL is deficient, contraindicated when PMTL graft reconstruction required.
- Provides large graft reconstruction of FCL and posterior graft arm to augment PL structures. PL capsule plicated.
- FCL graft provides cornerstone for plication or repair of the other PL structures. In global knee ligament reconstructions, procedure provides lateral stability with less operative time and complexity compared with anatomic reconstruction.
- Straight lateral incision, approximately 15 cm in length, centered over lateral joint line.
- Inferior incision along posterior aspect of ITB and attachments overlying the biceps muscle.
- CPN identified, protected.
- Proximal fibular head exposed anteriorly and posteriorly 12-15 mm by subperiosteal dissection.
- 6-mm drill hole anteriorly and posteriorly center of fibular head.
- 6-mm drill hole anterior-to-posterior beneath FCL femoral insertion.
- Curved curette used to make bone tunnel underneath FCL femoral insertion without removing excess bone.
- Autograft or allograft, 6-8 mm in diameter, prepared with sufficient length (19-20 cm) for proximal and distal posterior arms to overlap posteriorly.
- Graft inserted through bony tunnels in femur and fibula with disrupted FCL between graft arms.
- Interrupted sutures through anterior-posterior arms of graft.
- Popliteus tendon, PFL sutured to graft to restore PFL.
- PL capsule plication or advancement performed under sufficient tension to allow 0 degree of extension without hyperextension.
- Knee taken through 0-90 degrees, normal internal-external rotation determined at 30 degrees of flexion to avoid overconstraining joint.

CPN, Common peroneal nerve; *FCL*, fibular collateral ligament; *ITB*, iliotibial band; *PFL*, popliteofibular ligament; *PL*, posterolateral.

is to place a tunnel using a 6-mm drill hole anterior-to-posterior to the FCL insertion. The drill hole is deepened, leaving approximately 10 mm of cortex between the anterior and posterior tunnels. This step requires care to preserve the lateral femoral cortex at the FCL attachment site. A curved curette is used to make a bony tunnel underneath the ligament insertion without removing excess bone, which would weaken the insertion site.

A tendon allograft or semitendinosus-gracilis (STG) autograft (6 to 8 mm in diameter) is prepared. The graft is measured to allow sufficient length (19 to 20 cm) for the anterior and posterior arms of the circle graft to overlap posteriorly, which provides additional collagenous tissue to the PL aspect of the joint (Fig. 17-19, *A* and *B*). Two interlocking closed loop sutures (FiberLoop, Arthrex) are placed into both ends of the graft. The graft is initially stretched for 15 minutes under an 89-N load with a ligament-tensioning device.

An incision is made vertically just behind the FCL into the PLC. The tissues of the PLC, PMTL, and FCL are carefully inspected. The popliteus tendon is inspected from its insertion site to the muscle belly. If the PLC has excessive redundancy, then a simple capsular plication can be performed. The graft is inserted through bone tunnels in the femur and fibula, with the graft strands next to the slack FCL. The graft is placed under slight tension with the knee at 30 degrees of flexion, neutral tibial rotation, and with the lateral side of the joint closed (after repair of meniscal attachments when necessary). It is important not to internally rotate the tibia during graft tensioning, which would result in an abnormal restraint of external rotation. Multiple interrupted sutures are used through the posterior overlapped arms of the graft (see Fig. 17-19, *C* and *D*). The disrupted FCL fibers are interposed between the anterior and posterior arms of the circled graft, and horizontal sutures are placed between both structures (see Fig. 17-19, *E* and *F*). Sutures are placed between the popliteus tendon at the musculotendinous junction to restore the attachment to the fibula (PFL). If the PMT is lax, the tendon may be shortened by direct repair or the tendon is advanced and recessed at its anatomic femoral attachment into a tunnel and fixated with an absorbable interference screw.

The knee is taken through a range of 0 to 90 degrees of flexion, and normal internal-external rotation is ascertained at 30 degrees of knee flexion to avoid overconstraining the joint. The PLC plication or advancement is then performed under sufficient tension to allow 0 degree of extension without hyperextension.

There are many different types of femoral-fibular reconstructions with modification of the two graft arms crossing as discussed or with a graft strand passing posteriorly from the femoral to posterior tibial attachment to reconstruct the PMTL. Clinical data are insufficient to recommend one procedure over another.

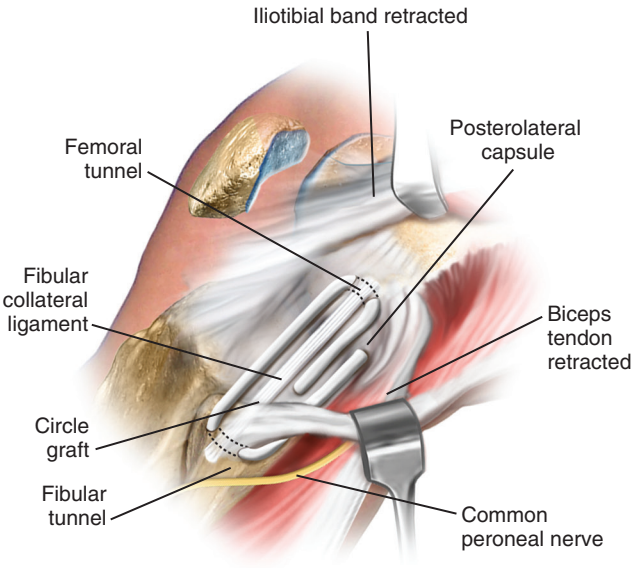
Proximal Advancement of the Posterolateral Structures

A straight lateral incision, approximately 12 cm in length, is used centered over the lateral joint line and dissection proceeds as already described. The incision extends distally to allow exposure of the fibular head and proximally to allow exposure of the attachment of the FCL to the femur. The skin flaps are mobilized beneath the subcutaneous tissue and fascia, protecting the vascular and neural supply. The attachment of the ITB is identified. An incision is made along the posterior border of the ITB and continued proximally, as already discussed for the initial approach. The attachment of the ITB to the lateral intramuscular septum is preserved.

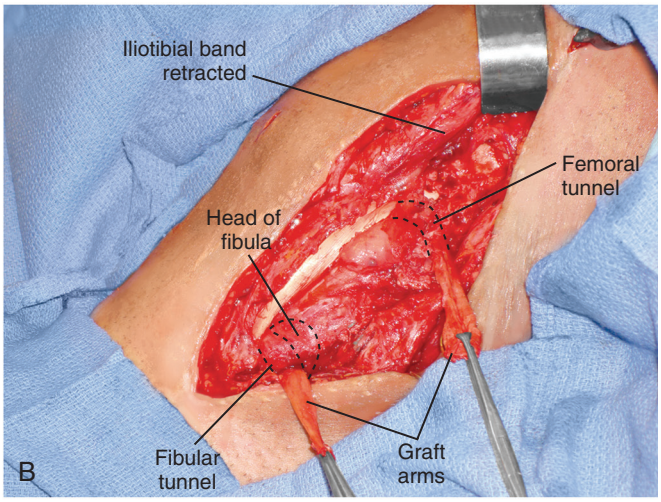
The PL structures are carefully identified. A definitive FCL of normal width and integrity (although lax) is identified, and the PL structures are verified to have adequate thickness (and not replaced by scar tissue). It is important to verify that the popliteus attachments to the fibula (PFL) and tibia are intact. If a definitive normal-appearing FCL is not observed, or if there is scar tissue replacement of the PL structures, then an anatomic reconstruction is required. The PL structures appear normal except for a mild to moderate increase in elongation.

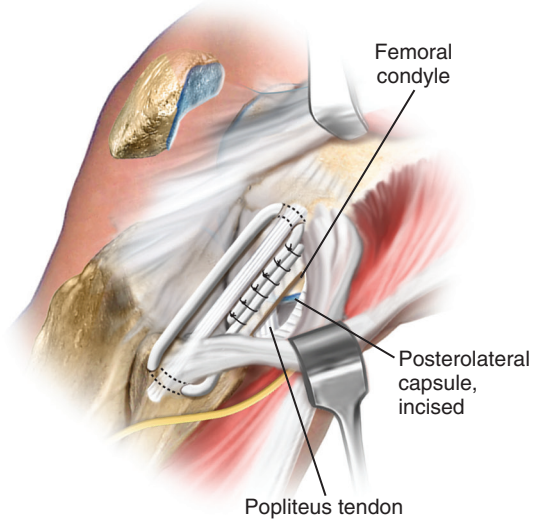
The CPN is palpated and protected throughout the procedure and is not dissected from its anatomic position. The joint capsule of the knee is incised vertically 10 mm anterior to the popliteal tendon's femoral attachment site, preserving the anterolateral capsular ligament. This permits the popliteal tendon attachment to be visualized on the lateral femoral condyle. A Kelly clamp is passed through this opening in the capsule and under the popliteus tendon, FCL, and anterior third of the lateral gastrocnemius muscle tendon attachment. An anterior-to-posterior incision is made in the periosteum just proximal to the FCL attachment. This incision is continued with a vertical, posterior arm into the anterior third of the LGT and anterior arm just anterior to the popliteus tendon attachment.

A straight osteotome initially cuts the rectangular edges, followed by a curved osteotomy that is used to remove an 8-mm-thick × 15-mm-wide wedge of bone at the attachment site of the PL structures, extending distally to the joint, avoiding the articular cartilage (Fig. 17-20, *A* and *B*). Two Alice clamps are placed on the osteotomized bone attachment of the PL structures. Any remaining soft tissue attachments are incised. The PLC attachment is incised along its posterior attachment approximately 10 to 15 mm to tension the capsule with final fixation (see Fig. 17-20, *C* and *D*).

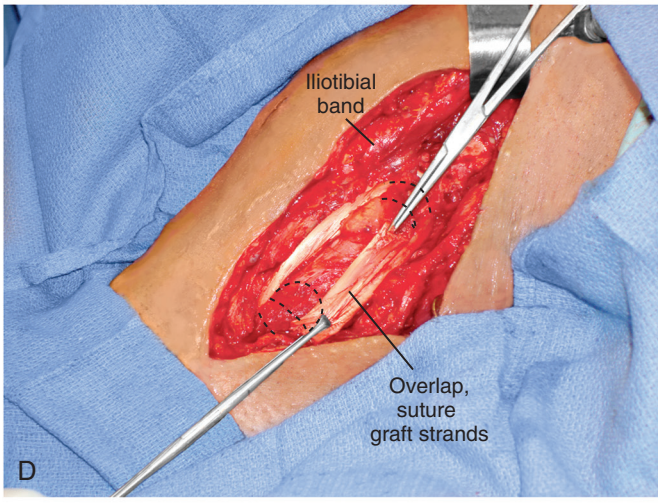


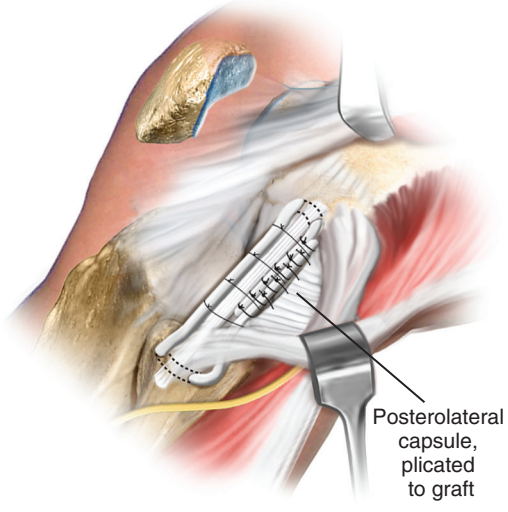
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C





E

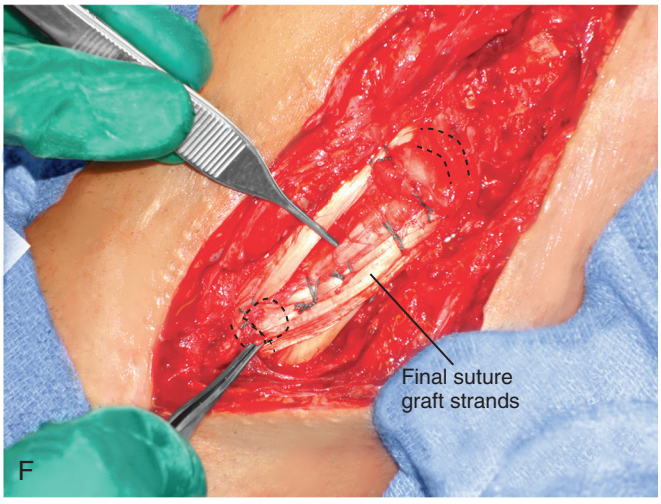
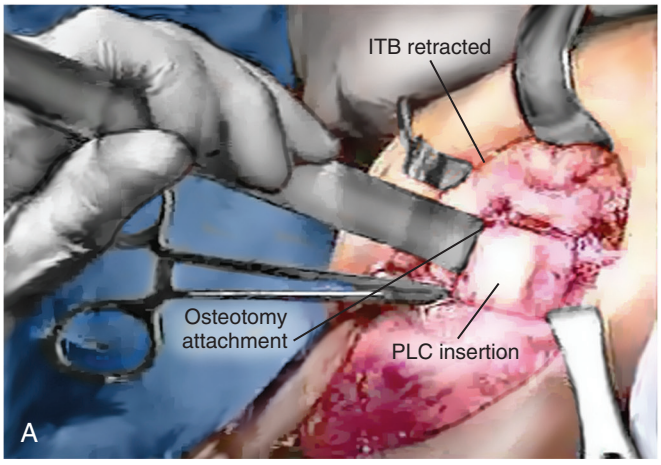
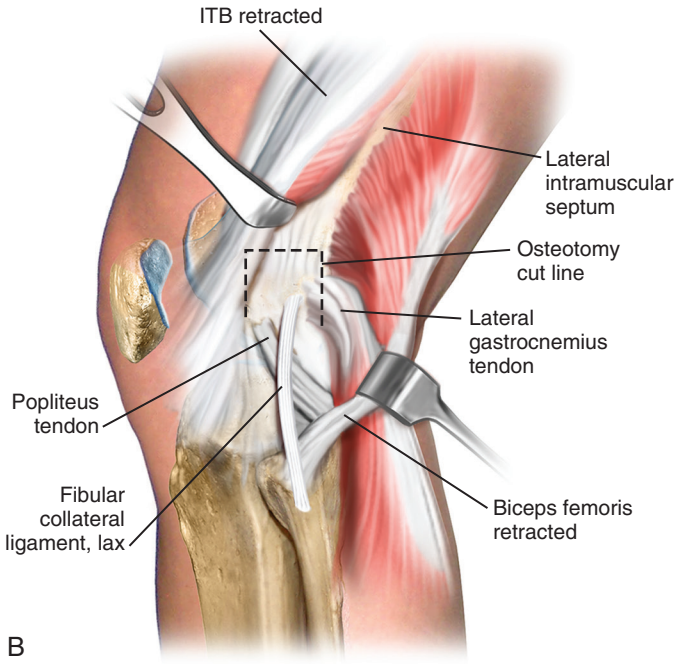
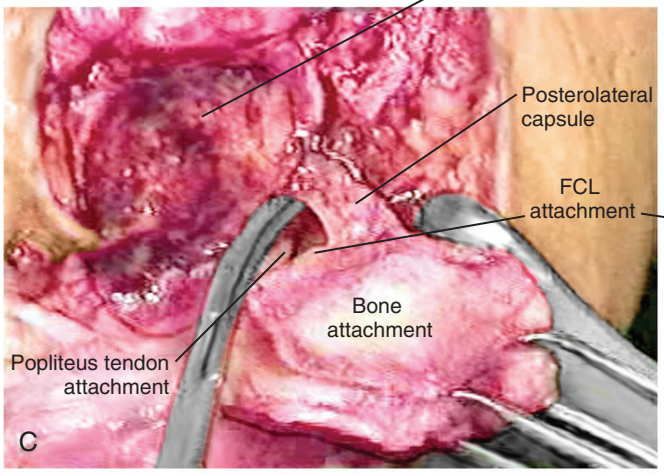


FIG 17-19 Femoral-fibular reconstruction. **A** and **B,** Placement of femoral and fibular tunnels and fibular collateral ligament (FCL) graft. **C** and **D,** Suturing and tensioning of graft arms. **E** and **F,** Multiple sutures are used through both arms of the graft and the slack FCL. Plication of the posterolateral capsule is performed to the graft.







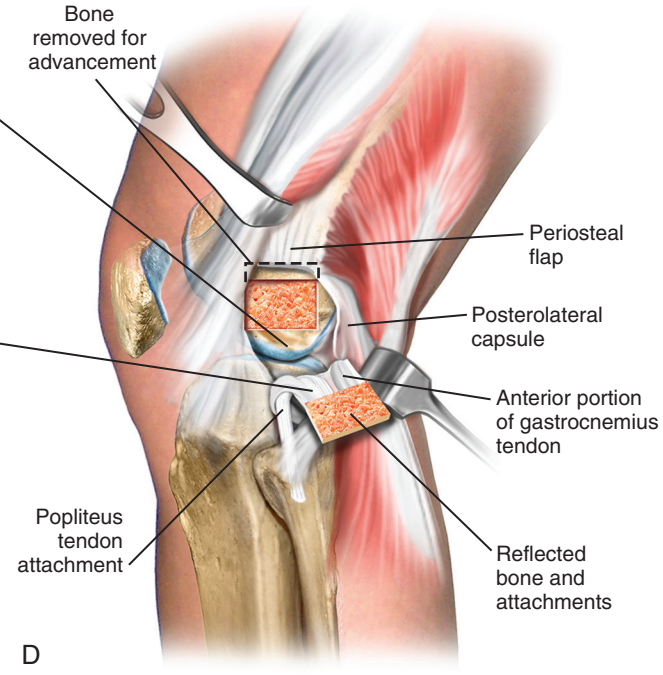


FIG 17-20 Proximal advancement of intact but lax posterolateral (PL) structures **A** and **B,** The PL structures are identified and have a normal, although lax, appearance. The line for the osteotomy of the femoral attachment of the fibular collateral ligament (FCL), popliteus muscle tendon, and anterior portion of the gastrocnemius tendon is shown. **C** and **D,** The osteotomy is 8 mm deep to provide sufficient bone to maintain the attachments of the FCL, popliteus tendon, anterior gastrocnemius tendon, and PL capsule. The PL capsule is incised 10 to 15 mm in length.

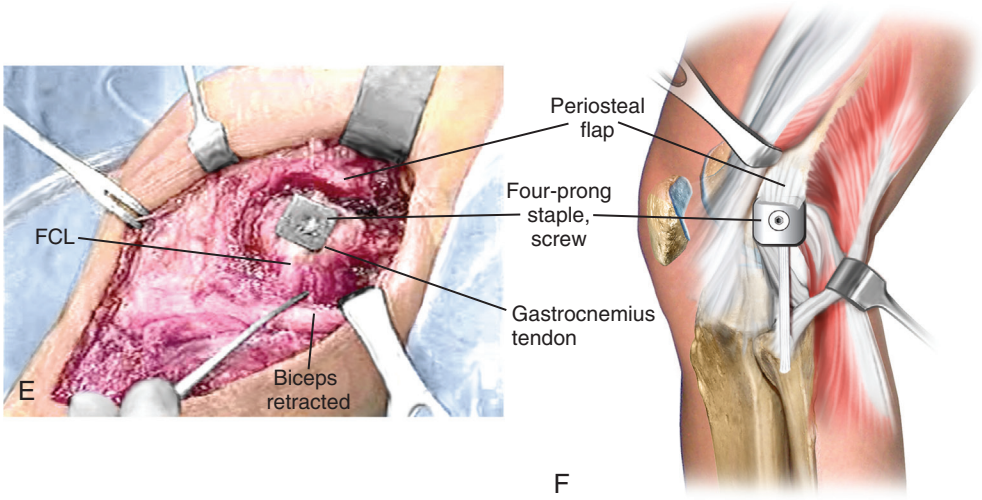


FIG 17-20, cont'd E and **F,** The bone attachment of the PL structures is advanced proximally in line with the FCL, with the knee in neutral tibial rotation and 30 degrees of flexion. Reattachment of the bone is achieved with a four-pronged staple and screw. *ITB*, Iliotibial band.

CRITICAL POINTS **Proximal Advancement of Posterolateral Structures**

- Straight lateral incision, 12 cm in length, centered over lateral joint line.
- Incision made along posterior border of ITB. Attachment of ITB to lateral intramuscular septum preserved. Posterior ITB incision may be required.
- Identify definitive FCL of normal area and integrity (although lax). Verify PL structures have adequate thickness, not replaced by scar tissue.
- CPN palpated, protected.
- Kelly clamp passed through opening in capsule and under popliteus tendon, FCL, and anterior third of lateral gastrocnemius muscle tendon attachment.
- Incision in periosteum just superior and proximal to FCL femoral attachment.
- New attachment site for PL structures prepared by elevating periosteum proximal to FCL.
- Curved osteotome elevates 8-mm thick × 15-mm wide wedge of bone at attachment site of PL structures, extending distally to the joint avoiding the articular cartilage.
- PL capsular attachments incised posteriorly, avoiding popliteus tendon.
- Proximal attachment site dissected subperiosteally, contoured with an osteotome. Sufficient amount of bone removed to allow the osteotomized bone attachment inlay to be placed and the staple to not be prominent.
- Bone attachment site of PL structures advanced in proximal direction of FCL with knee in 30 degrees of flexion, neutral tibial rotation.
- Inferior margin of staple placed at FCL anatomic attachment site to restore normal FCL length.
- PL function determined after fixation: 2- to 3-mm lateral joint opening, no abnormal external tibial rotation or hyperextension.

CPN, Common peroneal nerve; *FCL*, fibular collateral ligament; *ITB*, iliotibial band; *PL*, posterolateral.

The proximal attachment site is dissected subperiosteally, contoured with an osteotome, and a sufficient amount of bone is removed to allow the osteotomized bone attachment to be placed as an inlay, which decreases the prominence of the four-prong staple and screw fixation. It is necessary to inspect that the popliteus tendon is well attached to the anterior portion of the osteotomized bone so that it will be taut when tension is applied. The bone attachment of the PL structures is advanced in the proximal direction of the FCL with the knee in 30 degrees of flexion and neutral tibial rotation. The 90 degrees of flexion position is not recommended because this produces an anterior and distal attachment of the PL structures, which induces large forces with knee flexion-extension and risks stretching out the PL structures.

The goal is to advance the FCL in a proximal direction to remove excessive slackness and to use staple fixation at the normal anatomic site. The bone attachment site may be slightly rotated to adjust the tension in the posterior capsular tissues with extension. Fixation is with a large four-prong staple (see Fig. 17-20, *E* and *F*), and the distal margin of the staple is directly at the anatomic attachment of the FCL to restore normal FCL length. A cancellous bone screw is used for additional fixation.

The function of the FCL is determined after fixation to ensure that there is only 2 to 3 mm of LJO on varus stress testing and no abnormal external tibial rotation or hyperextension. The PL tissues are tensioned to allow the knee to come to 5 degrees of flexion and to resist further extension after this point, gradually reaching 0 to −2 degrees hyperextension during the postoperative rehabilitation period. The ITB tension is determined. A distal advancement of the ITB at the tibial attachment may be (rarely) required to restore normal tension in this structure. The ITB is closed with absorbable sutures. To prevent lateral tethering on the patella, any incisions into the ITB and lateral patellar retinaculum are loosely closed (Fig. 17-21).

An example of the proximal advancement with an all-inside PCL reconstruction is shown in Figure 17-22. The PL complex was functionally intact but lax and did not require graft reconstruction as previously described.

OUR CLINICAL STUDIES

The results of a series of prospective clinical studies of consecutive patients are reported using the CKRS and the International Knee Documentation Committee (IKDC) system.[2] The results were evaluated by a senior clinical research associate and not the surgeon.

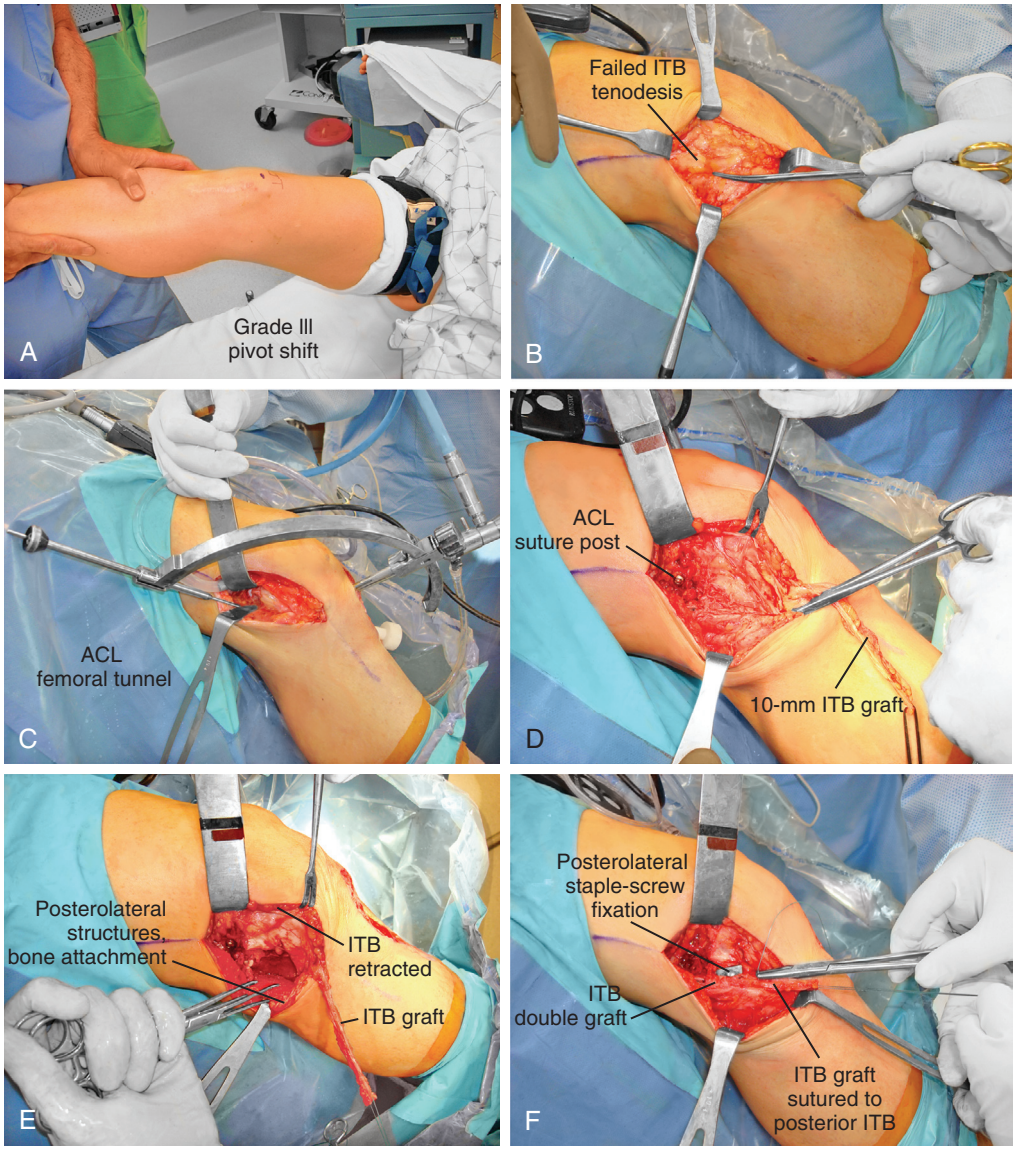


FIG 17-21 A 38-year-old female physician with symptomatic chronic anterior cruciate ligament (ACL) rupture referred to our center after failure of iliotibial band (ITB) tenodesis. An acute superficial medial collateral ligament repair at the index procedure was successful. **A,** Grade III pivot shift. A harvest of a semitendinosus-gracilis graft was performed (not shown) through the prior medial incision. **B,** Identification of failed ITB tenodesis with deficient anterolateral structures. **C,** Outside-in femoral tunnel at ACL anatomic site on lateral wall of femur. **D,** Harvest of ITB for extraarticular (EA) reconstruction because of severe anterior instability. **E,** Osteotomy and advancement of posterolateral (PL) structures that were intact but lax, allowing abnormal increased lateral joint opening and external tibial rotation at 30 degrees of flexion. **F,** Internal fixation of proximal advancement and EA reconstruction. The ITB graft was looped under one of the staple prongs and sutured to itself and the remaining ITB to provide a secondary restraint. The remaining ITB was closed. This procedure was successful in restoring PL and anterior stability.

Anatomic Posterolateral Reconstruction

A consecutive group of knees that had an anatomic PL reconstruction including an FCL B-PT-B reconstruction were prospectively followed 2 to 13.7 years postoperatively.[45] All major PL structures were surgically restored as required. The procedure represented a primary reconstruction in seven patients and a revision in six patients. ACL ruptures were found in seven patients and bicruciate ruptures in five patients, all of which were reconstructed.

At follow-up, 13 of the 14 (93%) PL reconstructions restored normal or nearly normal LJO and external tibial rotation (Fig. 17-23). The ACL reconstructions were normal or nearly normal in 11 knees and abnormal in one knee. All patients achieved at least 0 to 135 degrees of knee motion; one required a gentle manipulation, and one had an arthroscopic lysis of adhesions to achieve this range of knee motion.

Significant improvements were found at follow-up for pain ($P = .0001$), swelling ($P = .02$), patient rating of the overall knee condition ($P < .001$), walking ($P < .05$), and stair climbing ($P < .05$). Before the operation, 9 of the 12 patients had moderate or severe pain with daily activities, but at follow-up, only 1 patient had such pain. Eleven of the



FIG 17-22 A proximal advancement and all-inside posterior cruciate ligament quadriceps tendon-patellar bone reconstruction with TightRope (Arthrex) fixation on the femur.

12 patients had given up sports activities completely before the operation, and 1 was participating in low-impact activities without problems. At follow-up, 11 patients were participating in mostly low-impact athletics (swimming, bicycling) without symptoms and 1 patient was participating in sports that involved pivoting and cutting with pain and limitations against advice.

The results of the anatomic PL reconstructions were similar for primary and revision cases. The only failure occurred in a revision knee. A total of 17 PL procedures had been performed in the six revision knees before the anatomic reconstruction. The failed PL procedures included nonanatomic graft augmentation procedures, primary repairs in knees with chronic PL ruptures, or biceps tendon procedures. None of these knees had surgical restoration of all of the PL structures in one setting. In addition, none of the revision knees had a successful ACL procedure; therefore all required ACL reconstruction or revision during the anatomic PL graft reconstruction.

Femoral-Fibular Allograft Reconstruction

Two investigations were performed on the femoral-fibular allograft reconstruction for chronic instability.[41] The first study followed 20 consecutive patients from 2 to 7.8 years postoperatively. Lateral stress radiographs and a comprehensive knee examination showed that 16 knees (76%) had a functional FCL and PL reconstruction and 5 failed. All knees but 1 had at least 0 to 135 degrees of knee motion at follow-up and no patient required an additional operation for a limitation of motion.

Significant improvements were found for symptoms and functional limitations ($P < .01$). Before the operation, 9 patients had moderate pain with activities of daily living, 7 had pain with any sports activities,

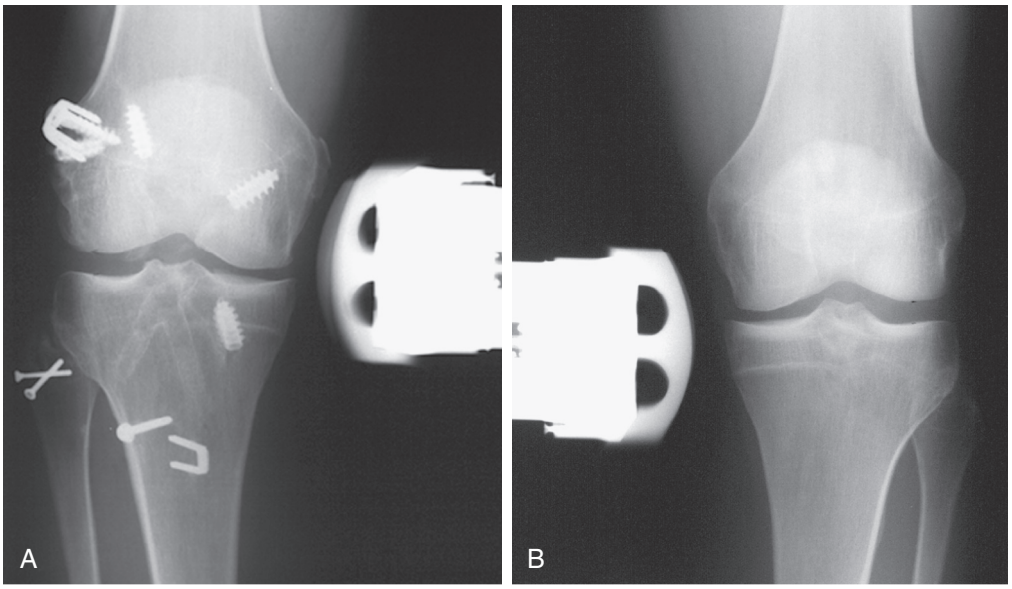


FIG 17-23 Lateral stress radiographs of a 22-year-old man 2 years after a combined fibular collateral ligament bone-patellar tendon-bone (B-PT-B) autogenous reconstruction, an anterior cruciate ligament B-PT-B allograft reconstruction, and a posterior cruciate ligament two-strand quadriceps tendon-patellar bone reconstruction. There is no measurable difference in the millimeters of lateral tibiofemoral joint opening between the reconstructed **(A)** and opposite **(B)** knee. (From Noyes FR, Barber-Westin SD. Posterolateral knee reconstruction with an anatomical bone-patellar tendon-bone reconstruction of the fibular collateral ligament. *Am J Sports Med.* 2007;35:259-273.)

and 4 had no pain with light sports but had pain with moderate sports (running, twisting, turning activities). At follow-up, 2 patients had pain with daily activities, 2 had pain with any sports activity, and 16 could participate in mostly light sports without pain.

A longer-term follow-up of the femoral-fibular reconstruction was conducted in a group of 27 patients. In 10 patients, the reconstruction failed before the minimum 2 years follow-up period. These cases were included in the overall failure rate, but not in the subjective and functional analyses. Five of these patients had undergone prior unsuccessful PL procedures before the femoral-fibular reconstruction. In six of these patients, a revision of the FCL and PL structures was performed and in two patients with chronic pain, a total knee replacement was done. In one patient, the allograft was removed, and in one patient, no further operative procedure had been done at the time of writing.

The remaining 17 patients were evaluated a mean of 15 years (range, 4-19 years) postoperatively. Statistically significant improvements were found in the scores for pain, swelling, giving-way, walking, stair climbing, running, and twisting ($P < .05$). Before the operation, 50% of the patients had moderate to severe pain with daily activities, but at follow-up, only 13% had these complaints. Before the operation, all patients had either given up all athletic activities or had severe limitations with even light recreational activities. At follow-up, 63% were participating in low-impact activities such as swimming and bicycling without problems, 6% were participating with symptoms, and 31% were not participating in athletic activities. In these 17 patients, the FCL reconstructions were rated as normal or nearly normal (IKDC ratings, LJO and external tibial rotation) in all knees. Twelve patients had required a concomitant ACL reconstruction, which were rated as normal or nearly normal in eight and abnormal in four.

CRITICAL POINTS

Our Clinical Studies: Anatomic PL Reconstruction

- $n = 14$ followed 2 to 3.7 years postoperative.
- ACL reconstructed in 7 knees, ACL and PCL reconstructed in 5 knees.
- Evaluation: comprehensive knee examination, lateral stress x-ray, KT-2000, 20 degrees, 134 N, IKDC, Cincinnati Knee Rating System.
- Results
  - 93% normal/nearly normal lateral tibiofemoral joint opening and external tibial rotation.
  - All knees at least 0-135 degrees.
  - Significant improvements pain, swelling, patient rating, walking, stair climbing.
  - 11 patients returned low-impact sports without problems.

Our Clinical Studies: Femoral-Fibular Allograft Reconstruction

- $n = 27$ followed mean 12.7 years (range, 2-1 years).
- Evaluation: comprehensive knee examination, lateral stress x-ray, KT-2000, 20 degrees, 134 N, IKDC, Cincinnati Knee Rating System.
- Results
  - 64% normal/nearly normal lateral tibiofemoral joint opening and external tibial rotation.
  - All knees at least 0-135 degrees.
  - Significant improvements pain, swelling, giving-way, walking, stair climbing.
  - 63% returned to low-impact sports without problems.

ACL, Anterior cruciate ligament; *IKDC*, International Knee Documentation Committee; *PCL*, posterior cruciate ligament.

Because of the increased failure rate, which was attributed to patients with poor PL tissues and prior failed PL procedures, we now recommend anatomic PL reconstruction. A femoral-fibular procedure is used only in chronic knees in which the PMTL is functional and the goal is to augment a deficient FCL. This operation is also useful in acute PL disruptions to restore FCL function, along with a primary repair of the remaining PL tissues.

Proximal Advancement of Posterolateral Structures

A proximal advancement of the PL structures was done in conjunction with a cruciate ligament reconstruction in 23 consecutive patients.[42] One patient was lost to follow-up. A second patient had an early failure and required a revision PL reconstruction; this result was included in the study's overall failure rate. Therefore 21 patients made up the study group and were evaluated 2 to 6.1 years postoperatively. The ACL was also reconstructed in nine knees, the PCL was reconstructed in 11 knees, and both cruciates were reconstructed in one knee.

At follow-up, 20 knees (91%) had normal or nearly normal LJO and external tibial rotation, and two (9%) failed. At least 0 to 135 degrees of knee motion was found in 16 patients. Two patients had mild limitations (between 1 and 5 degrees) in both extension and flexion, one patient had a mild limitation of extension only, and two patients had mild limitations in flexion only. No further operations were performed for losses of knee motion.

Before the operation, eight patients had pain with daily activities, eight had pain with any sports activity, and five could participate in light sports but had pain with moderate sports (running, twisting and turning activities). At follow-up, two patients had pain with daily activities, nine patients had pain with any sports activity, and 10 were able to participate in low-impact sports without pain. Overall, 71% of patients showed improvement in the pain score or had no symptoms with light sports.

Before the operation, all patients had either given up sports activities or were participating with symptoms and functional limitations. At follow-up, 62% had returned to mostly low-impact activities without symptoms. The other patients did not return owing to their knee condition. At the time of the operation, 52% of the patients had abnormal articular cartilage lesions (Grade 2-A, 2-B, or 3-A >15 mm, CKRS). This study shows the advantage of this operation in properly selected patients who have interstitial stretching of the PL structures without prior traumatic disruption, allowing advancement to restore normal tension.

CRITICAL POINTS Our Clinical Studies: Proximal Advancement Posterolateral Structures

- $n = 21$ followed 2-6.1 years.
- ACL reconstructed in 8 knees, PCL reconstructed in 10 knees, ACL and PCL reconstructed in 4 knees.
- Evaluation: comprehensive knee examination, lateral stress x-ray, KT-2000, 20 degrees, 134 N, IKDC, Cincinnati Knee Rating System.
- Results
  - 91% normal/nearly normal lateral tibiofemoral joint opening, external tibial rotation.
  - ACL normal/nearly normal in 92%.
  - 62% patients returned to low-impact sports without problems.

ACL, Anterior cruciate ligament; *IKDC*, International Knee Documentation Committee; *PCL*, posterior cruciate ligament.

TABLE 17-3 Factors Contributing to Failure of 57 Posterolateral Procedures

	ACUTE SUBGROUP		CHRONIC SUBGROUP	
Factor	Index PL Procedure* Knees (*n*)	Revision PL Procedures† (*n*)	Index PL Procedure‡ Knees (*n*)	Revision PL Procedures§ (*n*)
Untreated varus malalignment	4	3	6	8
Nonanatomic graft reconstruction	10	4	7	14
Inadequate internal fixation	0	2	1	3
Infection	4	1	0	0
Primary repair chronically deficient tissues	0	0	8	1
Traumatic reinjury	1	0	1	0
Unknown	0	1	0	1
ACL rupture	6	2	9	14
PCL rupture	2	1	3	0
ACL and PCL ruptures	4	0	3	2

*5 of 13 knees had more than one factor identified.
†3 knees had more than one factor identified.
‡7 of 17 knees had more than one factor identified.
§ACL and/or PCL rupture: either not treated or not adequately restored; procedure failed.
ACL, Anterior cruciate ligament; *PCL*, posterior cruciate ligament; *PL*, posterolateral.

Causes of Failure of Posterolateral Operative Procedures

The potential causes of failure of 57 operative procedures (30 index and 27 revisions) to the PL structures of the knee were studied in a consecutive series of 30 knees of patients who were referred to our center.[46] The index PL procedures were done for an acute knee injury in 13 knees (mean, 3 weeks; range, 1 to 11 weeks after the injury) and for chronic deficiency in 17 knees a mean of 56 months (range, 4 to 312 months) after the original injury.

The review of medical records in all cases was done by an independent surgeon not involved in the care of the patients. At the initial evaluation, a comprehensive knee examination and lateral stress radiographs were performed. KT-2000 testing was done in knees with ACL ruptures, and posterior stress radiographs were done in knees with PCL ruptures.

Overall, for all 57 failed PL operations, nonanatomic graft procedures had been done in 23 knees (77%, Table 17-3). The definition of an anatomic reconstruction was a graft placed in anatomic ligament attachment sites with secure internal fixation. Therefore suture repairs, extraarticular ITB augmentations, and biceps tendon rerouting methods (Fig. 17-24) were not considered anatomic procedures.

Untreated varus malalignment was identified in 21 failed PL procedures (37%) or in 10 of 30 knees (Tables 17-4 and 17-5). Patients who presented with PL deficiency and varus osseous malalignment were diagnosed with triple varus knees. Associated ACL, PCL, or bicruciate deficiency was identified in 27 knees (93%). ACL deficiency was identified in 41 of the 57 (72%) failed PL procedures and associated PCL deficiency was noted in 15 (26%) of the failed PL procedures.

PL deficiency subjects ACL and PCL grafts to excessive tensile loading owing to the abnormal lateral tibiofemoral joint opening that occurs with activity. Several in vitro studies report significantly increased forces on ACL and PCL grafts in knees with sectioned PL structures (see Chapter 15), providing further evidence of the deleterious effects of FCL and PMTL insufficiency after ACL or PCL reconstruction.

Limitations of this study were similar to those of other investigations in which the potential causes of ligament reconstruction failure were defined. It is difficult to determine in a retrospective manner the exact causes of failure. Several theoretical factors exist that cannot always be detected or measured. These include failure of grafts to fully remodel or heal, poor tissue quality caused by extensive disruption to the popliteus and FCL, limited healing potential of soft tissues caused by repeated operations and diminished blood supply, osteopenic bone preventing appropriate fixation, and gait hyperextension abnormalities that may have occurred postoperatively without the knowledge of the investigators.

In addition, since the study period extended over two decades, the evolution of the diagnosis and management of PL injuries and



FIG 17-24 A patient with a failed biceps femoris tenodesis for posterolateral instability was unable to actively rotate the left tibia externally. This procedure is not recommended.

TABLE 17-4 Analysis of Treatment of Associated Cruciate Ligament Ruptures and Varus Malalignment in 21 Failed Posterolateral Procedures in Knees Treated for Acute Injuries

		CRUCIATE LIGAMENTS			VARUS MALALIGNMENT	
Failed PL Procedure	No. Cruciates Ruptured	Ruptured or Deficient, Not Treated	Reconstructed with PL Procedure, Subsequently Failed	Reconstructed with PL Procedure, Functional	Not Treated	High Tibial Osteotomy
Index ($n = 13$)	18*	5	11	2	4	0
First revision ($n = 6$)	7†	3	0	4	2	1
Second revision ($n = 2$)	2	0	0	2	1	0
Total	27	8	11	8	7	1

*Bicruciate ruptures in 5 patients coded for treatment of ACL and PCL separately.
†Bicruciate ruptures in 1 patient coded for treatment of ACL and PCL separately.
ACL, Anterior cruciate ligament; *PCL*, posterior cruciate ligament; *PL*, posterolateral.

TABLE 17-5 Analysis of Treatment of Associated Cruciate Ligament Ruptures and Varus Malalignment in 36 Failed Posterolateral Procedures in Knees Treated for Chronic Injuries

		CRUCIATE LIGAMENTS			VARUS MALALIGNMENT	
Failed PL Procedure	No. Cruciates Ruptured	Ruptured or Deficient, Not Treated	Reconstructed With PL Procedure, Subsequently Failed	Reconstructed With PL Procedure, Functional	Not Treated	High Tibial Osteotomy
Index ($n = 17$)	20*	3	15	2	6	0
First revision ($n = 10$)	12†	5	4	3	3	1
Second revision ($n = 6$)	5	4	1	0	2	0
Third revision ($n = 2$)	2	1	1	0	0	2
Fourth revision ($n = 1$)	1	1	0	0	1	0
Total	40	14	21	5	12	3

*Bicruciate ruptures in three patients coded for treatment of ACL and PCL separately.
†Bicruciate ruptures in two patients coded for treatment of ACL and PCL separately.

CRITICAL POINTS Our Clinical Studies: Causes of Failure of Posterolateral Operative Procedures

- $n = 57$ failed PL procedures in 30 knees.
- Evaluation: review of medical records by an independent surgeon, comprehensive knee examination, lateral stress x-ray, KT-2000, 20 degrees, 134 N, PCL stress x-ray, IKDC, Cincinnati Knee Rating System.
- Causes of PL failure
  - 93% associated cruciate deficiency (either untreated or failed reconstruction).
  - 77% nonanatomic PL procedures (suture repair, iliotibial band augmentations, biceps tendon rerouting).
  - 37% untreated varus osseous malalignment (triple varus knee).
- Conclusions
  - Emphasis during index operation on anatomic PL reconstruction, concurrent reconstruction all torn cruciate ligaments.
  - If varus osseous malalignment exists, correct with osteotomy before PL reconstruction.

IKDC, International Knee Documentation Committee; *PCL*, posterior cruciate ligament; PL, posterolateral.

associated abnormalities has altered the treatment of these problems. Some of the procedures in this series represent operations that are no longer routinely performed. Even so, the results of this study suggest greater emphasis during the index operation for anatomic graft reconstruction of one or more of the PL structures as necessary, restoration of all ruptured cruciate ligaments, and correction of varus malalignment. We have long advocated anatomic PL reconstruction over suture repair in patients who sustain acute high-energy injuries and extensive disruption of the PL structures. Usually at least one component of the PL structures requires graft reconstruction, which is the FCL in nearly all cases.

OTHER OPERATIVE TECHNIQUES AND RESULTS

Several authors have reported clinical outcome data from PL reconstructive procedures (Table 17-6). LaPrade and coworkers[26] described an anatomic PL reconstruction shown in Figure 17-25, *A* and *B*. Biomechanic testing of this technique demonstrated restoration of normal knee motion limits to external tibial rotation and LJO. The operation restores the anatomic attachment sites for the FCL and popliteus tendon and allows load sharing between these two structures, which appears to have a distinct advantage over a single femoral-fibular graft reconstruction. The clinical outcomes of this operation were reported in 54 patients, 18 of whom had an isolated

Text continued on p. 569

TABLE 17-6 Clinical Outcome Data of Posterolateral Reconstructions

Study	N	Acute or Chronic	Follow-up (yr [Range])	Posterolateral Operative Procedure	Other Ligament Procedures	Objective Rating Criteria	External Tibial Rotation Results*	Lateral Joint Opening Results*	Other Ligaments Results
Cartwright-Terry et al[6] (2014)	25	Acute and chronic	7 (5.8-10.7)	Split biceps tenodesis	ACL STG or B-PT-B in all	Rolimeter AP 30 degrees, 90 degrees	All but one <5 degrees at 30 and 90 degrees of flexion	Not given	30 degrees: mean involved, 11.3 ± 2.0 mm; noninvolved, 9.7 ± 2.7 mm 90 degrees: mean involved, 6.3 ± 1.1 mm; noninvolved, 7.4 ± 2.0 mm
Tardy et al[62] (2014)	20 (20 controls)	Acute and chronic	3.2	FCL, popliteus tendon, PFL with STG	PCL (9), ACL (3), ACL + PCL (8)	Rotameter IR and ER 30 degrees, 5 N-m torque (dial test)	Mean differences in patients: IR, 2.5 ± 3.7 degrees; ER, −1.0 ± 4.1 degrees; mean differences in patients vs. controls: IR, 17.14 degrees; ER, 2.58 degrees; 65% patients significantly different from controls	IKDC: A, 9 (45%); B, 7 (35%); C, 4 (20%)	IKDC pivot shift: A, 15; B, 4; C, 1 IKDC posterior: A, 15; B, 4; C, 1
Yang et al[66] (2013)	60	Acute and chronic	3 (2-5.4)	Single fibular sling with tibialis anterior allograft	ACL STG autograft (9), PCL single-strand tibialis anterior allograft (42), ACL + PCL (3)	Varus stress x-ray 0 degrees, 150 N Posterior stress x-ray 90 degrees, 150 N	30 degrees of flexion 0 degrees: 42 (70%) <15 degrees: 16 (27%) >20 degrees: 2 (3%)	0: 46 (77%) Grade 1: 12 (20%) Grade 2: 2 (3%)	PCL stress x-ray: 4.06 ± 1.40 mm
Kim et al[20] (2013)	46	Acute and chronic	2.8	Tibialis posterior allograft for FCL, popliteus tendon	PCL (24)	Varus stress x-ray 30 degrees, posterior stress x-ray 90 degrees, dial test with goniometer	30 degrees of flexion: PL isolated 4.00 ± 1.83 degrees PL + PCL 4.04 ± 1.30 degrees 90 degrees of flexion: PL isolated 3.64 ± 1.18 degrees PL + PCL 3.67 ± 1.37 degrees	Varus stress x-ray: PL isolated, 1.55 ± 0.78; PL + PCL, 1.35 ± 1.00	PCL stress x-ray: < 5 mm, 26; >5 mm, 23

Continued

TABLE 17-6 Clinical Outcome Data of Posterolateral Reconstructions—cont'd

Study	N	Acute or Chronic	Follow-up (yr [Range])	Posterolateral Operative Procedure	Other Ligament Procedures	Objective Rating Criteria	External Tibial Rotation Results*	Lateral Joint Opening Results*	Other Ligaments Results
Kim et al[19] (2011)	46	Acute and chronic	2	Tibialis posterior allograft for FCL, popliteus tendon (25), biceps rerouting tenodesis (21)	PCL in all	Varus stress x-ray 30 degrees, posterior stress x-ray 90 degrees, dial test with goniometer	*30 degrees of flexion:* Anatomic: 0-5 degrees, 13 (62%); 6-10 degrees, 7 (33%); 11-15 degrees, 1 (5%) Biceps tenodesis: 0-5 degrees, 5 (20%); 6-10 degrees, 6 (24%); 11-15 degrees, 9 (36%); >15 degrees, 5 (20%)	*Varus stress x-ray:* Anatomic: <3 mm, 20 (95%); 3-5 mm, 1 (5%) Biceps tenodesis: <3 mm, 16 (64%); 3-5 mm, 9 (36%)	PCL stress x-ray: <3 mm, 11 (24%); 3-5 mm, 23 (50%); 6-10 mm, 12 (26%)
Geeslin & LaPrade[12] (2011)	26/29	Acute	2.4 (2-3.9)	Reconstruction or repair, variety of techniques	ACL (11), PCL (3), ACL + PCL (5)	Varus stress x-ray 20 degrees, posterior stress x-ray 90 degrees	30 degrees of flexion: IKDC A-B, 100% 90 degrees of flexion: IKDC A-B, 100%	Varus stress x-ray: mean, 0.1 mm (range, –1.5 to 5 mm) IKDC: A, 25 (96%); B, 1 (4%)	PCL stress x-ray: mean, 1.2 mm (range, 0-4 mm)
Lee et al[31] (2011)	70	Chronic	3.3 (2-8)	Sling reconstruction, fibular head tunnel (Larson), STG autograft	PCL in all	Posterior stress x-ray 90 degrees, 150 N, KT-1000 manual maximum	Overconstrained: 14 (20%) Constrained: 50 (71%) Lax: 6 (9%)	Grade 0: 68 (97%) Grade 1: 2 (3%)	PCL stress x-ray: <3 mm, 40 (57%); 3-5 mm, 26 (37%); >5 mm, 4 (6%)
Yoon et al[67] (2011)	32	Acute and chronic	2-5.2	Anatomic FCL with popliteal tendon reconstruction (17), no popliteal tendon reconstruction (15)	ACL (6), PCL (16), ACL + PCL (6)	Varus stress x-ray 30 degrees, posterior stress x-ray 90 degrees	No difference between groups; grade 0, 20 (62%); grade 1, 12 38%)	No difference among groups; grade 0, 24 (75%); grade 1, 7 (22%); grade 2, 1 (3%); varus stress x-ray: 0.26.4 mm	PCL stress x-ray: 0.58.5 mm
LaPrade et al[25] (2010)	54	Acute and chronic	4.3 (2-7.2)	AT-bone allograft, split, for FCL and popliteus tendon	ACL (22), PCL (14)	None	30 degrees of flexion: IKDC A-B, 50; C, 4	IKDC: A-B, 50; C, 4	NA
Rios et al[56] (2010)	21	Chronic	3.2 (2-6.7)	ST autograft or anterior or posterior tibialis allograft, dual femoral tunnels, transfibular tunnel	ACL (5), PCL (12), ACL + PCL (7)	Varus stress x-ray 20 degrees, posterior stress x-ray 90 degrees, KT-2000	IKDC: A, 18 (86%); B, 3 (14%)	Varus stress x-ray: <3 mm: 20 (95%) 3-5 mm: 1 (5%)	PCL stress x-ray: <3 mm, 8; 3-5 mm, 3; 6-10 mm, 6

Jakobsen et al[16] (2010)	27	Acute and chronic	3.8 (2-7.2)	STG double-strand FCL with sling technique; single-strand popliteal tendon	None	KT-1000	IKDC: A, 76%; B, 19%; C, 5%	IKDC: A, 89%; B, 7%; C, 4%	KT: <3 mm, 62%; 3-5 mm, 33%; >5 mm, 5%
Lee et al[32] (2010)	44	Acute and chronic	4.1 (25.7)	Sling reconstruction, fibular head tunnel (Larson), STG autograft	ACL in all	Anterior stress x-ray, varus stress x-ray, KT-1000 manual maximum	Dial test: grade 0, 9%; grade 1, 9%	Varus stress x-ray: 0.4 ± 0.8 mm; grade 0, 93%; grade 1, 7%	KT mean 1.5 ± 1.2 mm Pivot shift: grade 0, 89%; grade 1, 11%
Jung et al[17] (2008)	39	Chronic	2.9 (25.8)	Group 1: PL transtibial tunnel with either STG or AT allograft Group 2: fibular tunnel method with either STG or AT allograft	PCL single-strand STG autograft in all	Posterior stress x-ray 90 degrees, KT-1000 manual maximum 70 degrees	*30 and 90 degrees of flexion:* Group 1: <5 degrees, 63%; "lax," 37% Group 2: <5 degrees, 85%; "lax," 15%	Group 1: 0 mm, 84%; <5 mm, 11%; 5-10 mm, 5% Group 2: 0 mm, 95%; <5 mm, 5%	PCL stress x-ray: group 1, 2.1 ± 1.1 mm; group 2, 2.2 ± 0.9 mm
Zhao et al[68] (2006)	28	Chronic	2-4	Biceps tendon slip used to reconstruct FCL, PFL, PMT	PCL STG autograft (18), ACL ST autograft (3), ACL + PCL: STG autograft (6), ACL + PCL + PMC STG autograft (1)	External rotation device (Magnetic Angle Finder)	*30 degrees of flexion:* grade 0, 25 (89%); <5 degrees, 3 (11%)	Varus rotation 0 degrees of flexion; all patients 0, 30 degrees of flexion: 0 mm: 25 (89%) < 5 mm: 2 (7%) 7 mm: 1 (4%)	Not given for ACL, PCL; overall IKDC ratings: A, 58%; B, 33%; C, 9%
Stannard et al[59] (2005)	57	Acute and chronic	2.7 (2-4.9)	Primary repair PL (35), allograft (tibialis anterior or tibialis posterior) reconstruction of FCL, PFL, popliteus (22)	ACL + PCL (35), ACL (14), PCL (4); type of grafts NA	KT-2000 30 degrees, 70 degrees, total AP	Repair group: <5 degrees, 21; 5-10 degrees, 2; 10-15 degrees, 5; >15 degrees, 7 Reconstruction group: <5 degrees, 19; 5-10 degrees, 1; >15 degrees, 2	Repair group: 0 mm, 19; 5 mm, 4; 10 mm, 5; >10 mm, 7 Reconstruction group: 0 mm, 14; 5 mm, 6; 10 mm, 1; >10 mm, 1	Not given for ACL, PCL; failure rates for PL: 37% repair, 9% reconstruction

*All data involved knee compared with noninvolved knee.

ACL, Anterior cruciate ligament; *AP*, anteroposterior; *AT*, Achilles tendon; *B-PT-B*, bone-patellar tendon-bone; *ER*, external rotation; *FCL*, fibular collateral ligament; *F/U*, follow-up; *IKDC*, International Knee Documentations Committee; *IR*, internal rotation; *MCL*, medial collateral ligament; *NA*, not available; *PCL*, posterior cruciate ligament; *PD*, posterior drawer; *PFL*, popliteofibular ligament; *PL*, posterolateral; *PMT*, popliteus muscle tendon; *PMC*, posteromedial complex; *ST*, semitendinosus; *STG*, semitendinosus-gracilis.

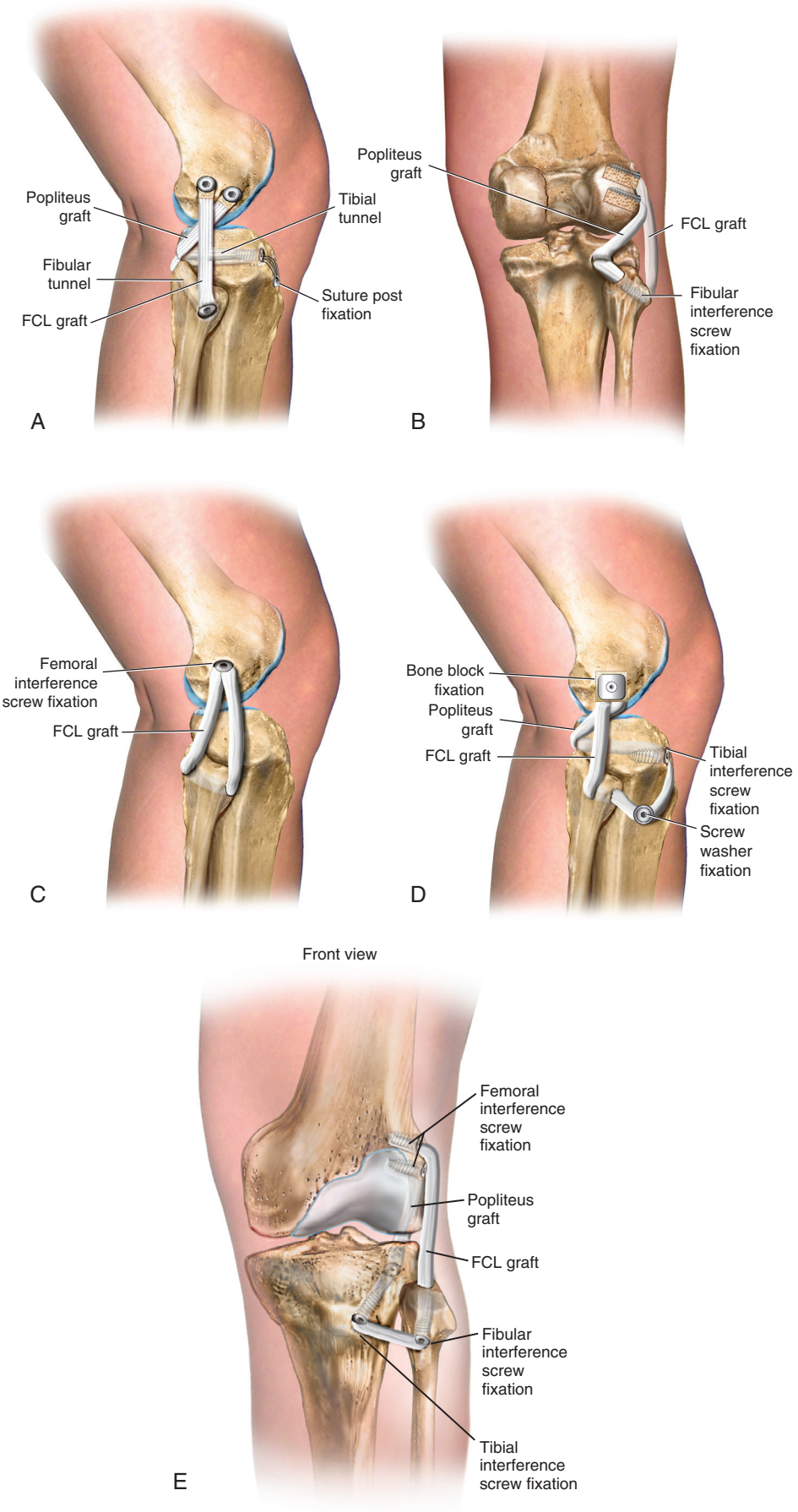


FIG 17-25 Alternative techniques for posterolateral (PL) reconstructions. **A** and **B,** The anatomic PL reconstruction described by LaPrade and coworkers[26] that uses Achilles tendon-bone (AT-B) allografts. **A,** The bone portion of the graft is placed at the femoral insertion of the fibular collateral ligament (FCL) and popliteus tendon. **B,** The popliteus graft is passed through a tunnel at the PL tibia. The FCL graft is passed through a fibular tunnel. **C,** PL technique described by Larson and Belfie[30] that uses a semitendinosus autograft. **D,** A technique demonstrating a single AT-B allograft in which a bone inlay is placed at the FCL femoral insertion. This technique avoids creating two femoral tunnels that may potentially weaken the lateral femoral condyle and is considered advantageous in knees that have prior tunnels from anterior cruciate ligament surgery. **E,** Technique using a single graft to replace the FCL and popliteus tendon described by Kim and associates.[21] The proximal ends of the graft are fixed by using bioabsorbable screws.

posterolateral reconstruction and the remainder of whom required concomitant cruciate ligament reconstruction.[25] At a mean of 4.3 years postoperatively, IKDC ratings for varus opening and external tibial rotation (30 degrees) were A or B in 50 patients and C in 4. The IKDC subjective mean score was 62.6 points (range, 20-100) and the overall modified Cincinnati score was 65.7 points (range, 20-100). Three patients required a revision posterolateral reconstruction for recurrent instability.

Tardy and colleagues[62] reviewed 20 patients who underwent combined PL-cruciate ligament reconstructions a mean of 3.2 years postoperatively. The PL procedure used a hamstrings autograft to reconstruct the FCL, popliteus tendon, and PFL. Static measurements were made of internal and external tibial rotation using the rotameter knee laxity measurement device,[33] which measured the dial test at 30 degrees under a 5 N-m torque. Side-to-side differences were measured between the reconstructed and contralateral knees of the patients. These differences were then compared with side-to-side differences in 20 healthy controls. There was no significant mean difference in external rotation between the knees of the patients (−1.0 ± 4.1 degrees) or between the patients and controls (2.5 degrees). However, there was a significant difference between patients and controls in internal tibial rotation of 17.15 degrees ($P < .05$). The authors reported that 65% of the patients had an *altered* rotational profile of either increased external or internal tibial rotation compared with the 95% CIs of the control group.

Buzzi and colleagues[5] described an FCL reconstruction using a semitendinosus tendon autograft. In a group of 13 patients studied at a mean of 5 years postoperatively, all had normal or nearly normal restoration of LJO and external tibial rotation postoperatively. Cooper and Stewart[8] presented two operative options for PL ruptures. One consisted of a combined FCL and PFL reconstruction (with a semitendinosus tendon autograft) with capsular imbrication. The second option consisted of reconstruction of the PFL only in knees with an intact FCL. In a group of 19 patients with combined PCL and PL ruptures, no patient had greater than 10 degrees of external rotation or more than 1+ increase in LJO postoperatively.

Stannard and colleagues[59] followed 57 patients who received either a primary repair of acutely ruptured PL structures or a graft reconstruction of chronically deficient FCL, PFL, and popliteus tendon structures. At an average of 2.7 years postoperatively, 37% of the primary repair procedures had failed, compared with 9% of the graft reconstructions. The authors concluded that primary repair of the FCL is indicated only for bony avulsions that are amendable to internal fixation. Otherwise, graft reconstruction of the FCL is recommended, especially if an immediate knee motion program is to be used postoperatively.

The PL technique described by Larson and Belfie[30] that uses a semitendinosus autograft is shown in Figure 17-25, *C*. The operative procedure is designed to restore FCL function, as in acute operative cases. However, it does not restore the PMTL unit, which may be required in chronic PL reconstructions. The outcomes of this operation were reported by Lee and associates[31] in 70 patients with chronic PCL and PL deficiency. These investigators used this operation in patients with grade 2 PL injuries, reserving an anatomic reconstruction for patients with grade 3 PL injuries. At a mean of 3.3 years postoperatively, external tibial rotation was overconstrained in 20%, constrained in 71%, and lax in 9%. LJO was rated as grade 0 in 97% and grade 1 in 3%. Definitions of overconstrained, constrained, and lax were not provided. Zorzi and colleagues[69] performed this operation, along with a single-bundle PCL reconstruction, in 19 patients. At a mean of 3.2 years postoperatively, 17 patients had a negative dial test and varus stress test and 14 patients had a grade 0 posterior step-off. There was a mean reduction of 10 degrees of knee flexion. This investigation did not use stress radiographs.

A technique demonstrated in Figure 17-25, *D* avoids creating two femoral tunnels that may potentially weaken the lateral femoral condyle. This procedure is considered advantageous in knees that have prior tunnels as in ACL revision surgery and the surgeon wishes to avoid an additional tunnel and, instead, use a single bone inlay technique for femoral graft fixation. An alternative technique using a single graft to replace the FCL and popliteus tendon described by Kim and associates[21] is illustrated in Figure 17-25, *E*. This technique was compared with a biceps rerouting tenodesis in a cohort of 46 patients.[19] At 2 years postoperatively, the FCL reconstruction produced significantly less mean side-to-side difference compared with the tenodesis procedure in external rotation at 30 degrees and 90 degrees of flexion (differences of 4 ± 1 degrees and 7 ± 1 degrees, respectively; $P = .02$). The IKDC overall knee examination rating was A or B in 76% of the knees that underwent the FCL reconstruction compared with 40% of the knees that had the tenodesis procedure.

ILLUSTRATIVE CASES

Case 1: Revision of ACL and PL Failed Procedures in a Salvaged Knee. A 28-year-old man was referred with a history of four failed ACL reconstructions that included an extraarticular Iliotibial band procedure, a B-PT-B autograft, and two B-PT-B allografts. The most recent surgical procedure done elsewhere had consisted of an ACL B-PT-B allograft and a semitendinosus tendon graft reconstruction of the PMTL. The FCL was not surgically addressed. The patient complained of pain and giving-way with daily activities and had been unable to work since his original injury. The examination demonstrated a grade III pivot shift, 12 mm of increased lateral joint opening, and 10 degrees of increased external tibial rotation.

Diagnostic arthroscopy performed before the revision ACL and PL procedure demonstrated an abnormal lateral tibiofemoral gap test (Fig. 17-26, *A*), a deficient PMTL (see Fig. 17-26, *B*), and fissuring and fragmentation of the articular cartilage (Grade 2-B damage, see Chapter 44) in the patellofemoral, medial tibiofemoral, and lateral tibiofemoral compartments.

The patient underwent an ACL quadriceps tendon-patellar bone autograft reconstruction using a notch approach owing to the close proximity of prior femoral tunnels that had not healed completely (but did not require bone grafting). In addition, an anatomic FCL B-PT-B allograft reconstruction, repair of the popliteofibular ligament advancement of the popliteus tendon, and advancement of the posterolateral corner were performed (see Fig. 17-26, *C* and *D*).

Our comment: This case demonstrates the protracted course and failure of three ACL reconstructions owing to unrecognized PL deficiency. Secondly, when the PL deficiency was recognized, a popliteal tendon reconstruction was done without addressing the FCL deficiency, which most likely led to failure of all of the procedures. The importance of surgical reconstruction of both the FCL and PMTL is emphasized.

Case 2: Treatment of Combined Failure of ACL and Posterolateral Deficiencies in a Varus-Angulated Knee. A 35-year-old man presented 5 months after failure of a PL biceps tendon transfer procedure and ACL B-PT-B autograft reconstruction. AP (Fig. 17-27, *A*) and lateral (see Fig. 17-27, *B*) radiographs demonstrated abnormal expansion of both the femoral and tibial tunnels and a vertical ACL graft.

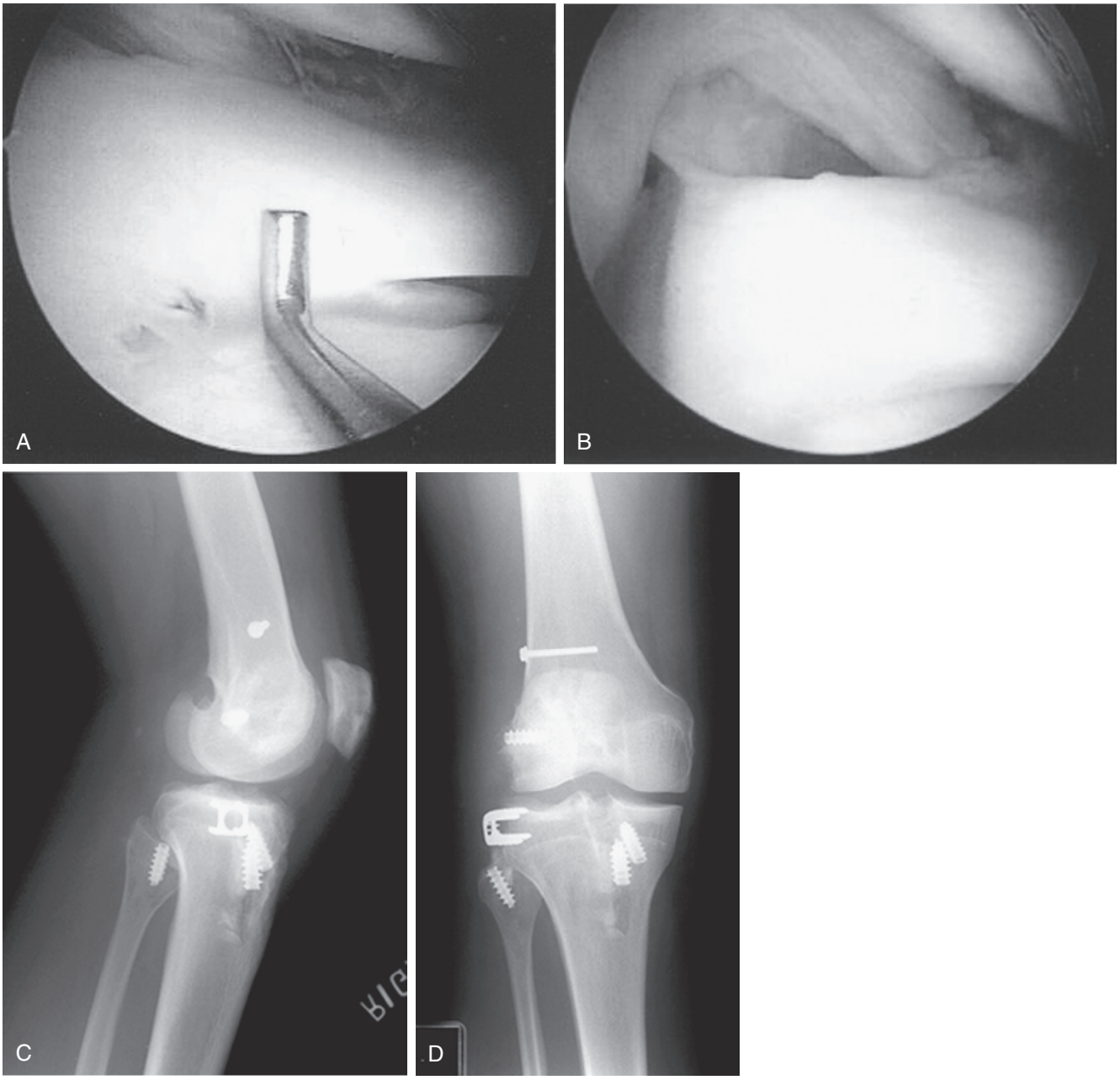


FIG 17-26 Case 1.

Physical examination revealed a grade III pivot shift, 7 mm of increased AP displacement on KT-2000 testing, and 10 mm of increased LJO. Full standing radiographs showed a weight-bearing line of 42%. The patient had not been able to return to work since his original injury and had moderate pain with daily activities.

The patient was treated with a staged approach of a corrective closing-wedge high tibial osteotomy, followed 4 months later with an anatomic PL reconstruction consisting of a fibular collateral ligament B-PT-B allograft, a popliteus muscle-tendon-ligament B-PT-B allograft, and a PL capsule plication. In addition, an ACL quadriceps tendon-patellar bone autograft revision reconstruction was performed that bypassed the previously placed vertical graft (see Fig. 17-27, *C*). At the latest follow-up evaluation, 4.4 years postoperative, there was no increase in LJO or external tibial rotation and the pivot shift test was negative. The patient had returned to work and light recreational sports without problems.

Our comment: This case demonstrates the increased failure rate when a PL reconstruction is performed in a varus-angulated knee. The first ACL reconstruction had a vertical ACL graft that was placed on the femoral notch roof outside the normal ACL femoral attachment.

Case 3: Treatment of Prior Multiple Failed Posterolateral Procedures in a Dislocated Knee. A 21-year-old man was referred 2 years after a knee dislocation sustained during football. He had undergone three failed PL operative procedures, including a biceps tendon reconstruction, a FCL allograft reconstruction, and a popliteal tendon allograft reconstruction. The deficient ACL had not been surgically treated. The medial collateral ligament was repaired during the first operative procedure.

Physical examination revealed a grade III pivot shift, 8 mm of increased AP displacement on KT-2000 testing, 12 mm of increased LJO, and 20 degrees of increased external tibial rotation. Stress radiographs demonstrated a severe increase in lateral joint opening (Fig. 17-28, *A*).

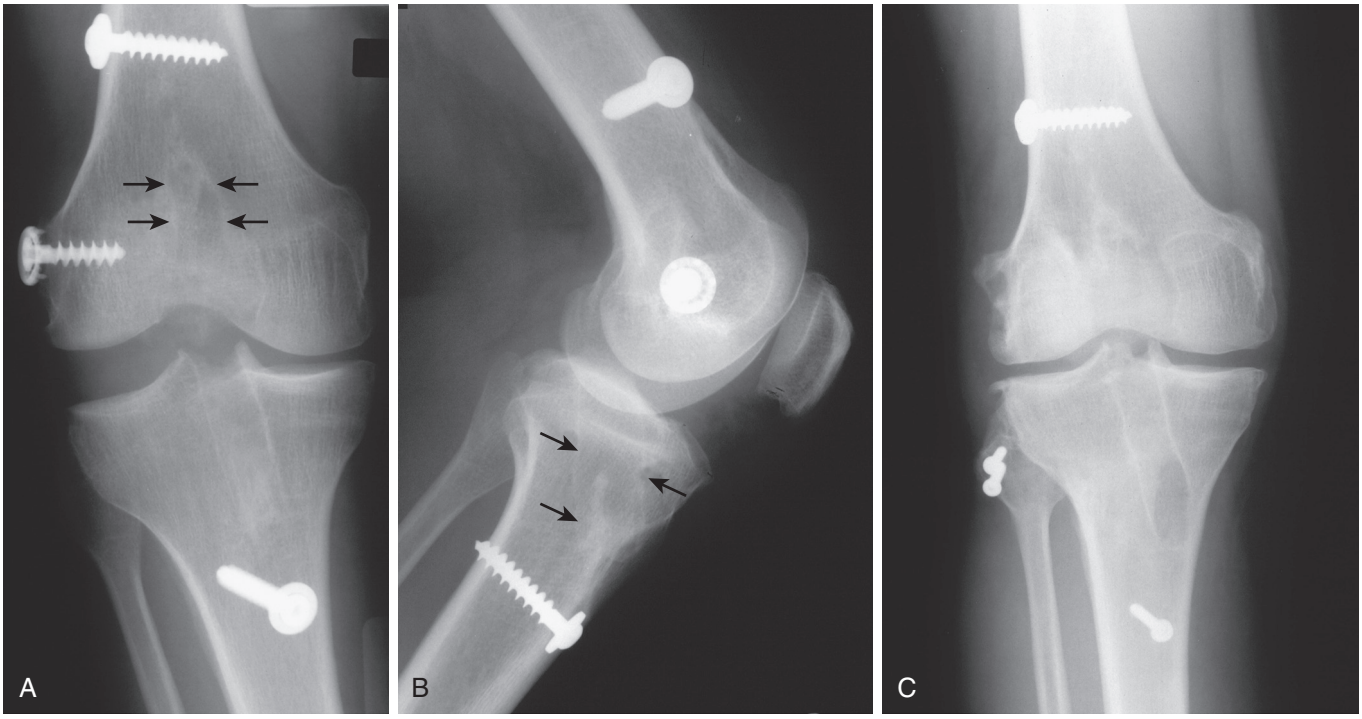


FIG 17-27 Case 2. (From Noyes FR, Barber-Westin SD, Albright JC. An analysis of the causes of failure in 57 consecutive posterolateral operative procedures. *Am J Sports Med.* 2006;34:1419-1430.)

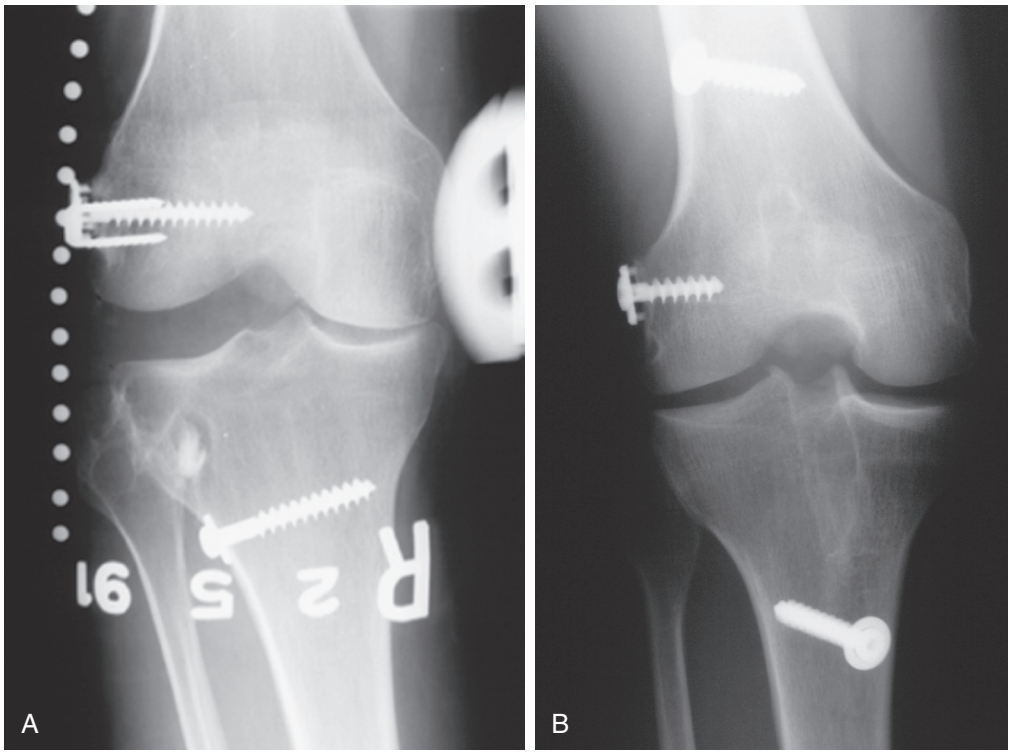


FIG 17-28 Case 3. (From Noyes FR, Barber-Westin SD, Albright JC. An analysis of the causes of failure in 57 consecutive posterolateral operative procedures. *Am J Sports Med.* 2006;34:1419-1430.)

The patient also had 5 mm of increased medial joint opening and 5 mm of increased posterior tibial translation. He complained of pain and giving-way with daily activities and rated the overall condition of his knee as poor.

The patient underwent an anatomic FCL B-PT-B autograft reconstruction (harvested from the contralateral knee) and a proximal advancement of the popliteus tendon. An ACL quadriceps tendon-patellar bone autograft was placed at the anatomic tibial and femoral attachment sites (see Fig. 17-28, *B*). Fissuring and fragmentation (grade 2-A damage) were noted in all three compartments.

At the most recent follow-up examination, 13.7 years postoperatively, the patient had no increase in LJO or external tibial rotation and

3 mm of increased AP displacement on KT-2000 testing. He was participating in low-impact activities without symptoms.

Our comment: In revision PL cases, it is necessary to address all PL structures as described. In this knee, after failure of three prior PL procedures, a contralateral B-PT-B autograft provided stability.

Case 4. A 50-year-old male physician presented 5 months after a right knee dislocation sustained during an attempted side tackle while playing soccer. The injury had been treated conservatively and the patient was experiencing increasing symptoms with daily and work activities. Physical examination revealed a lower limb varus malalignment with a mechanical axis of 5 degrees varus, a grade III pivot shift, 12 mm of increased LJO, and 10 mm of increased posterior tibial translation. The patient desired surgical reconstruction to return to his active lifestyle, which included skiing and mountain climbing.

An opening-wedge high tibial osteotomy was performed, followed 5 months later with a multiligament reconstruction that included an ACL B-PT-B allograft, a two-strand posterior cruciate ligament quadriceps tendon-patellar bone autograft, a fibular collateral ligament B-PT-B allograft, and a popliteus muscle-tendon-ligament reconstruction. The lateral meniscus was repaired. The patient had noteworthy articular cartilage damage (grade 2-B) on the patella undersurface and in the medial tibiofemoral compartment.

At follow-up, 4 years postoperatively, the patient had a full range of knee motion, no effusion, a grade 0 pivot shift, an increase of 5 mm of anteroposterior displacement on KT-2000 testing (at 20 degrees of knee flexion), 2 mm of increase in posterior tibial translation on posterior stress radiographs (Fig. 17-29, *A* and *B*), and no increase in LJO

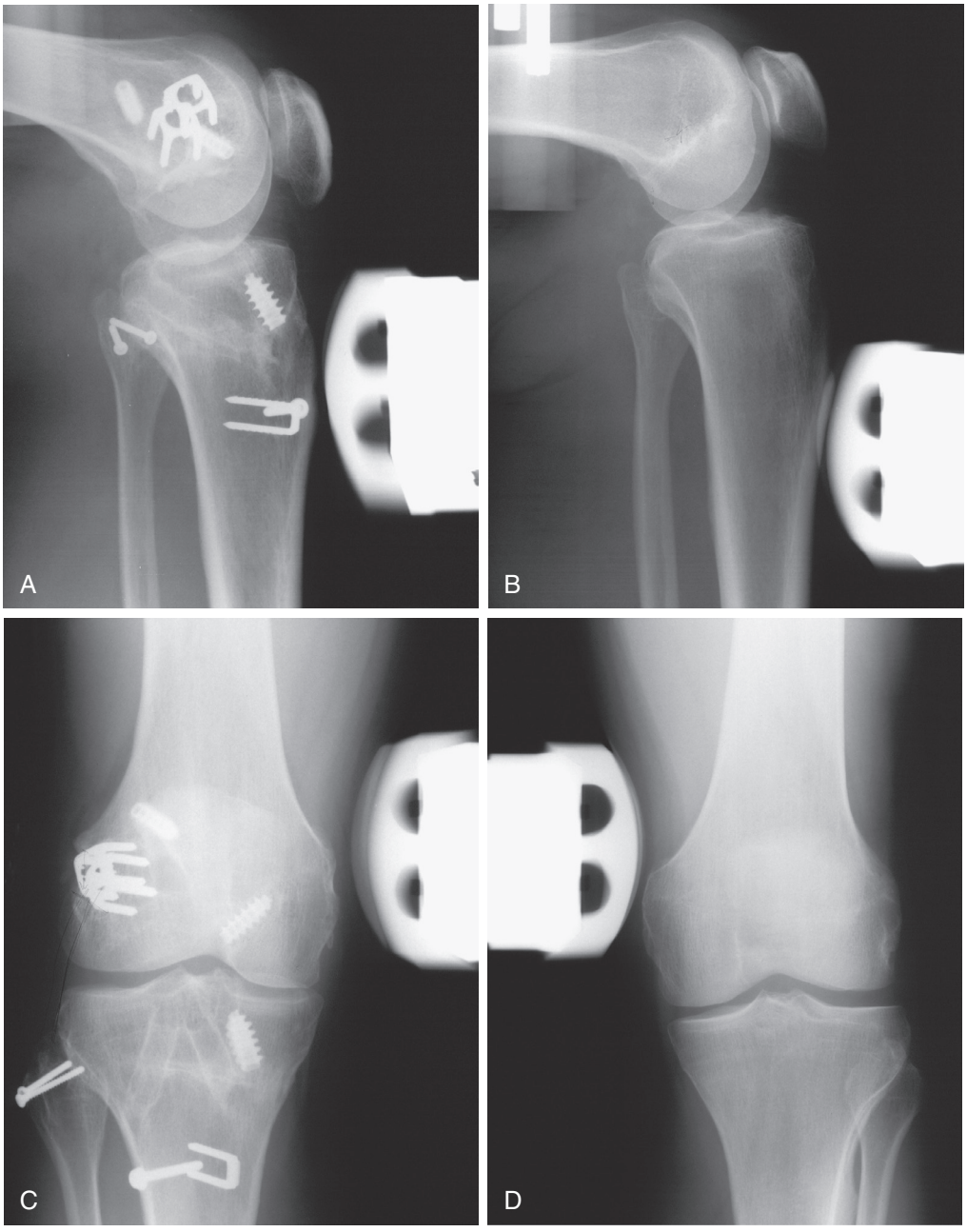


FIG 17-29 Case 4.

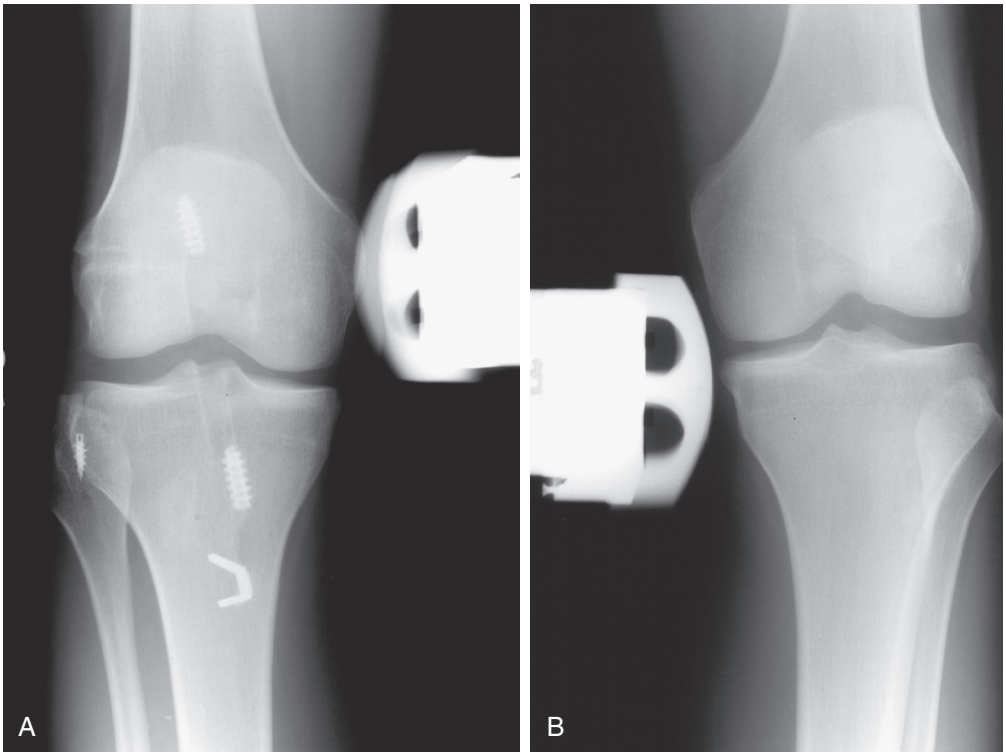


FIG 17-30 Case 5.

on lateral stress radiographs (Fig. 17-29, *C* and *D*). He had successfully returned to skiing and mountain climbing without symptoms, had run a marathon, and rated the overall condition of his knee as very good.

Case 5. A 15-year-old male presented 2 weeks after a contact injury to his right knee sustained while playing football. Physical examination revealed a moderate effusion, knee motion from 0 to 110 degrees, moderate lateral joint line tenderness, a grade II pivot shift, 12 mm of increased LJO, and 5 mm of increased posterior tibial displacement. Magnetic resonance imaging demonstrated a complete rupture of the FCL, popliteal tendon, and ACL and a partial disruption of the PCL.

After an initial week of rehabilitation and protected knee motion, the patient underwent an ACL B-PT-B autograft (harvested from the contralateral knee), an FCL B-PT-B autograft, a direct repair of the popliteus muscle-tendon-ligament and posterolateral capsule, and a lateral meniscus repair.

At follow-up, 4 years postoperatively, the patient had a normal range of knee motion, an increase of 3 mm in anteroposterior displacement on KT-2000 testing, no increase in lateral joint opening stress radiographs (Fig. 17-30, *A* and *B*), and a grade 0 pivot shift. He had returned to basketball, baseball, and football without symptoms or limitations and rated the overall condition of his knee as normal.

Case 6. A 35-year-old man presented 2 years after bilateral knee injuries sustained during a motor vehicle accident. The right knee was initially treated with an ACL B-PT-B autograft reconstruction, an MCL repair, and a medial meniscus repair. The left knee was initially treated with a primary repair of the ACL and FCL. A second surgery involved a left ACL semitendinosus-gracilis autograft and an FCL B-PT-B autograft reconstruction. A third surgery involved a left high tibial osteotomy and biceps tendon transfer. The patient presented with left knee symptoms of moderate pain, swelling, and lateral giving-way with daily activities and was unable to work.

Physical examination of the left knee demonstrated no effusion, a normal range of motion, a grade II pivot shift, 25 mm of increased LJO, and 10 degrees of increased external tibial rotation. The patient's left lower limb was in valgus, with a weight-bearing line of 74%; however, he drifted into varus in the unloaded position secondary to the lateral ligament instability. The biceps femoris muscle was nonfunctional.

The patient was treated first with a biceps femoris muscle reconstruction and neurolysis of the peroneal nerve. At this operation, arthroscopy showed grade 2-A articular cartilage lesions on the undersurface of the patella, trochlea, and medial femoral condyle. Five months later, he underwent an ACL B-PT-B allograft, an anatomic FCL B-PT-B autograft, proximal advancement of the posterolateral capsule, and distal advancement of the iliotibial band.

At follow-up, 12 years postoperatively, the patient had a normal range of knee motion, no effusion, 4 mm of increased anteroposterior displacement on KT-2000 testing, 2 mm of increase in LJO on stress radiographs on the involved left knee (Fig. 17-31, *A*) compared with the right knee (Fig. 17-31, *B*), and a grade 0 pivot shift. Weight-bearing posteroanterior radiographs showed preservation of tibiofemoral joint space in both compartments compared with the contralateral limb (Fig. 17-31, *C*). He had no symptoms with low-impact athletic activities or with his occupation and rated the overall condition of his knee as good.

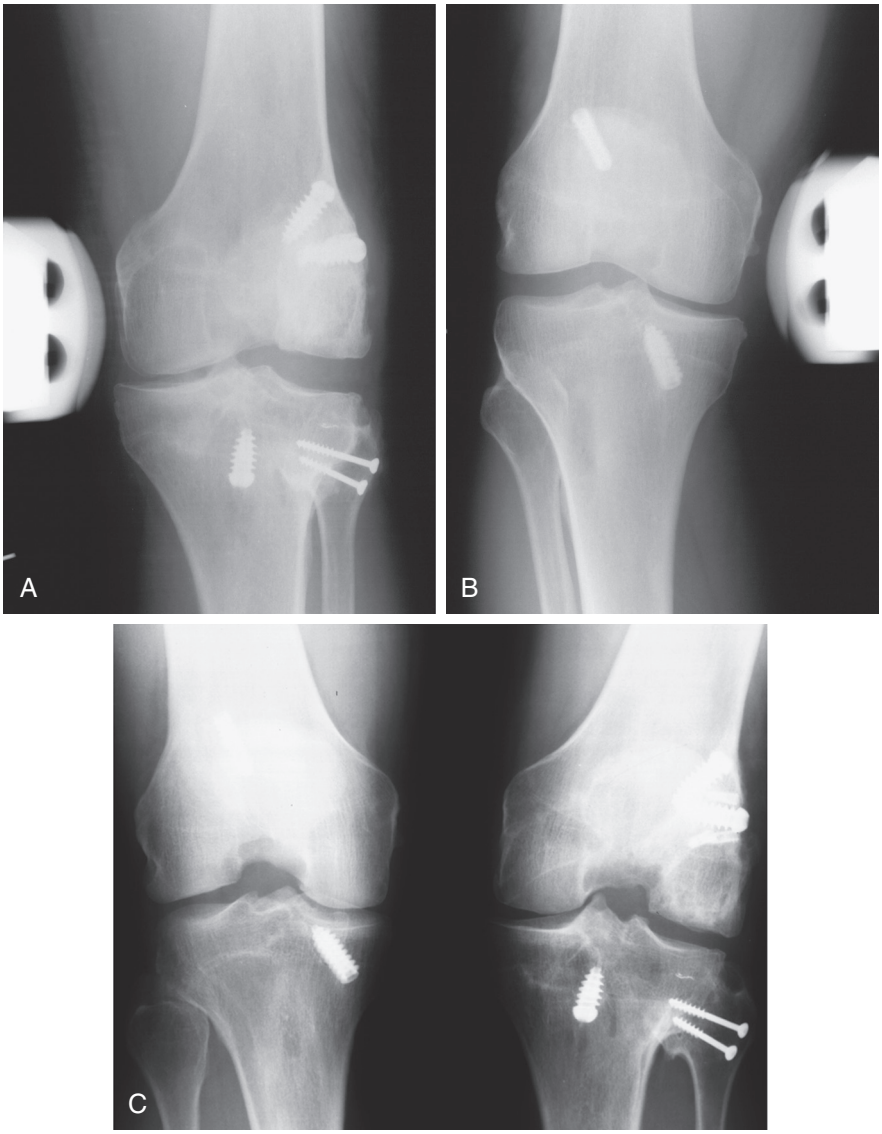


FIG 17-31 Case 6.

Case 7. A 15-year-old male presented 3 weeks after a knee dislocation sustained during football. The patient was placed into an immobilizer but had not undergone any further medical treatment for his injury. Physical examination revealed moderate swelling, only 20 degrees of knee motion, a loss of sensation over the lateral aspect of the leg as well as the dorsum of the foot, and a complete foot drop with 0 to 5 dorsiflexion and 0 to 5 extension of the great toe. His vascular status was intact. Magnetic resonance imaging revealed torn ACL, PCL, FCL, and PL structures. He underwent 2 months of supervised physical therapy. A staged global reconstruction was then performed involving first an ACL B-PT-B allograft and arthroscopic PCL two-strand B-PT-B allograft reconstruction. One week later, an FCL B-PT-B allograft reconstruction and a popliteofibular ligament and popliteus tendon reconstruction were done (Fig. 17-32, *A* and *B*).

Three years postoperative, the patient had a negative pivot shift, no increase in anterior tibial translation, no increase in external tibial rotation, and no increase in medial or LJO. He had a neurovascular intact lower extremity and a full range of knee motion. Lateral (Fig. 17-32, *C*) and posterior (Fig. 17-30, *D*) stress radiographs showed no increase in LJO or posterior tibial translation. The patient had returned to recreational basketball and running without symptoms. He rated the overall condition of his knee as normal.

Our comment: This patient had an arthroscopic ACL and PCL reconstruction, at which time the decision was made, owing to operative time, to later stage by 1 week the anatomic PL reconstruction. During that week, it is required that no abnormal LJO occurs that would place the ACL and PCL grafts at risk for stretching or failure.

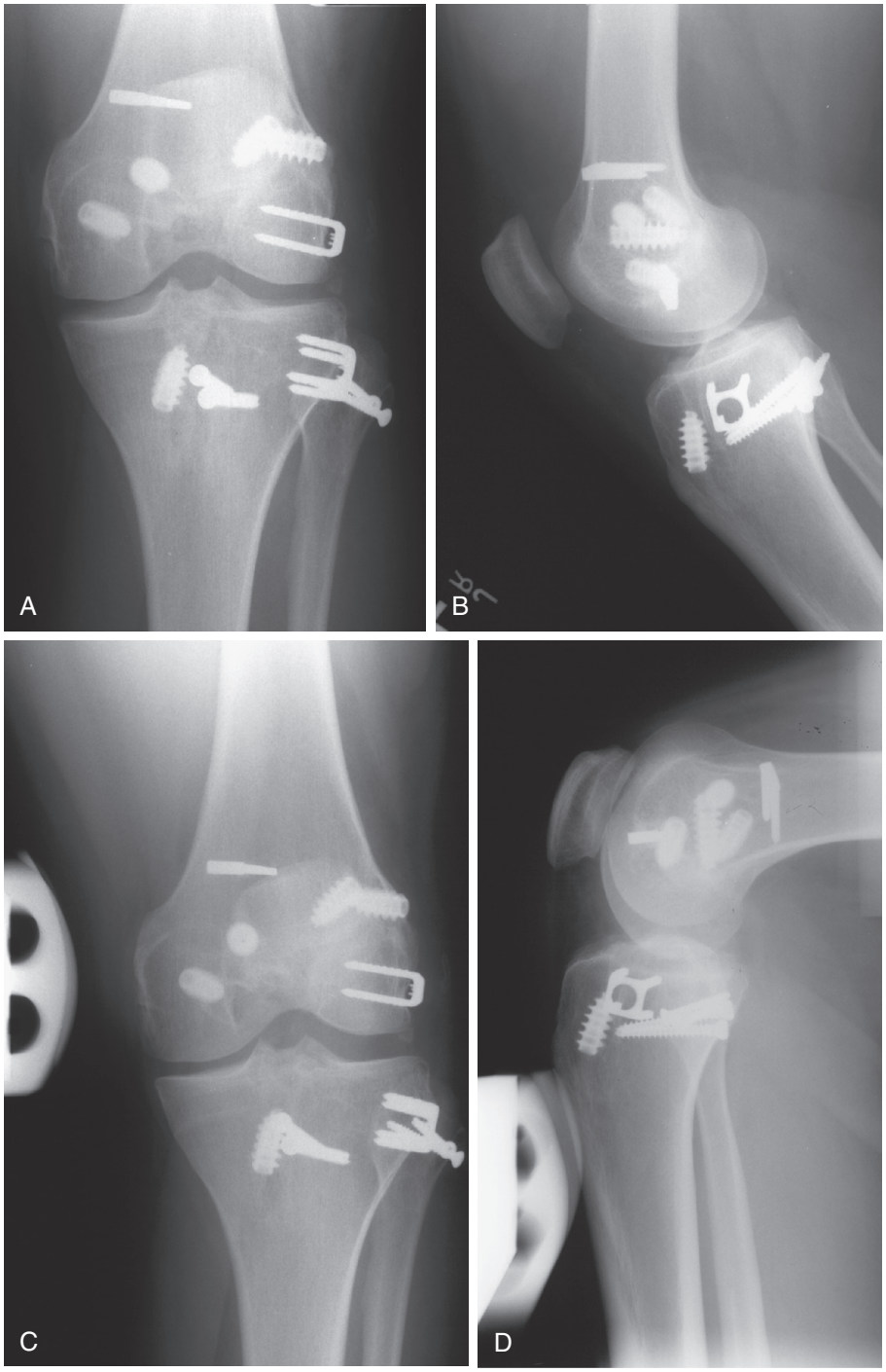


FIG 17-32 Case 7.

Video Content

Video 2-1
Video 3-1
Video 11-1
Video 11-3
Video 16-5
Video 16-6

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18

Rehabilitation of Posterior Cruciate Ligament and Posterolateral Reconstructive Procedures

Frank R. Noyes, Sue D. Barber-Westin, Timothy P. Heckmann

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CLINICAL CONCEPTS

A paucity of information exists in the literature regarding rehabilitation for injuries to the posterior cruciate ligament (PCL) and posterolateral structures. The posterolateral structures comprise the fibular collateral ligament and popliteus muscle-tendon-ligament unit, including the popliteofibular ligament and posterolateral capsule. A recent systematic review[36] failed to find high-level evidence studies of rehabilitation protocols for either conservative or operative treatment of these injuries. The rehabilitation protocols described in this chapter consist of a careful incorporation of exercise concepts supported by biomechanic and clinical data[3-7,9,11-13,15-17,30,31,33,35,43,44] and over 3 decades of patient experience.[19-26,28] The goal is to progress a patient at a rate that takes into account the condition of the articular surfaces and menisci, return of muscle function and lower limb control, postoperative graft healing and remodeling, and athletic and occupational goals. Modifications to the postoperative exercise program may be required if noteworthy articular cartilage deterioration is found during surgery.

The protocol for PCL reconstruction was developed for high-strength quadriceps tendon-patellar bone (QT-PB) autografts or Achilles tendon-bone allografts with interference screw fixation of the bone and soft tissue portions (and additional suture fixation of the tendon portion over a suture post; see Chapter 16). The protocol for posterolateral reconstruction may be used after the various operative options described in detail in Chapter 17, including anatomic reconstructions, femoral-fibular reconstructions, and proximal advancement techniques of the posterolateral structures.

The supervised rehabilitation programs are always supplemented with home exercises performed daily. The therapist must routinely examine the patient in the clinic to implement and progress the appropriate protocol. Therapeutic procedures and modalities are used as required for successful rehabilitation. For the majority of patients, a range of 11 to 21 postoperative physical therapy visits is expected to produce a desirable result. A few more visits may be required between the sixth and twelfth postoperative months for certain patients who desire to return to strenuous activities for advanced training.

For all patients, joint swelling, pain, gait pattern, knee motion, patellar mobility, muscle strength, and flexibility are continually monitored postoperatively.

Patients are warned to avoid any exercises or activities that place high posterior shear forces on the tibia such as walking down inclines or squatting for the first 6 postoperative months. In addition, patients are cautioned that an early return to strenuous activities postoperatively carries a risk of a repeat injury or the potential of compounding the original injury. These risks cannot always be scientifically predicted, and patients are cautioned to avoid strenuous activities for 9 to

CRITICAL POINTS Clinical Concepts

- Protocol for posterior cruciate ligament reconstruction for procedures with high-strength two-strand graft (quadriceps tendon-bone, bone-patellar tendon-bone).
- Progress patient on athletic and occupational goals, condition of the articular surfaces and menisci, return muscle function, postoperative healing, remodeling.
- Supervised rehabilitation program supplemented with home exercises performed daily.
- Monitor joint swelling, pain, gait pattern, knee motion, patellar mobility, muscle strength, and flexibility continually after surgery.
- Avoid any exercises or activities that place high posterior shear forces on the tibia, such as walking down inclines, squatting, or hamstring flexion curl machines for the first 6 postoperative months.
- Avoid strenuous activities for 9 to 12 months and activities that produce pain, swelling, or a feeling of instability.
- Posterolateral reconstruction: too early resumption of weight bearing is deleterious to healing graft.

12 postoperative months and to avoid activities that produce pain, swelling, or a feeling of instability. These patients are monitored after surgery with posterior drawer testing and stress radiography if an increase in posterior tibial displacement is detected.

Patients with posterolateral reconstruction are warned specifically at the fourth to eighth postoperative weeks when weight bearing and weaning of crutches occur to avoid hyperextension, varus, or internal tibial rotation positions that could place high tensile forces on the posterolateral structures.[29,32] It is important that the patient demonstrates good lower extremity control with suitable muscle strength to maintain tibiofemoral compression and avoid a lift-off of the lateral tibiofemoral joint that would disrupt the posterolateral reconstruction.

PCL CLINICAL BIOMECHANICS

Many studies have demonstrated that posterior tibial subluxation occurs in PCL-deficient knees during activities of daily living in high knee flexion positions, but not usually at low flexion positions where smaller posterior shear forces are present. In activities such as sudden stopping, deceleration, or walking down a ramp, a posterior subluxation of the tibia is expected to occur.

Using knee models created from magnetic resonance imaging (MRI) and dual fluoroscopy, several recent investigations found significant differences in knee kinematics at higher knee flexion angles during a single-leg lunge between PCL-deficient and contralateral normal knees.[8,14,40-42] For instance, Gill and colleagues[8] reported PCL-deficient knees had significantly increased posterior tibial translation between 60 degrees and 120 degrees of flexion compared with normal knees (mean difference, 3.5 ± 1.1 mm, $P < .05$). Significant decreases in patellar rotation and tilt were also observed between PCL-deficient knees and normal knees between 75 degrees and 120 degrees of knee flexion.

Using lateral radiographs, Castle and colleagues[5] measured posterior tibial subluxation during a static double-legged squat in patients with PCL-deficient knees. The results revealed a statistically significant mean increase of 5.9 mm in posterior tibial translation ($P < .05$) of the injured knee compared with the contralateral knee at high knee flexion angles. At low flexion angles, the magnitude of increase in mean posterior tibial translation was only 2.1 mm. Tibiofemoral shear forces were small compared with tibiofemoral joint compression forces.

CRITICAL POINTS PCL Clinical Biomechanics

- Isokinetic flexion exercise exerts moderate posterior shear forces; use cautiously after PCL reconstruction.
- Posterior shear forces significantly increased during standing by anterior flexion of the trunk.
- Static squat: significant increase in posterior tibial translation occurs at high knee flexion angles.
- Large posterior shear forces exist during jogging, ascending and descending stairs.
- Open kinetic chain flexion exercise produces posterior shear forces beyond 30 degrees of knee flexion.
- Closed kinetic chain leg press produces significantly less posterior shear forces than OKC flexion. Cocontraction of quadriceps and hamstrings occurs during CKC, greatest at 30 degrees and 60 degrees of knee flexion.
- Posterior shear forces during CKC squat exercise are relatively low from 0 to 45 degrees of knee flexion. Cocontraction of quadriceps and hamstrings occurs from 0 to 30 degrees of flexion.
- OKC knee extension produces posterior shear forces from 60 to 100 degrees of knee flexion, but these forces are lower than those measured during CKC leg press and squat exercises.
- Leg press induces minimal hamstring muscle activity.
- In situ forces in the PCL significantly increase with knee flexion in response to an isolated hamstrings load, reaching a maximum at 90 degrees of flexion. A simulated cocontraction of the quadriceps and hamstrings reduces the in situ forces in the PCL.
- Isokinetic extension exercise at knee flexion angles less than 70 degrees safe early postoperatively.
- Isokinetic flexion and deep squats should be avoided early after PCL reconstruction.
- Hamstrings load significantly increases PCL force from 15 to 120 degrees of knee flexion.
- The application of tibial torque in either an anterior or posterior direction when the knee is flexed greater than 60 degrees increases PCL force. Isolated hamstrings activity (with tibial torque) further increases PCL force.

Two- and 3-dimensional biomechanic models have been used to predict forces generated during exercises and on standing at different knee flexion angles. Kaufman and coworkers[13] used a 3-dimensional biomechanic model to predict dynamic patellofemoral and tibiofemoral forces generated during isokinetic exercises at 60 degrees/sec and 180 degrees/sec. During isokinetic extension, posterior shear forces were detected at knee flexion angles of 40 degrees and greater. The maximum posterior shear force occurred at 70 to 80 degrees of knee flexion and measured 0.5 ± 0.1 body weight at 60 degrees/sec and 0.6 ± 0.1 body weight at 180 degrees/sec. A posterior shear force occurred throughout the entire flexion exercise at all knee flexion angles, reaching a peak at 75 degrees of knee flexion of 1.7 ± 0.8 body weight (60 degrees/sec) to 1.4 ± 0.5 body weight (180 degrees/sec). The authors concluded that isokinetic exercise exerted moderate posterior shear forces and should be used cautiously after PCL rupture and reconstruction.

Ohkoshi and associates[35] used a 2-dimensional model to calculate shear force exerted on the tibia during standing at various knee flexion angles in 21 healthy subjects. Posterior shear forces were found in the upright position of the trunk and at knee flexion angles of 15 to 90 degrees (Fig. 18-1). At 30 degrees and 60 degrees, the posterior drawer force was significantly increased by anterior flexion of the trunk.

Berchuck and coworkers[3] calculated large posterior shear forces during gait analysis for the activities of jogging, ascending stairs, and

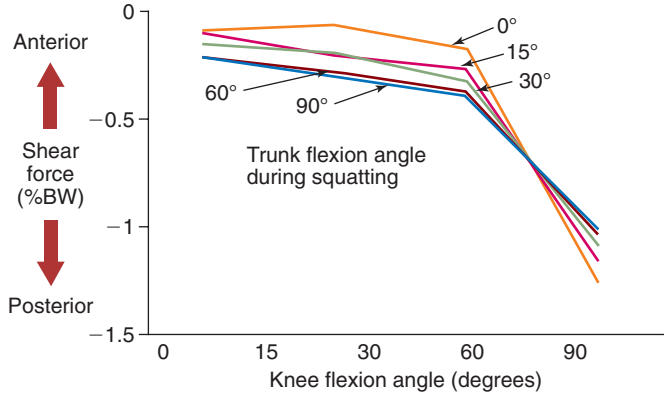


FIG 18-1 Calculated shear force (kilograms) per body weight (BW) (kilograms) while standing on both legs at various flexion angles of the knee and trunk. (From Ohkoshi Y, Yasuda K, Kaneda K, et al. Biomechanical analysis of rehabilitation in the standing position. *Am J Sports Med.* 1991;19:605-611.)

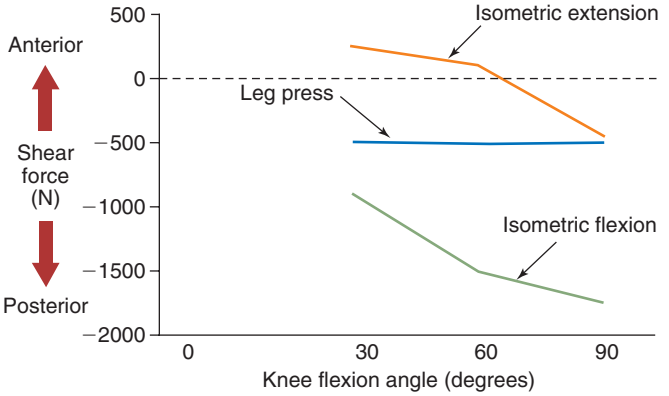


FIG 18-3 Average tibiofemoral shear forces observed during the closed kinetic chain leg press, the open kinetic chain extension, and the open kinetic chain flexion exercise. (From Lutz GE, Palmitier RA, An KN, Chao EY. Comparison of tibiofemoral joint forces during open-kinetic-chain and closed-kinetic-chain exercises. *J Bone Joint Surg Am* 1993;75:732-739.)

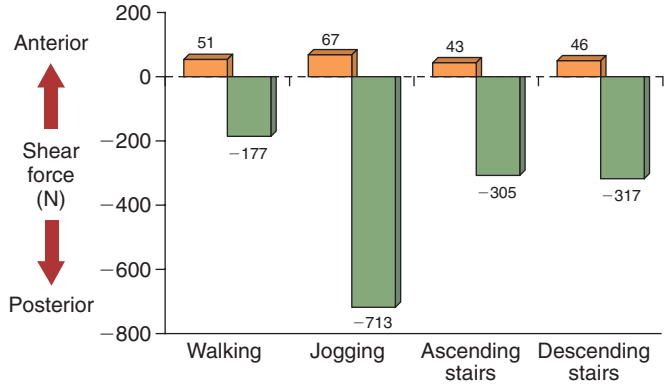


FIG 18-2 Calculated tibiofemoral shear forces during activities.

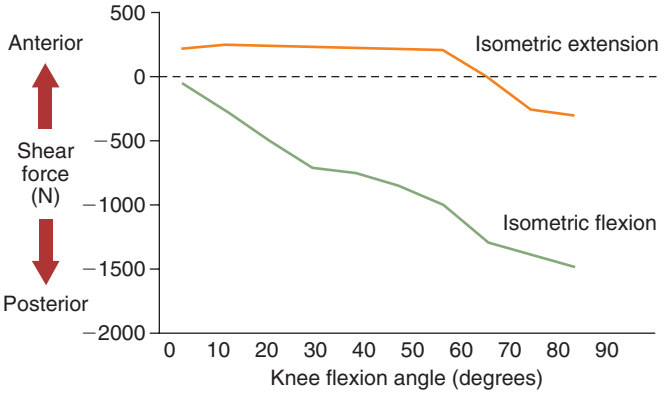


FIG 18-4 Calculated tibiofemoral shear forces during isometric knee extension and flexion.

descending stairs (Fig. 18-2) in five normal subjects. Lutz and associates[15] evaluated tibiofemoral joint shear and compressive shear forces using a 2-dimensional biomechanic model and electromyographic (EMG) of hamstrings and quadriceps muscle activity during a closed kinetic chain (CKC) leg press exercise, an isometric open kinetic chain (OKC) extension exercise, and an OKC flexion exercise. Measurements of maximum muscle contractions were obtained at 30, 60, and 90 degrees of knee flexion. The OKC isometric flexion exercise produced posterior shear forces at all knee flexion angles (Fig. 18-3), ranging from –939 ± 174 N at 30 degrees of knee flexion to a maximum of –1780 ± 699 N at 90 degrees of knee flexion. The CKC exercises produced significantly lower posterior shear forces at 60 degrees and 90 degrees of flexion (–538 N, $P < .05$). These findings were similar to those reported by Smidt[38] during isometric knee extension and flexion exercises (Fig. 18-4). Maximum hamstrings EMG activity was detected during the OKC exercise at 90 degrees of flexion (82% ± 15% of maximum contraction). The antagonistic muscle activity was minimal during this exercise at all knee flexion angles. In contrast, cocontraction of the quadriceps and hamstrings was observed during the CKC exercise, which was greatest at 30 degrees and 60 degrees of flexion. The authors concluded that CKC exercise produced significantly lower tibiofemoral shear forces compared with OKC exercise ($P < .05$).

Wilk and colleagues[43] evaluated tibiofemoral shear forces and EMG activity of the quadriceps, hamstrings, and gastrocnemius muscles during OKC extension and CKC leg press and squat exercises. Both CKC exercises produced posterior shear forces. However, during the squat, these forces were relatively low (245 to 565 N) from 0 to 45 degrees of knee flexion. A rapid increase in posterior shear forces was detected from 45 to 72 degrees of flexion. In addition, cocontraction of the quadriceps and hamstrings occurred from 0 to 30 degrees of flexion.

Wilk and colleagues[43] also found that the knee extension exercise produced posterior shear forces from 60 to 100 degrees of knee flexion; however, these forces were lower than those measured during both CKC exercises. The leg press induced minimal hamstring muscle activity.

Hoher and coworkers[11] reported that the in situ forces in the PCL significantly increased with knee flexion in response to an isolated hamstrings load, reaching a maximum at 90 degrees of flexion. These findings were in agreement with other authors[6,44] who also reported increased strain in the PCL with knee flexion. The addition of a 200-N quadriceps load (simulating cocontraction of the quadriceps and hamstrings) reduced the in situ forces in the PCL.

Toutoungi and associates[39] combined noninvasive experimental measurements with geometric modeling of the lower extremity to calculate ligament forces during isometric, isokinetic, and squat exercises. The data indicated that isokinetic extension at knee flexion angles less than 70 degrees should be safe in the early postoperative period

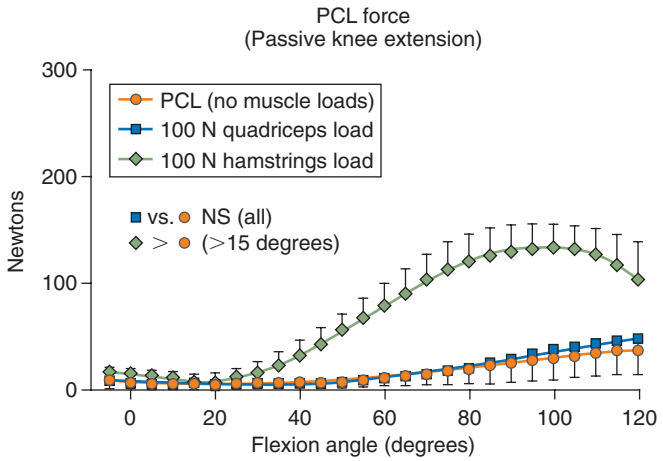


FIG 18-5 Posterior cruciate ligament (PCL) forces from 0 to 120 degrees of knee flexion with no tibial force. Application of a 100-N hamstring load significantly increased mean PCL force at flexion angles greater than 15 degrees. (From Markolf KL, O'Neill G, Jackson SR, McAllister DR. Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *Am J Sports Med.* 2004;32:1144-1149.)

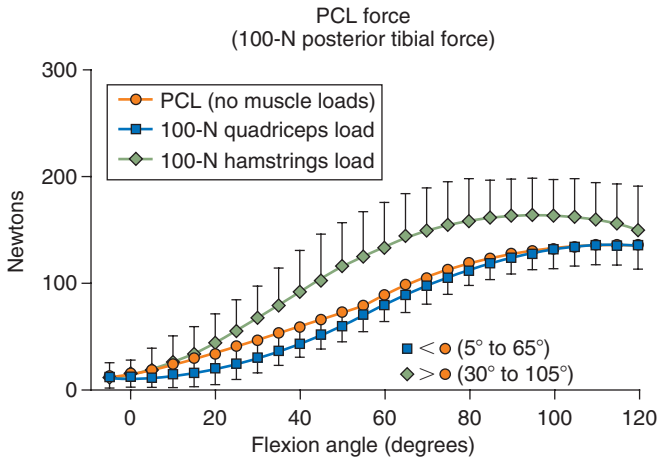


FIG 18-6 Posterior cruciate ligament (PCL) forces from 0 to 120 degrees of knee flexion under a constant 100-N posterior tibial force. Application of a 100-N hamstrings load significantly increased mean PCL force at flexion angles between 30 and 105 degrees. (From Markolf KL, O'Neill G, Jackson SR, McAllister DR. Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *Am J Sports Med.* 2004;32:1144-1149.)

following PCL reconstruction. However, isokinetic flexion and deep squats should be avoided. During isokinetic flexion, only the PCL is loaded and peak forces may reach over four times the patient's body weight at 90 degrees of knee flexion. During squatting, PCL forces may reach 3.5 times body weight at high knee flexion angles. Shallow squats with knee flexion angles kept below 50 degrees may be considered.

Markolf and colleagues[16] studied the effects of muscle loads on cruciate force levels when the knee was subjected to external forces and moments. Load cells were installed into cadaveric knees to record forces in the ACL and PCL under five loading conditions. These force measurements were repeated with a 100-N load applied to the quadriceps tendon and with a combined 50-N load applied to both the biceps and semimembranosus-semitendinosus tendons.

With no applied tibial force, application of hamstrings load significantly increased mean PCL force from 15 to 120 degrees of knee flexion (Fig. 18-5). With the application of a 100-N posterior tibial force, the addition of hamstrings load significantly increased mean PCL force between 30 degrees and 105 degrees of flexion (Fig. 18-6). When a 5 N-m external tibial torque was applied, the addition of hamstrings load significantly increased mean PCL force beyond 75 degrees of knee flexion ($P < .05$). Under a 5 N-m internal tibial torque, application of hamstrings load also significantly increased mean PCL force between 60 degrees and 100 degrees of flexion ($P < .05$). The authors concluded that, in general, the hamstrings were more effective in producing changes in cruciate force levels. Application of tibial torque in either an anterior or posterior direction when the knee was flexed greater than 60 degrees increased PCL force, and isolated hamstrings activity (with tibial torque) further increased PCL force.

PROTOCOL FOR PARTIAL OR ACUTE ISOLATED PCL RUPTURES

This program does not apply to PCL avulsions in which surgery may be indicated, and partial PCL tears with 5 mm or less of increased posterior tibial translation. The goal with complete PCL disruptions (8-10 mm of increased posterior tibial translation at 90 degrees of flexion) is to allow PCL healing and reduce abnormal posterior tibial translation. Importantly, this includes maintaining normal tibiofemoral contact at full knee extension or with knee flexion. An anterior drawer produced by the therapist during motion in the early phases of rehabilitation will allow for protection of healing PCL fibers. This protective program for acute PCL ruptures has been used by us for over 20 years. The rules to treat partial or acute isolated PCL tears are as follows:



FIG 18-7 Knee extension brace with posterior calf pad to maintain tibiofemoral reduction.

1. Patient is within 14 days of the injury.
2. Protect for 6 weeks in full knee extension with a brace and posterior calf pad (Fig. 18-7) or bivalved cylinder cast to maintain tibiofemoral reduction.[1] Use quadriceps isometrics, electrical muscle stimulation (EMS), leg raises, and 25% weight bearing.
3. Obtain a lateral radiograph to verify no posterior tibial subluxation exists, which can occur in up to 50% of knees.
4. At 2 weeks, the therapist initiates 0 to 90 degrees of motion, maintaining anterior tibial translation load during knee motion

exercises. The patient must sleep in the brace and is not allowed unsupervised knee motion. Only passive flexion with the therapist is permitted.

5. At 4 weeks, the patient is allowed to perform active quadriceps extension without the brace, use 50% weight bearing with crutch support, and continue brace protection.
6. At 5 to 6 weeks, the patient is weaned from the brace and crutch support and the rehabilitation protocol (described later) is begun. It should be noted that some centers use a Jack PCL Brace (Albrecht, Germany) to provide added protection against posterior tibial subluxation, which may be considered if insomnia issues are resolved.
7. At 6 months, a posterior stress radiograph determines the amount of posterior tibial translation compared with the opposite knee.

PCL RECONSTRUCTION REHABILITATION PROTOCOL

Immediate Postoperative Management

Patients are instructed in the rehabilitation program preoperatively. They present to physical therapy the first day after surgery on bilateral axillary crutches in a postoperative dressing with a long-leg brace locked in full extension with a posterior calf pad (Table 18-1). The postoperative bandage and dressing are changed to allow the application of thigh-high compression stockings and a compression bandage. Early control of postoperative effusion is essential for pain management and early quadriceps reeducation. In addition to compression, cryotherapy is important in this time period.

Patients are instructed to keep the lower limb elevated as frequently as possible during the first week. The initial response to surgery and progression during the first 2 weeks sets the tone for the initial phases of the rehabilitation program. Common postoperative complications include excessive pain or swelling, quadriceps shutdown, and range of motion (ROM) limitations. Early recognition and treatment of these problems are critical for a successful outcome.

Patients who undergo a QT-PB autograft harvest have increased pain with knee flexion and during quadriceps contractions. They require added attention for the first 4 weeks postoperatively to ensure the rehabilitation goals are achieved.

Modalities

Therapeutic modalities after PCL reconstruction are used as required by the evaluation. If the patient demonstrates a fair or poor rating of the quadriceps or vastus medialis obliquus (VMO) musculature, then EMS is initiated. Electrodes are placed over the VMO and on the central to lateral aspect of the upper third of the quadriceps muscle belly. The patient actively contracts the quadriceps muscle simultaneously with the machine's stimulation. Treatment sessions last for 20 minutes. A portable neuromuscular electric stimulator such as the Empi Continuum or Phoenix (garment device, DJO Global) may be helpful in individuals whose muscle rating is poor. These devices are used 4 to 6 times per day for 15 minutes per session until the muscle grade is rated as good.

Biofeedback therapy is also quite useful in facilitating quadriceps muscle contractions. The surface electrode is placed over the selected muscle component to provide information to the patient and clinician regarding the quality of active or voluntary quadriceps contraction. This modality can enhance relaxation of the hamstring musculature if the patient has difficulty achieving full knee extension because of knee pain or muscle spasm. The electrode is placed over the belly of the hamstring muscle while the patient performs ROM exercises.

Cryotherapy is begun in the recovery room after surgery. Several different modalities are available for use in both the clinic and home settings. Clinically, devices such as the Game Ready cryotherapy machine are used to provide compression simultaneously with the cold program. For most patients, cryotherapy is accomplished with an ice bag or commercial cold pack. Patients may also receive a commercial cooling unit that is used four to eight times daily at home. Other commercially available cold therapy units include motorized cooler units that maintain a constant temperature and circulation of ice water through a pad that provides excellent pain control. Gravity-flow units also provide effective pain management; however, the maintenance of a constant temperature is more difficult with these devices. The temperature can be controlled by using gravity to backflow and drain the water, refilling the cuff with fresh ice water as required. Standard treatment times are 20 minutes in length, performed from four times a day to every waking hour depending on the extent of pain and swelling. In some cases, the treatment time can be extended based on the thickness of the buffer used between the skin and the device. Cryotherapy is typically used after exercise or when required for pain and swelling control and is maintained throughout the entire postoperative rehabilitation protocol.

Brace Support

For patients who undergo PCL reconstruction without a concurrent posterolateral procedure, a long-leg hinged postoperative brace with a posterior calf pad is worn for the first 6 weeks postoperatively. The brace is worn 24 hours a day, including during sleep, to avoid sudden knee flexion motions that may occur. Initially, the brace is worn in full extension for the first 3 to 4 weeks and is then opened to 0 to 90 degrees. For individuals evaluated with physiologic joint laxity or poor muscle control of the lower limb, the brace is used for up to 12 weeks postoperatively.

During this phase, the patient may also be measured for a functional PCL brace, which is indicated for higher-level occupational or sports activities. For patients who return to lower levels of activity or who develop patellofemoral symptoms, a patellofemoral knee sleeve may be indicated for prolonged standing and walking activities.

A standard soft-hinged brace is not considered adequate for protection of complex reconstructions that involve both the PCL and posterolateral structures. These braces do not prevent excessive lateral forces (joint opening) that place the posterolateral reconstruction at risk in the initial 4 weeks postoperatively. In these knees, a bivalved cast is used to limit lateral joint opening during ambulation and activities of daily living. The bivalved cast is removed four times a day under controlled conditions, and active knee extension and passive knee flexion are performed in a seated position. The cast is then carefully reapplied to protect the knee joint during walking activities. After the first 4 postoperative weeks, sufficient healing of the posterolateral ligamentous reconstructive procedure should occur, and the patient is placed in a long-leg hinged brace.

Range of Knee Motion

Passive knee motion from 0 to 90 degrees is allowed immediately postoperatively. The return of full knee flexion to 135 degrees places high shear forces on the PCL reconstruction and it is unknown when this amount of flexion is safe to obtain. Accordingly, the program is designed to initially regain 120 degrees by 8 weeks, with final flexion gradually achieved at 10 to 12 weeks. Knee flexion greater than 135 degrees is not encouraged unless athletic or occupational indications exist. The total number of daily knee motion cycles is limited to 60 (20 cycles, three times/day) for the first 4 weeks to limit undue abrasion of the PCL graft at the tibial and femoral tunnels.[19,37]

Text continued on p. 590

TABLE 18-1 Rehabilitation Protocol After Posterior Cruciate Ligament Reconstruction

	POSTOPERATIVE WEEKS					POSTOPERATIVE MONTHS			
	1-2	3-4	5-6	7-8	9-12	4	5	6	7-12
Hinged long-leg postoperative brace	X	X	X						
Patellar knee sleeve				X	X	X	X		
Functional brace								X	X
Range of motion minimum goals (degrees):									
0-90	X								
0-110		X							
0-120			X	X					
0-135					X				
Weight bearing:									
25% body weight	X								
50% body weight		X							
Full			X						
Patellar mobilization	X	X	X	X					
Modalities:									
EMS	X	X	X	X	X				
Pain/edema management (cryotherapy)	X	X	X	X	X	X	X	X	X
Stretching: hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X	X
Strengthening:									
Quadriceps isometrics, straight-leg raises, active knee extension	X	X	X	X	X				
Closed-chain: gait retraining, toe raises, wall-sits, minisquats			X	X	X	X	X	X	
Knee flexion hamstring curls*						X	X	X	X
Knee extension quads*		X	X	X	X	X	X	X	X
Hip abduction-adduction, multihip					X	X	X	X	X
Leg press (70-10 degrees)				X	X	X	X	X	X
Balance/proprioceptive training:									
Weight-shifting, cup walking, BBS			X	X					
BBS, BAPS, perturbation training, balance board, minitrampoline				X	X	X	X	X	X
Conditioning:									
UBC	X	X	X	X	X				
Bike (stationary)			X	X	X	X	X	X	X
Aquatic program						X	X	X	X
Swimming (kicking)						X	X	X	X
Walking					X	X	X	X	X
Stair-climbing machine						X	X	X	X
Ski machine						X	X	X	X
Elliptical cross-trainer						X	X	X	X
Running: straight								X	X
Cutting: lateral carioca, figure 8s									X
Plyometric training									X
Full sports							X	X	X

PHASE 1: WEEKS 1-2 (VISITS 2-4)

General Observation

Toe-touch to 25% weight bearing
Brace

Evaluation (Goal)

Pain (controlled)
Hemarthrosis (mild)
Patellar mobility (good)
ROM minimum (0-90 degrees)
Quadriceps contraction and patella migration (good)
Soft tissue contracture (none)

Goals

ROM 0-90 degrees
Adequate quadriceps contraction
Control inflammation, effusion
Prevent soft tissue contracture
Protect ligament reconstruction at insertion sites

Continued

TABLE 18-1 Rehabilitation Protocol After Posterior Cruciate Ligament Reconstruction—cont'd

PHASE 1: WEEKS 1-2 (VISITS 2-4)

	Frequency	Duration
ROM	3-4 ×/day, 10 min	
0-90 degrees (active extension/passive flexion with 10-lb anterior drawer)		20 cycles
Patellar mobilization		10 reps, 30 sec
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps, 30 sec
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion, 0- to 5-lb ankle weight)		3 sets × 10 reps
Active quadriceps isometrics		1 set × 10 reps
Knee extension (active assisted, 90-30 degrees)		3 sets × 10 reps
Aerobic Conditioning	1-2 ×/day, 10 min	
UBC		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
ADLs		
Knee brace to avoid sudden knee flexion while asleep		

PHASE 2: WEEKS 3-4 (VISITS 2-4)

General Observation	50% weight bearing with one crutch when: • Pain is controlled • Hemarthrosis is controlled • Muscle control throughout ROM Brace
Evaluation (Goal)	Pain (controlled) Effusion (minimal) Patellar mobility (good) ROM minimum (0-110 degrees) Quadriceps contraction and patella migration (good) Soft tissue contracture (none)
Goals	ROM 0-110 degrees Control inflammation, effusion Muscle control Prevent soft tissue contracture Protect ligament reconstruction at insertion sites

	Frequency	Duration
ROM	3-4 ×/day, 10 min	
Passive (0-110 degrees, 10-lb anterior drawer)		20 cycles
Patella mobilization		10 reps, 30 sec
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps, 30 sec
Strengthening	2-3 ×/day, 20 min	
Straight-leg raises (flexion, adduction, abduction)		3 sets × 10 reps
Isometric training: multiangle (0, 60 degrees)		1 set × 10 reps
Knee extension (active assisted, 90-0 degrees, 0- to 7.5-lb weight)		3 sets × 10 reps
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Water walking		
Stationary bicycling (patellofemoral precautions)		

TABLE 18-1 Rehabilitation Protocol After Posterior Cruciate Ligament Reconstruction—cont'd

PHASE 2: WEEKS 3-4 (VISITS 2-4)

	Frequency	Duration
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
ADLs		
Knee brace to avoid sudden knee flexion while asleep		

PHASE 3: WEEKS 5-6 (VISITS 1-2)

General Observation	Full weight bearing when: • Pain is controlled without narcotics • Hemarthrosis is controlled • Muscle control throughout ROM Brace
Evaluation (Goal)	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-120 degrees) Muscle control (3/5) Inflammatory response (none) Joint arthrometry, 6 wk, 20 degrees at 89 N and 70 degrees at 89 N (<3 mm)
Goals	ROM 0-120 degrees Control inflammation, effusion Muscle control Recognition of complications (motion loss, CRPS, increased anteroposterior displacement)

	Frequency	Duration
ROM	3 ×/day, 10 min	
Passive (0-120 degrees)		
Patella mobilization		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion, abduction, adduction, ankle weight, not to exceed 10% of body weight)		3 sets × 10 reps
Isometric training: multiangle (90, 60, 30 degrees)		2 sets × 10 reps
Knee extension (active, 90-0 degrees)		3 sets × 10 reps
Closed-chain:		
Heel raise/toe raise		3 sets × 20 reps
Wall-sits		5 reps
Balance Training	3 ×/day, 5 min	
Weight shift side-side and forward-backward		
Balance board, two legged		
Cup walking		
Single-leg stance		
Aerobic Conditioning (Patellofemoral Precautions)	2 ×/day, 10 min	
UBC		
Stationary bicycling		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
ADLs		
Knee brace to avoid sudden knee flexion while asleep		

Continued

TABLE 18-1 Rehabilitation Protocol After Posterior Cruciate Ligament Reconstruction—cont'd

PHASE 4: WEEKS 7-8 (VISITS 1-2)

General Observation	Full weight bearing Brace	
Evaluation (Goal)	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-135 degrees) Inflammatory response (none) Joint arthrometry, 8 wk, 20 degrees at 89 N and 70 degrees at 89 N (<3 mm)	
Goals	Full weight bearing, normal gait Control inflammation, effusion Muscle control ROM 0-120 degrees	
	Frequency	**Duration**
ROM	3 ×/day, 10 min	
Passive (0-120 degrees)		
Patellar mobilization		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion, abduction, adduction)		3 sets × 30 reps
Straight-leg raises with rubber tubing		3 sets × 30 reps
Knee extension (active, 90-0 degrees)		3 sets × 10 reps
Knee flexion (active, 0-90 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits (0-40 degrees)		5 reps
Minisquats (rubber tubing, 0-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Balance board, two legged		
Single-leg stance		
Aerobic Conditioning (Patellofemoral Precautions)	2 ×/day, 10-15 min	
UBC		
Stationary bicycling		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
ADLs		
Knee brace to avoid sudden knee flexion while asleep		

PHASE 5: WEEKS 9-12 (VISITS 1-2)

General Observation	No effusion, painless ROM, joint stability ROM 0-135 degrees Brace optional Performs ADLs, can walk 20 min without pain
Evaluation (Goal)	Pain (minimal) Manual muscle test (hamstrings, quadriceps, hip abductors/adductors/flexors/extensors) (4/5) Swelling (none) Joint arthrometry, 12 wk, 20 degrees at 134 N and 70 degrees at 89 N (3 mm) Patellar mobility (good) Crepitus (none/slight) Gait (symmetric)

TABLE 18-1 Rehabilitation Protocol After Posterior Cruciate Ligament Reconstruction—cont'd

PHASE 5: WEEKS 9-12 (VISITS 1-2)		
Goals	Increase strength and endurance ROM 0-135 degrees Return to normal gait, ADLs	
	Frequency	**Duration**
ROM	3 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (add extension)		3 sets × 10 reps
Straight-leg raises with rubber tubing		3 sets × 30 reps
Knee extension with resistance (90-30 degrees)		3 sets × 10 reps
Knee flexion (active, 0-90 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue × 3 reps
Minisquats		3 sets × 20 reps
Lateral step-ups (2- to 4-inch block)		3 sets × 10 reps
Balance Training	2 ×/day, 5 min	
Balance board, two legged		
Single-leg stance		
Aerobic Conditioning (Patellofemoral Precautions)	1 ×/day, 15-20 min	
UBC		
Stationary bicycling		
Walking		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
ADLs		
Avoid squats, walking down hills and ramps, running down stairs, sudden deceleration movements		
PHASE 6: WEEKS 13-26 (VISITS 2-3)		
General Observation	No effusion, painless ROM, joint stability Performs ADLs, can walk 20 min without pain ROM 0-135 degrees Brace optional	
Evaluation (Goal)	Pain (minimal) Manual muscle test (5/5) Swelling (minimal) Joint arthrometry (<3 mm) Patellar mobility (good) Crepitus (none/slight) Gait (symmetric) Isometric test (% difference between quadriceps and hamstrings) (30)	
Goals	Increase strength and endurance	

Continued

TABLE 18-1 Rehabilitation Protocol After Posterior Cruciate Ligament Reconstruction—cont'd

PHASE 6: WEEKS 13-26 (VISITS 2-3)

	Frequency	Duration
ROM	2-3 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	3 ×/wk, 20-30 min	
Hamstring curls with resistance (0-90 degrees)		3 sets × 10 reps
Knee extension with resistance (90-30 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain:	3 ×/wk, opposite days (machines)	
Minisquats (0-40 degrees)		3 sets × 20 reps
Wall-sits		To fatigue × 3 reps
Lateral step-ups (2- to 8-inch block)		3 sets × 10 reps
Balance Training	1-2 ×/day, 5 min	
Balance board, two legged to single legged		
Single-leg stance to unstable platform		
Aerobic Conditioning (Patellofemoral Precautions)	1 ×/day, 20 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Stair-climbing machine (low resistance and stroke)		
Ski machine (short stride, low resistance)		
Elliptical cross-trainer (low resistance)		
Modalities	As required	
Cryotherapy		20 min
ADLs		
Avoid squats, walking down hills and ramps, running down stairs, sudden deceleration movements		

PHASE 7: WEEKS 27-52 (VISITS 2-3)

General Observation	No effusion, painless ROM, joint stability Performs ADLs, can walk 20 min without pain Brace optional
Evaluation (Goal)	Isokinetic test (isometric + torque 300 degrees/sec, % difference between quadriceps and hamstrings) (10-15) Swelling (none) Joint arthrometry (3 mm) Patellar mobility (good) Crepitus (none/slight) Single-leg function tests (9 mo: hop distance, timed hop, % involved vs. uninvolved) (≤15%)
Goals	Increase function Maintain strength and endurance Return to previous activity level

TABLE 18-1 Rehabilitation Protocol After Posterior Cruciate Ligament Reconstruction—cont'd

PHASE 7: WEEKS 27-52 (VISITS 2-3)

	Frequency	Duration
ROM	1 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	3 ×/wk, 20-30 min	
Hamstring curls with resistance (0-90 degrees)		3 sets × 10 reps
Knee extension with resistance (90-30 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain:	3 ×/wk, opposite days (machines)	
Minisquats (0-40 degrees)		3 sets × 20 reps
Wall-sits		To fatigue × 3 reps
Lateral step-ups (2- to 8-inch block)		3 sets × 10 reps
Balance Training	1 ×/day, 5 min	
Balance board, two legged to single legged		
Single-leg stance on unstable platform with secondary activity		
Aerobic Conditioning (Patellofemoral Precautions)	3 ×/wk, 20-30 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Stair-climbing machine (low resistance and stroke)		
Ski machine (short stride, low resistance)		
Elliptical cross-trainer (low resistance)		
Running Program (Straight, 30% Deficit Isokinetic Test)	3 ×/wk, 15-20 min	
Jog		¼ mile
Walk		⅛ mile
Backward run		20 yards
Cutting Program (20% Deficit Isokinetic Test, 9 mo)	3 ×/wk	
Lateral, carioca, figure-eights		20 yards
Functional Training	3 ×/wk	
Plyometric training: box hops, level, double leg (20% deficit isokinetic test, 9 mo)		4-6 sets, 15 sec
Sport-specific drills (10%-15% deficit isokinetic test)		
Modalities	As required	
Cryotherapy		20 min

*For knee motion limits, see text for each phase.

ADLs, Activities of daily living; *BAPS,* Biomechanical Ankle Platform System (Patterson Medical); *BBS,* Biodex Balance System; *CRPS,* complex regional pain syndrome; *EMS,* electric muscle stimulation; *ITB,* iliotibial band; *ROM,* range of motion; *UBC,* upper body cycle.



FIG 18-8 Extension overpressure using hanging weights.

Regaining knee extension as soon as possible is important to avoid excessive scarring in the intercondylar notch or a posterior capsular contracture. Patients who do not achieve this extension goal by the seventh postoperative day are placed into an overpressure program. The foot and ankle are propped on a towel or other device that elevates the hamstrings and gastrocnemius, allowing the knee to drop into full extension. This exercise is performed for 10 minutes and repeated approximately six times per day. A 10-lb weight may added to the distal thigh and knee to stretch the posterior capsule (Fig. 18-8). Care should be taken to keep the hanging weight away from the proximal tibia to avoid posterior shear stresses. Zero degrees of knee extension should be obtained by the third to sixth postoperative week. If this is not accomplished, or if the clinician notes a firm end feel, a serial casting program may be required (see Chapter 38). Hyperextension is avoided to protect the healing PCL graft.

Passive knee flexion exercises are performed in the seated position, using an anterior manual force to provide proximal tibial support to prevent posterior drop-back. A 10-lb anterior drawer is maintained on the proximal tibia during passive knee flexion (Fig. 18-9) because PCL forces significantly increase after 70 degrees of flexion. Knee flexion exercises are primarily passive for the first 6 weeks and are then active. Care must be taken to avoid activating the hamstrings. Other overpressure techniques to assist in gaining flexion include chair-rolling (Fig. 18-10), wall-sliding using the opposite extremity (Fig. 18-11), commercial devices (Fig. 18-12), and passive quadriceps stretching exercises.

Weight Bearing

Patients are allowed to bear 25% of their body weight during the first 1 to 2 postoperative weeks. Weight bearing is then slowly progressed and crutches are usually discontinued at postoperative week 6. Once the brace is unlocked, weight bearing is progressed using a normal gait technique, limiting a locked-knee position and encouraging normal flexion throughout the gait cycle. This allows for normal patterning of heel-to-toe ambulation, quadriceps contraction during midstance, and hip and knee flexion during the gait cycle. The prolonged locked-knee position is avoided owing to the potential of the development of a quadriceps-avoidance gait pattern.

Once patients are fully weight bearing, they are warned to avoid squatting, walking down hills or ramps, or any sudden deceleration movements that may place high forces on the PCL graft. These precautions are maintained for at least the first 6 postoperative months.



FIG 18-9 Flexion knee motion exercises using anterior tibial pressure to prevent posterior tibial drop-back.

Patellar Mobilization

Patellar mobilization is important in the promotion of a full range of knee motion. The loss of patellar mobility is often associated with knee motion complications and, in extreme cases, the development of patella infera.[34] Patellar glides are performed in all four planes (superior, inferior, medial, and lateral) with sustained pressure applied to the appropriate patellar border for at least 10 seconds (Fig. 18-13). This exercise is performed for 5 minutes before ROM exercises are completed. Caution is warranted if an extensor lag is detected, because this may be associated with poor superior migration of the patella, indicating the need for additional emphasis on this exercise. Patellar mobilization is performed for approximately 8 weeks postoperatively.

Flexibility

Hamstring and gastrocnemius-soleus flexibility exercises are begun the first postoperative day. A sustained static stretch is held for 30 seconds and repeated five times. The modified hurdler stretch is the most common hamstring exercise, and the towel pull is the most common gastrocnemius-soleus stretch. These exercises assist in controlling pain that occurs because of the reflex response created in the hamstrings when the knee is kept in the flexed position. As well, the towel-pulling exercise can help lessen discomfort in the calf, Achilles tendon, and ankle. These stretches represent critical components of the ROM program, because the ability to relax these muscle groups is imperative to achieving full passive knee extension. The patient must be instructed not to perform harsh, aggressive stretching, which could result in activation of the hamstring muscles. The PCL reconstruction is protected at all times with a posterior soft calf pad, maintaining knee extension.

Iliotibial band stretches are begun at the ninth postoperative week. These exercises assist in achieving full knee flexion and controlling

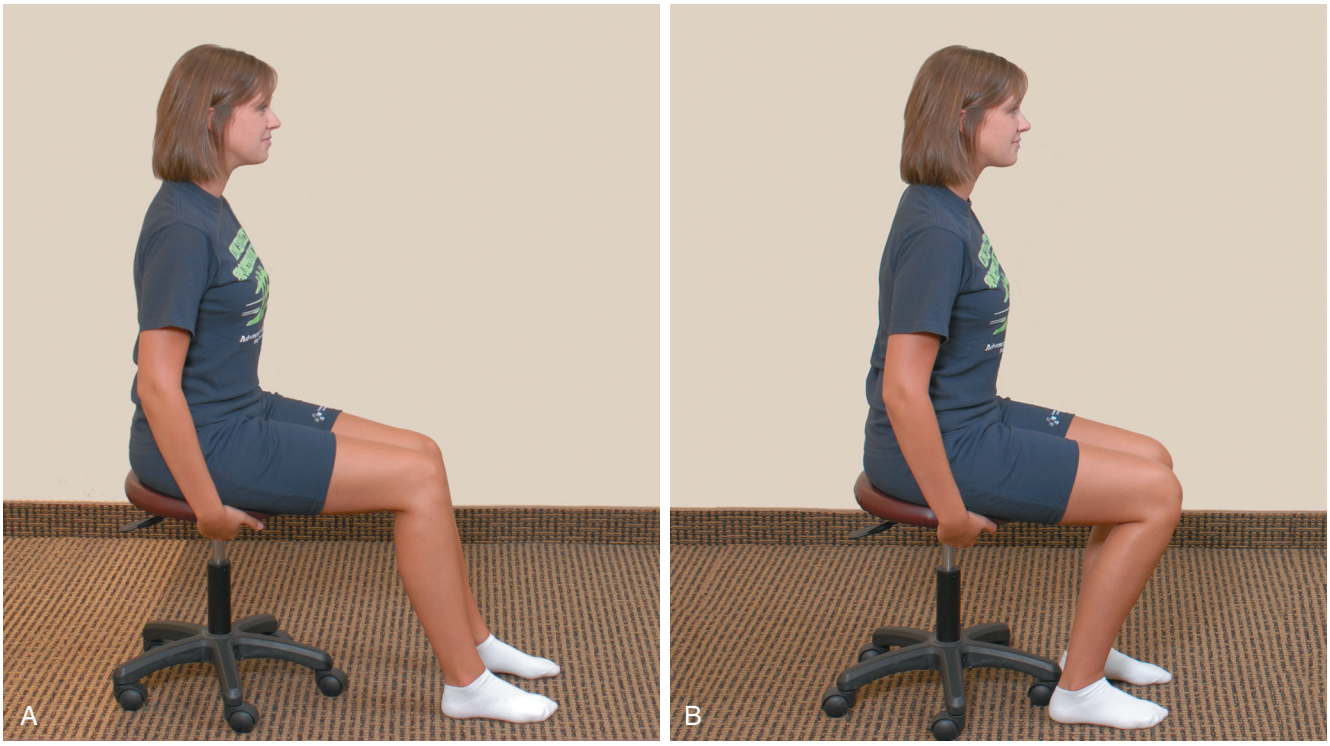


FIG 18-10 Flexion overpressure using a rolling stool.

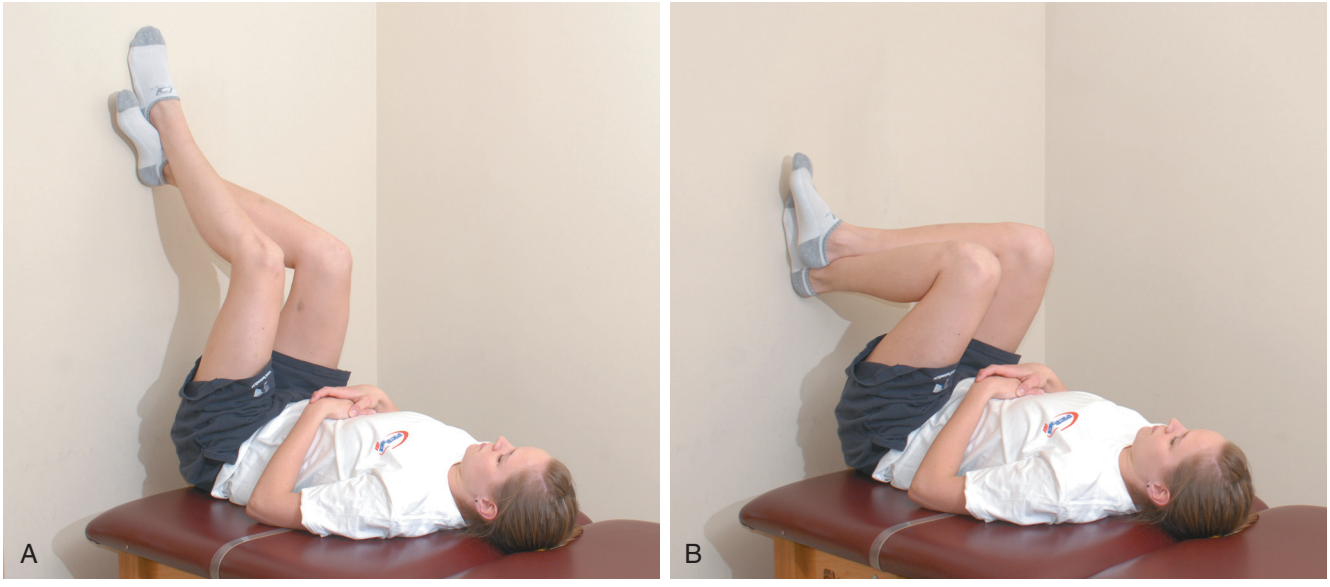


FIG 18-11 Flexion overpressure using a wall-slide technique.

lateral hip and thigh tightness. When designing a flexibility program, the therapist should determine the particular sport or activity the individual wishes to return to, as well as the position or physical requirements of that activity. The flexibility program should be continued after the patient is discharged from formal care.

Strengthening

The strengthening program is begun on the first postoperative visit. Early emphasis on the quadriceps muscle group is critical for a safe return to functional activities and to prevent posterior subluxation of the tibia from occurring during activities in which the knee is flexed greater than 50 degrees. In this phase of rehabilitation, initiation of a good voluntary quadriceps contraction sets the tone for the progression of the strengthening program.

Isometric quadriceps contractions are done every hour following the repetition rules of 10 second holds, 10 repetitions, 10 times per day. Evaluation of the contraction by both the therapist and patient is critical. The patient can monitor contractions by visual or manual means, comparing the quality of the contractions to those achieved by the contralateral limb. He or she can also assess the superior migration of



FIG 18-12 A commercial knee flexion overpressure device.



FIG 18-13 Patellar mobilization.

the patella during the contraction, which should be approximately 1 cm, and the inferior migration of the patella during the initial relaxation of the contraction.

Other exercises performed immediately postoperatively include supine straight-leg raises and active-assisted knee extension (70 to 0 degrees postoperative week 1 and 2, then 90 to 0 degrees). The patient must achieve a sufficient isometric quadriceps contraction with the leg raises to benefit the quadriceps. Initially, 1- to 2-lb ankle weights are used; eventually, an ankle weight up to 10 lb is used as long as this does not represent more than 10% of the patient's body weight.

Active-assisted extension exercises facilitate the quadriceps muscle if poor tone is observed during isometric contractions. At postoperative weeks 3 to 4, adduction and abduction straight-leg raises are incorporated. The exception are knees that undergo concomitant posterolateral procedures, for which abduction leg raises are delayed until postoperative weeks 7 to 8. Extension (prone) leg raises are initiated at postoperative week 9. These exercises are continued through at least postoperative week 12.

Once partial weight bearing is initiated, CKC exercises are begun. The first CKC exercise is cup walking, an activity designed to facilitate adequate quadriceps control during midstance of gait to prevent knee hyperextension from occurring (Fig. 18-14). When the patient progresses from 50% to 75% weight bearing, toe raises for gastrocnemius-soleus strengthening, wall-sitting isometrics for quadriceps control, and minisquats for quadriceps strengthening are begun. The goal of wall-sitting is to improve quadriceps contraction by performing the exercise to muscle exhaustion. This exercise may be modified to decrease patellar pain or place additional stress on the quadriceps muscle. Patellar pain may be decreased by either altering the knee flexion angle of the sit or by subtly changing the toe-out/toe-in angle by no more than 10 degrees.

Additional stress to the quadriceps during the wall-sit can be accomplished by several methods. First, the patient can voluntarily set the quadriceps muscle once he or she reaches his or her maximum knee flexion angle, which is typically between 30 and 45 degrees. This contraction and knee flexion position is held until muscle fatigue occurs, and the exercise is repeated two to three times, for eight repetitions per day. In a second modification, the patient performs a hip adduction contraction by squeezing a ball between the distal thighs. This modification promotes a stronger VMO contraction. In a third variation, the patient holds dumbbell weights in his or her hands to increase body weight, which promotes an even stronger quadriceps contraction. Finally, the patient can shift his or her body weight over the involved side to stimulate a single-leg contraction. These exercises are highly beneficial and result in the patient experiencing a true muscle burn as each repetition is held to maximum quadriceps muscle fatigue, which is typically not achieved at this point with other exercises. The sets should be performed ideally two times each and repeated four times a day.

The last CKC exercise is the minisquat. Initially, the patient's body weight is used as resistance. Gradually, TheraBand or surgical tubing is used as a resistance mechanism (Fig. 18-15). The depth of the squat is controlled to protect the patellofemoral joint. Quick, smooth, rhythmic squats are performed to a high-set/high-repetition cadence to promote muscle fatigue. Hip position is important to monitor to emphasize the quadriceps. Increased trunk flexion facilitates increased hamstring contractions[35] and therefore must be carefully monitored to avoid forceful hamstring contractions for a minimum of 3 to 6 months.

OKC exercises are included in the rehabilitation program owing to the advantage of muscle group isolation provided by weight machines. Initially, if the lightest amount of weight on the machine is too heavy to be lifted by the involved limb alone, the patient is instructed to lift the weight with both legs and lower it with the involved side. Eccentric contractions can also be used in the advanced stages of strength training if tendinitis or overuse syndromes develop. Weight training is used in the latter stages of rehabilitation and continues after the patient has returned to activity.

The timing of the initiation of extension, hip, leg press, and hamstring curl OKC exercises is shown in Table 18-1. Knee flexion hamstring curls and hip abduction-adduction exercises are delayed until the fourth postoperative month to avoid excessive posterior shear forces. Leg press (range, 50-0 degrees) is allowed at the eighth postoperative week. Caution is warranted owing to the potential problems knee extension OKC exercises may create for the healing graft and the patellofemoral joint. Many patients have an unsatisfactory outcome

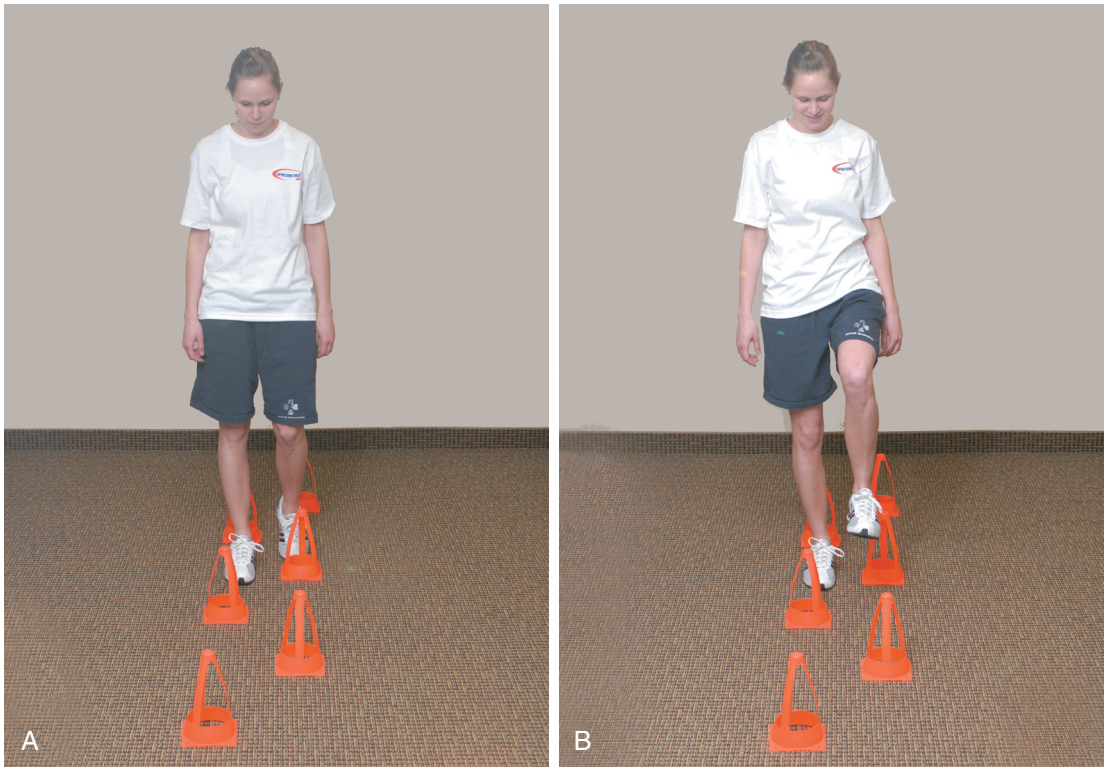


FIG 18-14 Cup walking used early postoperatively to develop symmetry between the surgical and contralateral limbs, hip and knee flexion, quadriceps control during midstance, hip and pelvic control during midstance, and adequate gastrocnemius-soleus control during push-off.



FIG 18-15 Minisquats made more difficult with a TheraBand.

based on persistent anterior or patellofemoral knee pain that can occur from improper training in the terminal phase of extension (0-30 degrees). Therefore this exercise may be initially delayed to protect the PCL graft (avoiding lower flexion angles) versus protecting the patella (not going into terminal extension). Recommendations for knee extension exercises include emphasis on patellofemoral protection (monitoring for changes in pain, swelling, and crepitus) and a gradual progression of weight to avoid overuse syndromes.

A full lower extremity strengthening program is critical for long-term success of the rehabilitation program. Gastrocnemius-soleus strength is a key component for both early ambulation and running. In addition, upper extremity and core strength programs are important for safe return to work or sports. These exercises are included as part of general conditioning and general strength-training concepts are emphasized. Sport and position specificity are taken into account when devising the program to maximize its benefits.

Balance, Proprioceptive, and Perturbation Training

Balance and proprioceptive training are initiated at approximately 4 to 6 weeks postoperatively when the patient is partially weight bearing. The first exercise involves weight shifting from side to side and front to back. This activity assists the patient's confidence in the leg's ability to withstand the pressures of weight bearing and initiates the stimulus to knee joint position sense. A second exercise is cup walking, which is designed to both promote strength and develop symmetry between the surgical and uninvolved limbs. Cup walking helps develop hip and knee flexion, quadriceps control during midstance, hip and pelvic control during midstance, adequate gastrocnemius-soleus control during push-off, and controls hip hiking.



FIG 18-16 Single-leg stance on an unstable platform.



FIG 18-17 Perturbation technique. The therapist stands behind the patient and intermittently touches the patient's back to disturb balance.

When full weight bearing is achieved, another helpful activity for balance control is the single-leg balance exercise. The stance position is key to making this exercise beneficial. The patient is instructed to point the foot straight ahead, flex the knee approximately 20 to 30 degrees, extend the arms outward to horizontal, and position the torso upright with the shoulders above the hips and the hips above the ankles. The object of this activity is to stand in position until balance is disturbed. A minitrampoline or unstable surface can be used to make this exercise more challenging. The unstable position created with the soft surface requires greater dynamic limb control than that used to stand on a flat surface (Fig. 18-16).

In the early phases of full, unassisted weight bearing, half foam rolls are used as part of the gait-retraining program. Walking on half rolls helps the patient develop balance and dynamic muscular control required to maintain an upright position and to be able to walk from one end of the roll to the other. Additional gait and balance activities may include band walking for forward, backward, lateral, and monster walking (diagonal forward walking). These activities challenge single-leg balance and proximal leg control. Developing a center of balance, limb symmetry, quadriceps control in midstance, and postural positioning are benefits obtained from this type of training.

Perturbation-training techniques are initiated at approximately the seventh to eighth postoperative weeks. The therapist stands behind the patient and disrupts her or his body posture and position periodically to enhance dynamic knee stability. The techniques involve either direct contact with the patient (Fig. 18-17) or disruption of the platform the patient is standing on (Fig. 18-18).

Another effective proprioceptive exercise is a balance board with the patient assuming first a double-leg stance and eventually a single-leg stance as strength and balance improve. To provide a greater functional challenge, patients may assume the single-leg stance position



FIG 18-18 Perturbation technique. The therapists stands behind the patient and intermittently taps the unstable platform to disturb balance.

and throw/catch a weighted ball against an inverted minitrampoline until fatigue occurs.

The use of more sophisticated devices adds another dimension to the proprioception program, because certain units objectively attempt to document balance and dynamic control. There are many balance systems available, with a wide cost variance. Two of the more common units include the Biodex Balance System and the Neurocom Balance System. Although these systems may provide objective information, more research is required to justify the cost and reliability of each unit.

Conditioning

The primary consideration for the conditioning program throughout the rehabilitation protocol is to stress the cardiovascular system without compromising the joint. Depending on accessibility, a cardiovascular program may be initiated at approximately the third to fourth postoperative week with an upper extremity ergometer. The surgical limb should be elevated to minimize lower extremity swelling. This exercise is performed to tolerance.

Stationary bicycling is begun at postoperative weeks 5 to 6. During bicycling, the seat height is adjusted to its highest level based on patient body size and a low resistance level is used during the workout. Toe clips should be avoided to decrease hamstring involvement. Gradually, between the ninth and twelfth postoperative weeks, cross-country skiing, elliptical cross-trainer, and stair-climbing machines are incorporated. Protection against high stresses to the patellofemoral joint is strongly advocated in patients with symptoms or articular cartilage deterioration. If a stair-climbing machine is tolerated, a short step and lower resistance levels should be encouraged. Monitoring the heart rate will ensure that work levels are sufficient to improve cardiovascular fitness.

The goals of early conditioning exercises include facilitation of full ROM, gait retraining, and cardiovascular reconditioning. To improve cardiovascular endurance, the program should be performed at least three times per week for 20 to 30 minutes, and the exercise performed to at least 60% to 85% of maximal heart rate. It is generally regarded that performing in the higher levels of percentage of maximal heart rate achieves greater cardiovascular efficiency and endurance.

A complete cardiovascular exercise program is an important component of the latter phases of rehabilitation. In addition to the previously described exercises, an aquatic program that includes lap work using freestyle or flutter kicking, water walking, water aerobics, and deep-water running is initiated. Determining which cardiovascular exercises are appropriate is based on each individual patient. Factors to assess include concomitant operative procedures, secondary injuries, access to specific equipment, individual preferences, and prior experience.

Running and Agility Program

Current studies do not allow a prediction of return of strength of PCL grafts; hence, conservative estimates regarding return to strenuous activities are warranted. To initiate the running program, the patient must demonstrate no more than a 30% deficit in average torque for the quadriceps and hamstrings on isometric testing, have no more than 3 mm of increase in anteroposterior displacement on arthrometer testing, and be at least 6 months postoperative. The running program in an elite athlete under ideal conditions described after a quadriceps tendon-patellar bone autograft has been found in our clinic to be safe and not result in graft stretching or an increase in posterior tibial translation. However, most recreational athletes do not start the program until 9 to 12 months after surgery. The rules for when to introduce more strenuous running and cutting activities for allografts have not been scientifically established. In general, a prudent rule is to provide additional time for graft healing and remodeling and wait until 12 months, although it is recognized that allograft healing is delayed even further. The running program is designed based on the sport the patient desires to return to, as well as the particular position or physical requirements of the activity. For instance, an individual returning to short-duration, high-intensity activities participates in a sprinting program rather than a long-distance endurance program.

The beginning level running program is first performed with a straight-ahead walk/run combination. Running distances are 20, 40, 60, and 100 yards (18, 37, 55 and 91 m) in both forward and backward directions. Initially, running speed is approximately one-fourth to one-half of the patient's normal speed and gradually progresses to three-fourths to full speed. An interval training-rest approach is applied where the rest phase is two to three times the length of the training phase. The running program is performed three times per week, on opposite days of the strength program. Because the running program may not reach aerobic levels initially, a cross-training program is used to facilitate cardiovascular fitness. The cross-training program is performed on the same day as the strength workout.

After the patient is able to run straight ahead at full speed, the program progresses to include lateral running and crossover maneuvers. Short distances, such as 20 yards (18 m), are used to work on speed and agility. Side-to-side running over cups may be used to facilitate proprioception. At this time, sport-specific equipment is introduced to enhance skill development (e.g., a soccer ball for a soccer player to work on dribbling and passing activities). These variations are useful to motivate the patient and minimize training boredom.

The third level of the running program incorporates figure-eight running drills. These drills begin with long and wide movement patterns to encourage subtle cutting. The training distance initially is 20 yards (18 m); as speed and confidence improve, the distance is decreased to approximately 10 yards (9 m). Progression through this phase is similar to that used in the lateral side-to-side program just described. Speed and agility are emphasized and, equipment is also introduced to develop sports-specific skills.

The fourth phase in the running program introduces cutting patterns. These patterns include directional changes at 45-degree and 90-degree angles that allow the patient to progress from subtle to sharp cuts.

Plyometric Training

Plyometric training is begun upon successful completion of the running program to minimize bilateral alterations in neuromuscular function and proprioception. This training begins after the ninth postoperative month for patients who desire to return to strenuous athletics. Again, this training should be delayed on an empiric basis for 12 months when PCL allografts are used. The patient should demonstrate no more than a 20% deficit for the quadriceps and hamstrings on isokinetic testing. Important parameters when performing plyometric exercises are surface, footwear, and warm-up. The jump drills should be done on a firm, yet forgiving surface such as a wooden gym floor. Very hard surfaces like concrete should be avoided. A cross-training or running shoe should be worn to provide adequate shock absorption, as well as adequate stability to the foot. Checking wear patterns and outer sole wear will help avoid overuse injuries.

During the jumps, the patient is instructed to keep the body weight on the balls of the feet, to jump and land with the knees flexed and shoulder-width apart to avoid knee hyperextension and an overall valgus lower limb position (Fig. 18-19), as described in detail in Chapter 14. The patient should understand that the exercises are reaction and agility drills and while speed is emphasized, correct body posture must be maintained throughout the drills.



FIG 18-19 An improper, overall valgus lower limb position on landing a plyometric jumping exercise.

The first exercise is level-surface-box jumping using both legs. A four-square grid is created with tape on the floor of four equally sized boxes. The patient is instructed to first jump from box 1 to box 3 (front-to-back) and then from box 1 to box 2 (side-to-side). The second level incorporates both of these directions into one sequence and also includes jumping in both right and left directions (e.g., box 1 to box 3 to box 4 to box 2 to box 1). Level three progresses to diagonal hops, and level four includes pivot jumps in 90 degrees and 180 degrees directions. Once the patient can perform level four double-leg jumps, the same exercises are done on a single leg. The next phase incorporates vertical box hops.

It is important to stress that plyometric exercise is intense and adequate rest must be included in the program. Individual sessions can be performed in a manner similar to interval training. Initially, the rest period lasts two to three times the length of the exercise period and is gradually decreased to one to two times the length of the exercise period. Plyometric training is performed two to three times weekly.

Improvement is measured by counting the number of hops in a defined time period. The initial exercise time period is 15 seconds. The patient is asked to complete as many hops among the squares as possible in 15 seconds. Three sets are performed for each direction and the number of hops recorded. The program is progressed as the number of hops increases, along with patient confidence.

For athletes who wish to resume high-risk sports that involve jumping, cutting, twisting, and pivoting, we recommend that a course of Sportsmetrics training be completed to reduce the risk of a reinjury before returning to these activities.[27] Although initially developed to prevent anterior cruciate ligament (ACL) injuries in female athletes, we empirically believe this program is applicable to end-stage postoperative rehabilitation after both ACL and PCL/posterolateral ligament reconstructions. This belief is caused by the fact that this program teaches athletes to control the upper body, trunk, and lower body position; lower the center of gravity by increasing hip and knee flexion during activities; and develop muscular strength and techniques to land with decreased ground reaction forces. In addition, athletes are instructed to preposition the body and lower extremity before initial ground contact to obtain the position of greatest knee joint stability and stiffness. The program consists of a dynamic warm-up, plyometric jump training, strengthening exercises, aerobic conditioning, agility, and risk-awareness training. The training is conducted three times a week on alternating days for 6 weeks, and is described in detail in Chapter 14.

Return to Sports Activities

Discharge criteria after PCL reconstruction are based on patient goals for athletics and occupations, the rating of symptoms, stress radiography (90 degrees of flexion), KT-2000 (MEDmetric) testing, muscle strength testing, and single-leg hop function testing (Table 18-2). First, patients complete the Cincinnati Sports Activity Scale and Occupational Rating Scale[2] to provide sports and occupational levels that are desired after surgery. Upon completion of the protocol, pain, swelling, and giving-way are rated on the Cincinnati Symptom Rating Scale.[2] The patient must not experience these symptoms at the level of activity that he or she wishes to participate in before discharge.

Stress radiography is performed as described previously[10] and the difference between knees must be within 5 mm before recommendation of return to strenuous activities.

Muscle strength testing is performed with a Biodex isokinetic dynamometer (Biodex) to ensure adequate strength exists before the initiation of the plyometric, running, and cutting programs. At least two single-leg hop function tests are completed and limb symmetry calculated as previously described[18] before the final discharge.

As previously discussed, athletes who wish to resume high-risk sports that involve jumping, cutting, and pivoting are encouraged to complete a course of Sportsmetrics training to reduce the risk of a reinjury before returning to these activities

A trial of function is encouraged where the patient is monitored for overuse symptoms or giving-way episodes. Upon successful return to activity, the patient is encouraged to continue with a maintenance program. During the in-season, a conditioning program of two workouts per week is recommended. In the off-season or preseason, this program should be performed three times per week to maximize gains in flexibility, strength, and cardiovascular endurance.

POSTEROLATERAL RECONSTRUCTION REHABILITATION PROTOCOL

Patients who have chronic ruptures to the posterolateral structures may develop over time an alteration in gait in which excessive knee hyperextension occurs during the stance phase, described in detail in Chapter 29. A preoperative gait-retraining program is implemented for these patients, as failure to correct this problem leads to an increased risk of failure of any posterolateral reconstructive procedure.

There are a variety of surgical options for ruptures of the posterolateral structures, which are detailed in Chapter 17. The rehabilitation protocol incorporates immediate protected knee motion but stresses maximal protection against undue joint loads to prevent stretching and failure of posterolateral grafts or advancement procedures (Table 18-3). Patients are warned to avoid hyperextension and activities that would incur varus loading on the joint. Delays in return of full knee flexion, full weight bearing, initiation of certain strengthening and conditioning exercises, running, and return to full sports activities are incorporated.

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TABLE 18-2 Discharge Rehabilitation Criteria After Posterior Cruciate Ligament Reconstruction

Desired Sports	Occupation Rating*	Symptom Rating,* Pain, Swelling, Giving Way	Stress Radiography, 70 Degrees, 89 N (mm)	KT-2000, 70 Degrees, Total AP, I-N (mm)	Biodex Isometric Test (% Deficit I-N)	Single-leg Hop Function Testing Limb Symmetry (%)
Jumping, pivoting, cutting†‡	Heavy/very heavy	None level 10	<3	<5	≤15	≥85
Running, turning, twisting	Moderate	None level 8	<5	<5	≤20	≥85
Swimming, bicycling	Light	None level 6	<8	5-7	≤30	≥75
None, daily activities only	Very light	None level 4	<8	5-7	>30	<75

*See Chapter 41.
†Level 10, normal knee, no symptoms with strenuous work/sports with jumping, hard pivoting; level 8, no symptoms with moderate work/sports with running, turning, twisting; level 6, no symptoms with light work/sports such as swimming, bicycling; level 4, no symptoms with daily activities.
‡Also consider completing a course of Sportsmetrics before return to these athletic activities.
AP, Anterior-posterior; *I-N*, involved minus noninvolved limb.

TABLE 18-3 Rehabilitation Protocol After Posterolateral Knee Reconstruction

	POSTOPERATIVE WEEKS					POSTOPERATIVE MONTHS			
	1-2	3-4	5-6	7-8	9-12	4	5	6	7-12
Brace:									
Bivalved cylinder cast	X	X							
Custom medial unloader or hinged soft tissue brace			X	X	X	X	X	X	X
Range of motion minimum goals (degrees):									
0-90	X	X							
0-110			X						
0-120				X					
0-130					X				
Weight bearing:									
None	X								
Toe-touch, 25% body weight		X							
25%-50% body weight			X						
Full, cane support				X					
Full					X				
Patellar mobilization	X	X	X	X					
Modalities:									
EMS	X	X	X	X					
Pain/edema management (cryotherapy)	X	X	X	X	X	X	X	X	X
Stretching: hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X	X
Strengthening:									
Quad isometrics, straight-leg raises	X	X	X	X	X				
Active knee extension	X	X	X	X	X				
Closed-chain: gait retraining, toe raises, wall-sits, minisquats			X	X	X	X	X	X	
Knee flexion hamstring curls (90 degrees)						X	X	X	X
Knee extension quads (90-30 degrees)			X	X	X	X	X	X	X
Hip abduction-adduction, multihip					X	X	X	X	X
Leg press (70-10 degrees)					X	X	X	X	X
Balance/proprioceptive training:									
Weight-shifting, cup walking, BBS				X	X				
BBS, BAPS, perturbation training, balance board, minitrampoline						X	X	X	X

Continued

TABLE 18-3 Rehabilitation Protocol After Posterolateral Knee Reconstruction—cont'd

	POSTOPERATIVE WEEKS					POSTOPERATIVE MONTHS			
	1-2	3-4	5-6	7-8	9-12	4	5	6	7-12
Conditioning:									
Upper body cycle		X	X	X					
Bike (stationary)			X	X	X	X	X	X	X
Aquatic program						X	X	X	X
Swimming (kicking)						X	X	X	X
Walking						X	X	X	X
Stair-climbing machine						X	X	X	X
Ski machine						X	X	X	X
Elliptical cross-trainer						X	X	X	X
Running: straight									X
Cutting: lateral, carioca, figure-eights									X
Plyometric training									X
Full sports									X

PHASE 1: WEEKS 1-2 (VISITS 2-4)

General Observation
Non–weight bearing, maximum protection
Bivalved cylinder cast
Must avoid hyperextension, varus loads, lateral joint opening

Evaluation (Goal)
Pain (controlled)
Hemarthrosis (mild)
Patellar mobility (good)
ROM minimum (0-90 degrees)
Quadriceps contraction and patellar migration (good)
Soft tissue contracture (none)

Goals
ROM 0-90 degrees
Protect ligament reconstruction
Adequate quadriceps contraction
Control inflammation, effusion

	Frequency	Duration
ROM	3-4 ×/day, 10 min	
Passive, 0-90 degrees with 10-lb valgus force		
Patellar mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion)		3 sets × 10 reps
Active quadriceps isometrics		1 set × 10 reps
Knee extension (active assisted, 90-30 degrees, per quad control)		3 sets × 10 reps
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

TABLE 18-3 Rehabilitation Protocol After Posterolateral Knee Reconstruction—cont'd

PHASE 2: WEEKS 3-4 (VISITS 2-4)

General Observation	Non–weight bearing, maximum protection Bivalved cylinder cast Must avoid hyperextension, varus loads, lateral joint opening	
Evaluation (Goal)	Pain (controlled) Effusion (mild) Patellar mobility (good) ROM minimum (0-90 degrees) Quadriceps contraction and patellar migration (good) Soft tissue contracture (none)	
Goals	ROM 0-90 degrees Protect ligament reconstruction Control inflammation, effusion Muscle control	
	Frequency	**Duration**
ROM	3-4 ×/day, 10 min	
Passive, 0-90 degrees with 10-lb valgus force		
Patellar mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2-3 ×/day, 20 min	
Straight-leg raises (flexion)		3 sets × 10 reps
Isometric training: multiangle (0, 60 degrees)		1 set × 10 reps
Knee extension (active assisted, 90-30 degrees, per quad control)		3 sets × 10 reps
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

PHASE 3: WEEKS 5-6 (VISITS 1-2)

General Observation	Partial (25%-50%) weight bearing when: • Pain is controlled without narcotics • Hemarthrosis is controlled • ROM 0-100 degrees • Muscle control throughout ROM Custom medial unloader brace or hinged soft tissue brace Avoid hyperextension, varus loads
Evaluation (Goal)	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-110 degrees) Muscle control (3/5) Inflammatory response (none)
Goals	ROM 0-110 degrees Control inflammation, effusion Protect ligament reconstruction Muscle control Early recognition of complications (motion abnormalities, CRPS, patellofemoral changes) 50% weight bearing

Continued

TABLE 18-3 Rehabilitation Protocol After Posterolateral Knee Reconstruction—cont'd

PHASE 3: WEEKS 5-6 (VISITS 1-2)

	Frequency	Duration
ROM	3 ×/day, 10 min	
Passive, 0-110 degrees		
Patellar mobilization		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (flexion, ankle weight <10% body weight)		3 sets × 10 reps
Isometric training: multiangle (90, 60, 30 degrees)		2 sets × 10 reps
Knee extension (active, 90-30 degrees)		3 sets × 10 reps
Closed-chain:		
Minisquats		3 sets × 20 reps
Heel raises/toe raises		3 sets × 20 reps
Aerobic Conditioning (Patellofemoral Precautions)	2 ×/day, 10 min	
UBC		
Stationary bicycling		
Gait Retraining (High Risk for Stretching Reconstruction With Resumption of Weight Bearing)		
Muscle control, quadriceps and hamstrings		
Walking with toe-out gait; avoid toe-in varus position		
Observe gait for any varus thrust or hyperextension		
Smooth stance phase flexion pattern		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

PHASE 4: WEEKS 7-8 (VISITS 1-2)

General Observation	Full weight bearing with cane when: • Pain is controlled • Hemarthrosis is controlled • ROM 0-120 degrees • Voluntary quadriceps contraction is achieved Custom medial unloader brace or hinged soft tissue brace
Evaluation (Goal)	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-120 degrees) Muscle control (4/5) Inflammatory response (none)
Goals	Full weight bearing Muscle control Protect ligament reconstruction Control inflammation, effusion ROM 0-120 degrees

TABLE 18-3 Rehabilitation Protocol After Posterolateral Knee Reconstruction—cont'd

PHASE 4: WEEKS 7-8 (VISITS 1-2)

	Frequency	Duration
ROM	2 ×/day, 10 min	
0-120 degrees		
Patellar mobilization		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (flexion, extension, abduction, adduction)		3 sets × 10 reps
Straight-leg raises with rubber tubing		3 sets × 30 reps
Knee extension (active, 90-30 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue ×3
Minisquats (with rubber tubing, 0-30 degrees)		3 sets × 20 reps
Heel raises/toe raises		3 sets × 20 reps
Balance Training	3 ×/day, 5 min	
Cup walking		
Balance board, two legged		
Aerobic Conditioning (Patellofemoral Precautions)	1-2 ×/day, 15 min	
UBC		
Stationary bicycling		
Gait Retraining		
Progress program		
Continue to observe for varus thrust, hyperextension		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

PHASE 5: WEEKS 9-12 (VISITS 1-2)

General Observation	Full weight bearing (week 12) when: • Pain and effusion are controlled • Muscle control throughout ROM ROM 0-135 degrees Custom medial unloader brace or hinged soft tissue brace
Evaluation (Goal)	Pain (mild/no CRPS) Manual muscle test (hamstrings, quadriceps, hip abductors/adductors/flexors/extensors) (4/5) Swelling (minimal) Patellar mobility (good) Crepitus (none/slight) Gait (symmetric)
Goals	Increase strength and endurance ROM 0-130 degrees Normal gait without varus, hyperextension

Continued

TABLE 18-3 Rehabilitation Protocol After Posterolateral Knee Reconstruction—cont'd

PHASE 5: WEEKS 9-12 (VISITS 1-2)

	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises		3 sets × 10 reps
Straight-leg raises with rubber tubing		3 sets × 30 reps
Knee extension (with resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 20 reps
Closed-chain:		
Wall-sits		To fatigue ×3
Minisquats (with rubber tubing, 0-40 degrees)		3 sets × 20 reps
Lateral step-ups (2- to 4-inch block)		3 sets × 10 reps
Heel raises/toe raises		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Cup walking		
Balance board, two legged		
Aerobic Conditioning (Patellofemoral Precautions)	1 ×/day, 15-20 min	
Stationary bicycling		
Modalities	As required	
Cryotherapy		20 min

PHASE 6: WEEKS 13-26 (VISITS 2-3)

General Observation	No effusion, painless ROM, joint stability Performs ADLs, can walk 20 min without pain ROM 0-130 degrees Custom medial unloader brace or hinged soft tissue brace
Evaluation (Goals)	Pain (minimal) Manual muscle test (4/5) Swelling (minimal) Patellar mobility (good) Crepitus (none/slight) Gait (symmetric)
Goals	Increase strength and endurance

	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	3 ×/wk, 20-30 min	
Straight-leg raises with rubber tubing, high speed		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (with resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps

TABLE 18-3 Rehabilitation Protocol After Posterolateral Knee Reconstruction—cont'd

PHASE 6: WEEKS 13-26 (VISITS 2-3)

	Frequency	Duration
Closed-chain:	3 ×/wk, opposite days (machines)	
Wall-sits		To fatigue ×3
Minisquats (with rubber tubing, 0-40 degrees)		3 sets × 20 reps
Lateral step-ups (2- to 4-inch block)		3 sets × 10 reps
Balance Training	1-2 ×/day, 5 min	
Balance board, two legged		
Single-leg stance		
Aerobic Conditioning (Patellofemoral Precautions)	3 ×/wk, 20 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Stair machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Elliptical machine		
Modalities	As required	
Cryotherapy		20 min

PHASE 7: WEEKS 27-52 (VISITS 2-3)

General Observation	No effusion, painless ROM, joint stability Performs ADLs, can walk 20 min without pain Custom medial unloader brace or hinged soft tissue brace	
Evaluation (Goal)	Isometric test (% difference between quadriceps and hamstrings) (10-15) Swelling (none) Patellar mobility (good) Crepitus (none/slight)	
Goals	Increase function Return to previous activity level Maintain strength, endurance	
	Frequency	**Duration**
ROM	1 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	3 ×/wk, 20-30 min	
Straight-leg raises with rubber tubing, high speed		3 sets × 30 reps
Hamstring curls (0-90 degrees)		3 sets × 10 reps
Knee extension (with resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Closed-chain:	3 ×/wk, opposite days (machines)	
Wall-sits		To fatigue ×3
Minisquats (0-40 degrees)		3 sets × 20 reps
Lateral step-ups (2- to 8-inch block)		3 sets × 10 reps
Balance Training	1 ×/day, 5 min	
Balance board, two legged		
Single-leg stance		

Continued

TABLE 18-3 Rehabilitation Protocol After Posterolateral Knee Reconstruction—cont'd

PHASE 7: WEEKS 27-52 (VISITS 2-3)

	Frequency	Duration
Aerobic Conditioning (Patellofemoral Precautions)	3 ×/wk, 20-30 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Stair machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Elliptical machine		
Running Program (9-mo Minimum, Straight, 30% Deficit Isometric Test)	3 ×/wk, 15-20 min	
Jog		¼ mile
Walk		⅛ mile
Backward run		20 yards
Cutting Program (12-mo Minimum, 20% Deficit Isometric Test)	3 ×/wk	20 yards
Lateral, carioca, figure-eights		
Functional Training (12 mo Minimum)	3 ×/wk	
Plyometric training: box hops, level, double legged		4-6 sets, 15 sec
Sport-specific drills (10%-15% deficit isometric test)		
Modalities	As required	
Cryotherapy		20 min

ADLs, Activities of daily living; *BAPS*, Biomechanical Ankle Platform System (Patterson Medical); *BBS*, Biodex Balance System; *CRPS*, complex regional pain syndrome; *EMS*, electrical muscle stimulation; *ITB*, iliotibial band; *ROM*, range of motion; *UBC*, upper body cycle.

Posterolateral reconstructions are monitored with manual examination of lateral joint opening and external tibial rotation. Any patient who experiences difficulty progressing through the protocol or who develops a complication is expected to require additional supervision in the formal clinic setting.

The immediate postoperative management is similar to that described for PCL reconstructions. A bivalved cast is used for the first 4 postoperative weeks to provide maximum protection to the knee joint and posterolateral structures. The cast is used in this time period because many soft-hinged postoperative braces do not provide sufficient protection against excessive lateral joint opening that could occur with ambulation and produce a failure of the posterolateral reconstruction. The cast is removed four times per day for passive knee motion exercises, which are performed in a seated position with a 10-lb valgus load applied to decrease lateral joint forces. If associated with a PCL reconstruction, a combined medial-anterior load should be applied to control both varus and posterior loads. At 4 weeks postoperative, a lower extremity, hinged, double-upright brace is applied locked at 10 degrees of flexion. The brace is removed four times daily for ROM exercises. At 6 weeks postoperative, the brace is unlocked as knee flexion to 110 degrees is encouraged and partial weight bearing allowed.

It is important to recognize that, on occasion, there will be excessive soft tissue swelling or skin problems in which the bivalved cylinder cast is contraindicated. There are commercially available soft tissue hinged braces with a design where the hinge support and medial-lateral arms are more rigid, providing (when properly applied) a resistance to prevent abnormal lateral joint opening with ambulation. A more flexible hinged soft tissue brace is not advised. The surgeon provides information on the expected strength of the posterolateral reconstruction. For example, a double-graft anatomic reconstruction provides considerable strength to allow a soft-hinged brace. A single femorofibular graft reconstruction has less strength, and more postoperative protection is required for the first 4 weeks.

At 7 to 8 weeks, a custom medial unloading brace is applied as weight bearing progresses to full and flexion is advanced to 120 degrees. The brace is also used as patients return to activity to provide protection against knee hyperextension and excessive varus loads.

Patients are allowed 0 to 90 degrees immediately postoperatively. Flexion is slowly advanced to 110 degrees by postoperative week 5, 120 degrees by week 8, and 130 degrees by week 12. Patients are cautioned to avoid varus tensioning when performing knee flexion exercises. They are taught (and the assistance of a partner is encouraged) to place a hand on the lateral aspect of the knee and create a 10-lb valgus load to protect the posterolateral structures.

Patients are not allowed to bear weight for the first 2 postoperative weeks. Then, partial weight bearing (25% of the patient's body weight) is begun at postoperative weeks 3 to 4. There is a slow advancement to full weight bearing by weeks 8 to 10 with the brace unlocked and cane or crutch support, which is used for approximately another 3 to 4 weeks. The patient must have good control of the lower extremity and adequate muscle strength to maintain joint compression and avoid an abnormal lift-off of the lateral tibiofemoral compartment. Patients are warned to avoid knee hyperextension and activities that would incur varus loading, internal tibial rotation, or lateral joint opening.

TABLE 18-4 Discharge Rehabilitation Criteria After Posterolateral Reconstruction

Desired Sports	Occupation Rating*	Symptom Rating* Pain, Swelling, Giving Way	Lateral Joint Opening (20 Degrees, I-N, mm)	Biodex Isometric Test (% Deficit I-N)	Single-leg Hop Function Testing Limb Symmetry (%)
Jumping, pivoting, cutting*†‡	Heavy/very heavy	None, level 10	None	≤15	≥85
Running, turning, twisting	Moderate	None, level 8	<3	≤20	≥85
Swimming, bicycling	Light	None, level 6	3-5	≤30	≥75
None, daily activities only	Very light	None, level 4	3-5	<30	≥75

*See Chapter 41.
†Level 10, normal knee, no symptoms with strenuous work/sports with jumping, hard pivoting; level 8, no symptoms with moderate work/sports with running, turning, twisting; level 6, no symptoms with light work/sports such as swimming, bicycling; level 4, no symptoms with daily activities.
‡Also consider completing a course of Sportsmetrics before return to these athletic activities.
I-N, Involved minus noninvolved limb.

Patellar mobilization, flexibility exercises, modality usage, and the strengthening and conditioning programs are all similar to those described in the PCL reconstruction protocol.

In select athletes, a running program is begun at approximately the ninth postoperative month, and plyometric- and sports-specific-training programs are initiated at the twelfth postoperative month. However, the majority of patients who require multiple ligament reconstructive procedures do not desire to return to high-impact sports; therefore this advanced conditioning and training is usually not required. Patients who have articular cartilage damage are advised to return to low-impact activities only to protect the knee joint.

Discharge criteria after lateral and posterolateral graft reconstructions is based on patient goals for athletics and occupations and the rating of symptoms, lateral joint opening, muscle strength testing, and function testing (Table 18-4). Lateral joint opening is assessed either by stress radiography or manual testing at 20 degrees of flexion. The remainder of the assessment is performed as previously described for PCL reconstructions.

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19

Medial and Posteromedial Ligament Injuries: Diagnosis, Operative Techniques, and Clinical Outcomes

Frank R. Noyes, Sue D. Barber-Westin

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VIDEO CONTENT

Video 1-1 The Key to the Knee: A Layer-by-Layer Demonstration of Medial and Anterior Knee Anatomy
Video 3-1 Comprehensive Knee Exam: Clinical Rationale and Diagnosis

INDICATIONS

Medial ligament injuries are among the most frequently treated problems of the knee joint, with the majority not requiring operative intervention. Whereas isolated superficial medial collateral ligament (SMCL) ruptures are common,[60] concomitant damage to the anterior cruciate ligament (ACL) also occurs in many cases, especially in young and active patients.[10,14,22,49,58,71]

Overall, there are four types of SMCL injury patterns: (1) SMCL tears that also almost always involves the meniscofemoral and meniscotibial attachments (deep medial collateral ligament [DMCL]); (2) associated posteromedial capsular (PMC) tears (posterior oblique ligament [POL]); (3) associated ACL or posterior cruciate ligament (PCL) tears with patterns 1 or 2; and (4) multiple ligament injuries or knee dislocations.

The mechanism of injury to the medial ligaments involves a valgus stress with usually a combined external tibial rotation component from either a noncontact (pivoting or cutting) or a contact injury (direct blow to the lateral side of the thigh or knee). The decision process regarding the appropriate treatment of medial ligament injuries involves determining the severity of the injury to the entire knee, including the other knee ligaments, and the specific injury pattern of the medial structures and menisci.

The medial structures identified for purposes of surgical treatment consist of the SMCL, DMCL (including meniscus attachments), and the PMC, which includes the structures referred to as the POL and semimembranosus attachments.[32,68] The key to the diagnosis and treatment of medial ligament injuries relies on a comprehensive understanding of the intricate anatomy on the medial side of the knee. This is presented in detail in Chapter 1. In Figure 19-1, the osseous attachments of the medial structures are shown. Figure 19-2 shows the medial and posteromedial ligament structures, which are discussed in detail. Figure 19-3 shows the relationship of the semimembranosus muscle attachments to the posteromedial structures and POL. These include the bifurcation of the semimembranosus tendon into a direct and anterior arm just distal to the joint line and a minor attachment of the direct arm to the medial coronary ligament along the posterior horn of the medial meniscus. The semimembranosus tendon sheath makes up a distal tibial expansion that includes a medial and lateral division. A major attachment of the semimembranosus forms the oblique popliteal ligament, which is a broad fascial band that courses laterally attaching to the fabella, posterolateral capsule, and plantaris (see Chapter 1, Fig. 1-6).

It is important to understand and classify the soft tissue injury of all the medial structures. The majority of acute medial ligament injuries that involve damage to the SMCL alone, or SMCL and PMC, are treated conservatively. The nonoperative treatment algorithm is shown in Figure 19-4 and discussed later in more detail. Gross major disruption of all of the medial structures alone or in addition to the ACL or

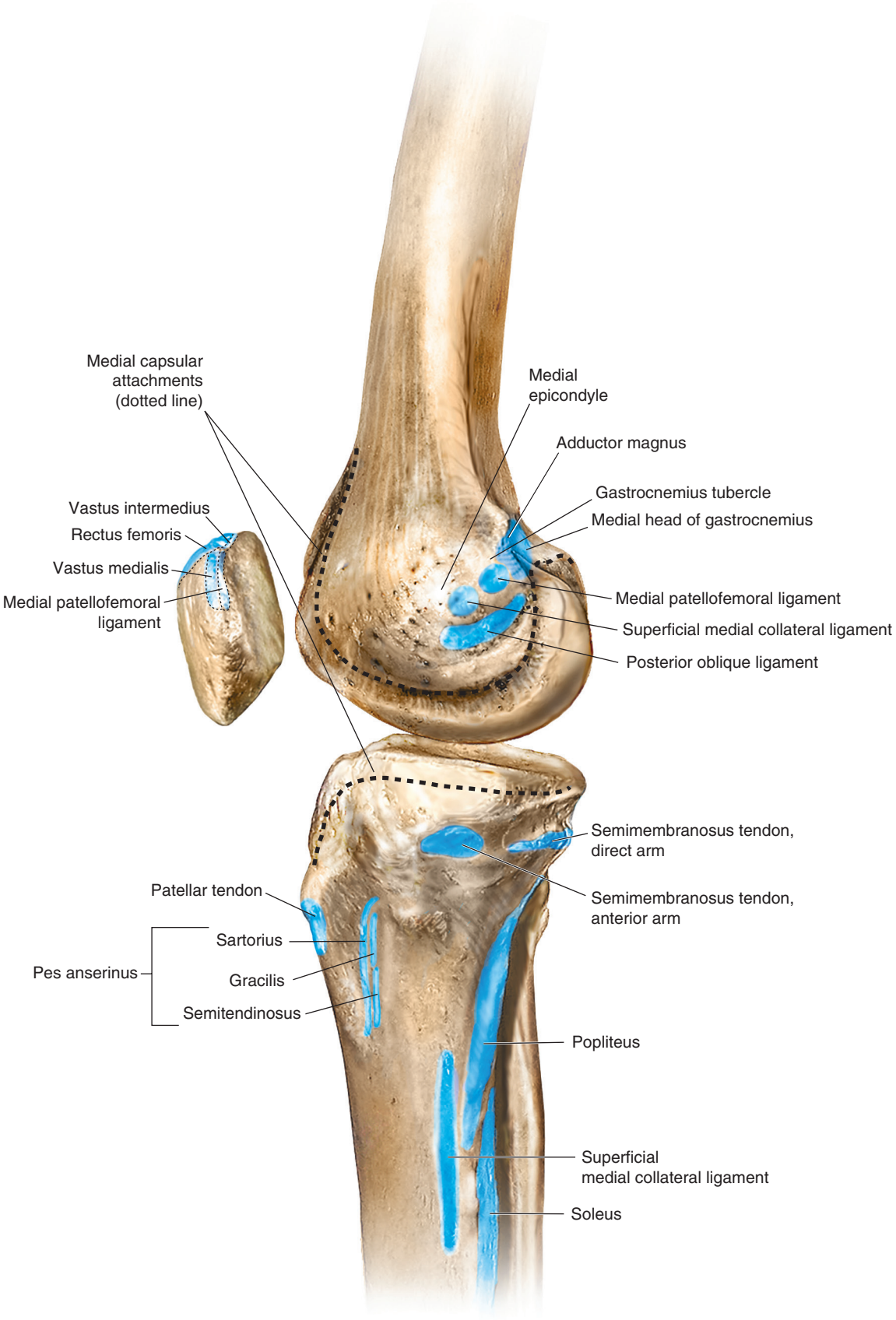


FIG 19-1 The medial capsule, ligament, and muscle bone attachments are shown. A key to surgical repair and reconstruction of medial injuries is to restore normal anatomy and attachment locations.

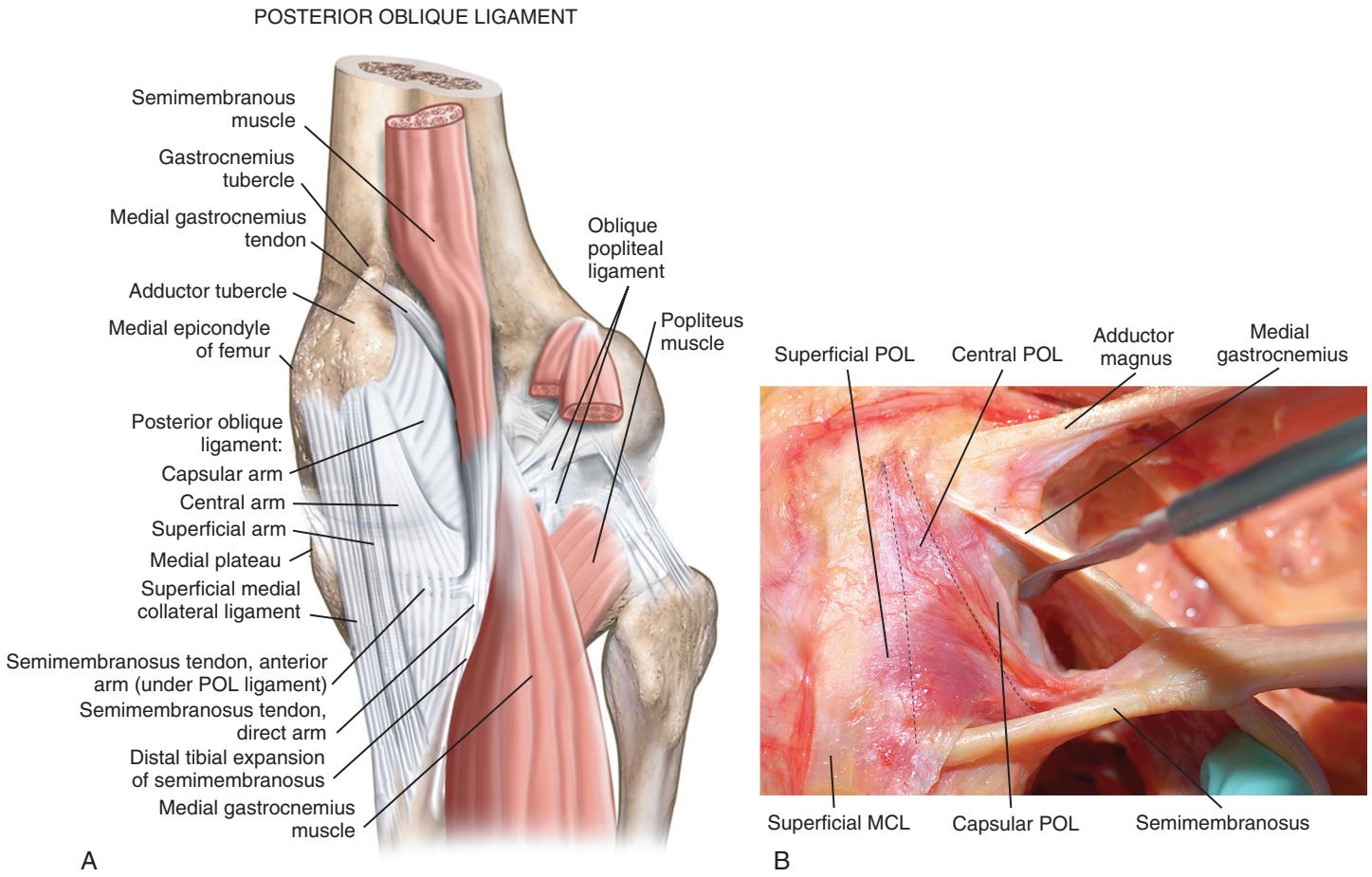


FIG 19-2 **A** and **B,** The anatomy of the medial and posteromedial aspect of the knee. The posteromedial capsule is shown divided into three functional regions, commonly designated as the *posterior oblique ligament* (POL). *MCL,* Medial collateral ligament.

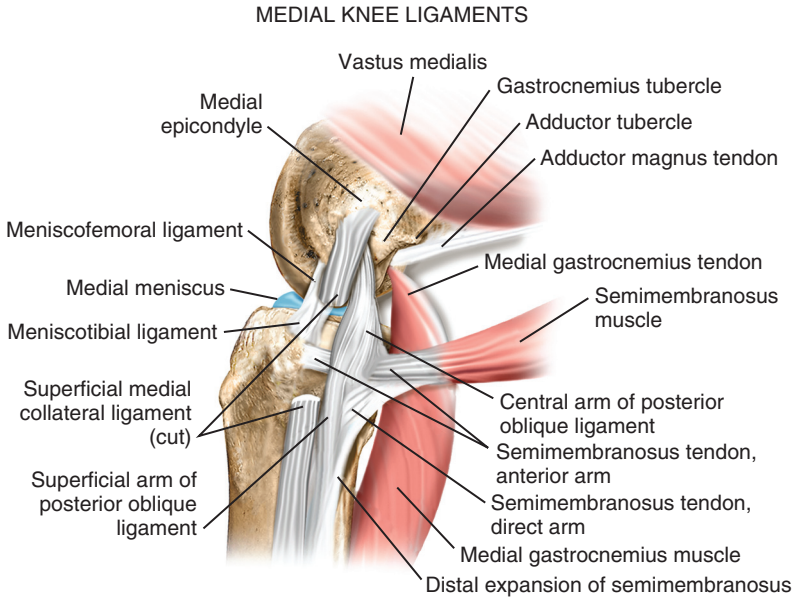


FIG 19-3 Semimembranosus muscle attachments to the posteromedial structures.

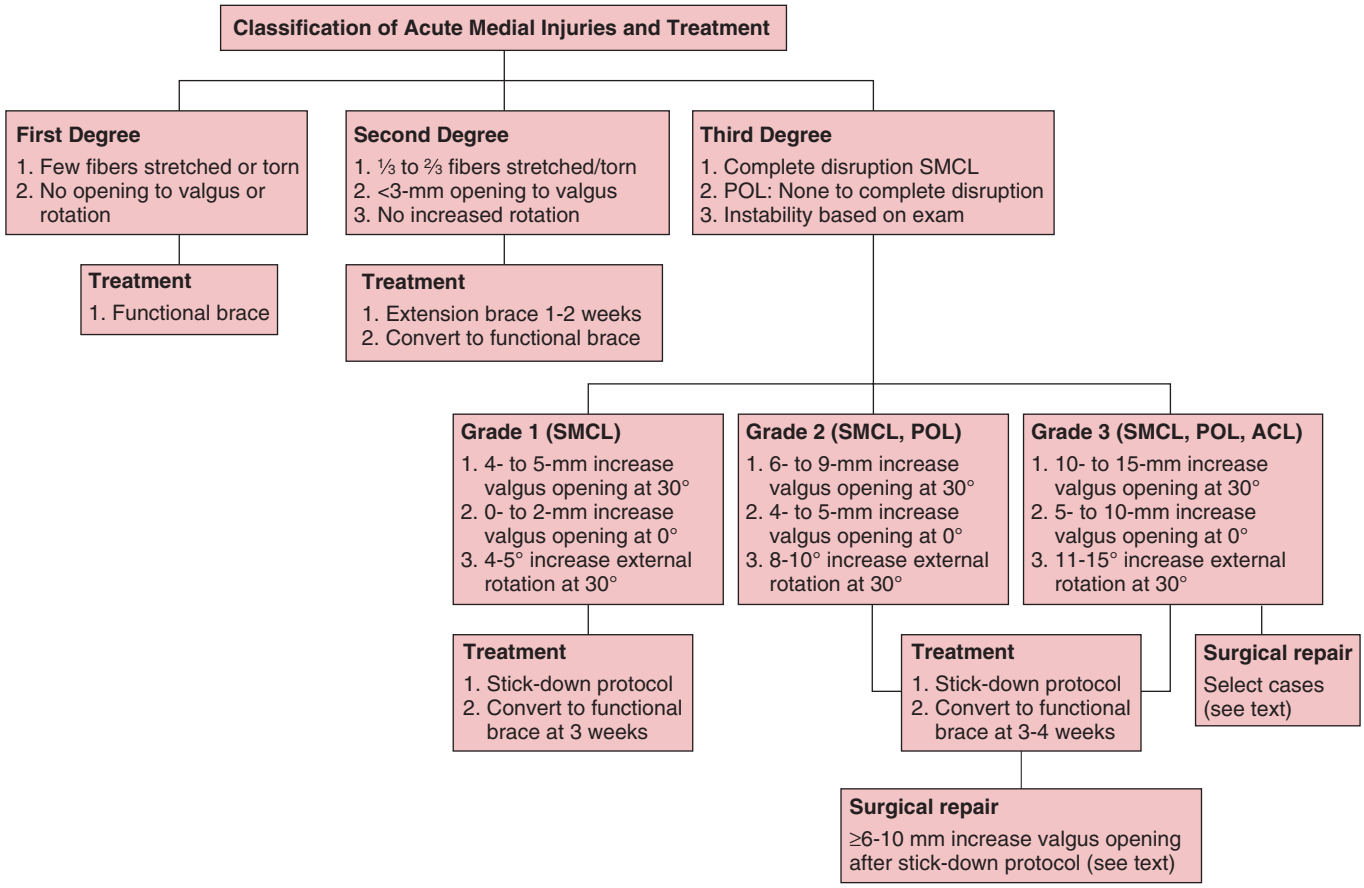


FIG 19-4 Treatment algorithm for patients with acute medial ligament ruptures. *ACL*, Anterior cruciate ligament; *POL*, posterior oblique ligament; *SMCL*, superficial medial collateral ligament.

PCL tears involve a group of select knees. The treatment of these gross ligament disruptions is discussed in a later section of this chapter.

In cases of chronic injury to the medial ligaments, it is important to obtain a complete history and objective and functional rating. We use the Cincinnati Knee Rating System (CKRS) for this analysis (see Chapter 41) to determine patient complaints of giving-way and the levels of activity at which this symptom occurs as an indication for surgical stabilization procedures. In this chapter, *instability* refers to an increase in abnormal motion limits as detected on the physical examination and is not used to indicate giving-way events.

CONTRAINDICATIONS

Patients who have medial ligament tears classified as first, second-, or third degree that demonstrate either no increase or a mild to moderate increase in medial joint opening at 0 and 30 degrees of flexion do not require acute medial ligament repair or reconstruction.

A valgus malalignment and valgus thrust on walking contraindicates a medial ligament reconstruction in chronic cases without first performing an osteotomy to correct the lower limb malalignment. Alternatively, a genu varus provides a theoretical benefit of decreased tensile loads on the medial ligament structures.

In chronic cases of disruption of the medial ligaments, particularly associated with ACL or PCL tears, joint arthritis and associated pain and swelling may exist that contraindicate a soft tissue reconstruction. The patient goals and anticipated symptoms from the preexisting arthrosis are carefully considered.

Sedentary, nonathletic patients who do not experience pain, swelling, or giving-way with daily activities do not require surgery. These patients are advised to maintain their ideal body weight and obtain yearly consultations to monitor the knee joint.

In chronic cases, patients with marked lower extremity muscle atrophy are not candidates for surgery until adequate muscle strength is regained. The high potential for postoperative complications exceeds the potential benefits in these patients, especially in regard to developmental patella infera, quadriceps shutdown, and arthrofibrosis. A formal program of physical therapy should be pursued, which may be required for many months to improve overall lower limb muscle strength and function, particularly in multiligament injuries.

Associated medical problems may exist that either require treatment or contraindicate surgery, including complex regional pain syndrome, diabetics, vascular insufficiency, skin lesions, infectious conditions, obesity, or other medical diseases.

CLINICAL BIOMECHANICS

Classification of Ligament Injury and Instability

A considerable amount of discrepancy exists in the literature regarding the use of terminology to describe and classify the medial ligament injuries from an anatomic standpoint and the abnormal motion limits that exist (see Chapter 3). We agree with Hughston and coworkers[29] that the clinician must clearly separate and classify medial ligament tears as either first degree (tear involving a few fibers), second degree (partial tear, no instability, 3 mm or less of medial joint opening), or

TABLE 19-1 Published Classification Systems for Ruptures to the Medial Structures of the Knee

Reference	System
Hughston et al[30,31] (1976, 1983)	Injury severity: • First degree: Involves a few fibers resulting in localized tenderness but no instability • Second degree: Disruption of more fibers with more generalized tenderness but no instability • Third degree: Complete disruption of the ligament with resultant instability Degree of instability (total separation medial joint, not increase): • 1+: ≤5-mm separation medial joint surfaces • 2+: 5- to 10-mm separation medial joint surfaces • 3+: >10-mm absolute medial separation
Fetto & Marshall[14] (1978)	Grade I: Full anatomic integrity, full stability to valgus stress both 0 and 30 degrees of flexion, hard endpoint, no opening on stress x-rays Grade II: Partial anatomic discontinuity, unstable to valgus stress 30 degrees but stable at 0 degrees. Firm endpoint if chronic, soft if acute, some medial opening stress x-rays Grade III: Complete anatomic disruption, unstable to valgus stress at both 0 and 30 degrees of flexion, no endpoint, marked medial opening stress x-rays
Garrick[16] (2004)	Primary (grade I): Stretching of fibers with localized tenderness, no instability Second degree (grade II): More disruption of fibers, mild to moderate instability Third degree (grade III): Complete disruption of the ligament, gross instability
Bergfeld[6] (1979)	First degree: No valgus instability at 20 degrees Second degree: Definite valgus laxity at 20 degrees, 5-15 degrees greater laxity than the opposite knee, but firm endpoint Third degree: Opening >15 degrees with no or a "mushy" end point
Shelbourne & Patel[66] (1995)	Grade I: No laxity, solid end point Grade II: Some medial laxity, firm end point Grade III: Complete disruption of the MCL with substantial medial opening and no detectable end point
Petersen & Laprell[57] (1999)	First degree: Painful valgus stress test with no instability Second degree: Positive valgus stress test with an endpoint Third degree: Positive valgus stress test without an endpoint
Fanelli & Harris[13] (2007)	A: Axial plane rotation, instability, usually represents posteromedial capsular laxity B: Combined axial plane rotation and valgus laxity with a firm end point, usually caused by posteromedial and medial capsular laxity combined with superficial MCL laxity C: Combined axial plane rotation and valgus laxity with no end point, often caused by posteromedial and medial capsular laxity, disruption, or avulsion, combined with superficial MCL laxity, disruption, or avulsion

MCL, Medial collateral ligament.

third-degree (complete rupture, see Table 19-1 and Fig. 19-4). This is one of the earliest systems devised and is based on a classification proposed by the American Medical Association.[1] The problem has arisen, as amply demonstrated in Table 19-1, that this classification system has been modified extensively by different authors and it is often not possible to categorize the injury severity of the knees under treatment. A grade 1 instability (0 to 5-mm increased joint opening) may represent a second-degree injury (0 to 3-mm increased joint opening) or a third-degree injury (5-mm increased joint opening), requiring protection to allow healing as discussed. This also applies to a grade 2 instability where a 6- to 9-mm increased joint opening is treated conservatively with immobilization, whereas other studies include these as operative cases. Thus it is necessary in the review of the literature to perform a subset analysis, which has been done in this chapter, to try to obtain the category or type of injury under treatment and our treatment recommendations.

For purposes of this chapter, the injury classification in acute cases of medial ligament injuries is based on the clinical examination shown in Figure 19-4. Note that the medial ligament injuries are based on the first-, second-, and third-degree original classification system. The approximate increases in medial joint opening and external tibial rotation are shown for the different categories of injury. Some classification schemes use a system in which each grade represents a further 5-mm increase in joint opening (grades 1, 2, and 3) over the contralateral normal knee, whereas Hughston and colleagues use a grade to classify the degree of injury and then represent the absolute amount of joint opening in the injured knee (1+, 2+, and 3+ in 5-mm increments; see Table 19-1). This chapter uses the increase in millimeters of medial joint opening between the injured and contralateral normal knee because this is the system used in published biomechanical and kinematic studies to be discussed.

A review of the in vitro cadaveric biomechanical function of the medial ligaments and ACL in resisting medial joint opening, external tibial rotation, and internal tibial rotation is provided in Figure 19-5, summarized in Table 19-2,[20] and discussed in more detail in Chapter 3. A finding of increased medial joint space at 30 degrees of flexion (third-degree sprain, parallel fibers of the SMCL), but not at 0 degrees of flexion indicates the PMC (including the POL) is still functional. Any further increase in medial joint opening at 0 degrees indicates concurrent damage to the PMC. With complete disruption of the SMCL and PMC, the ACL and PCL become a restraint to further medial joint opening. The increase in abduction for a combined MCL/POL injury and MCL/ACL injury at 15 to 45 degrees of flexion is nearly the same (see Fig. 19-5, *B*). The major difference between these injuries is in increased abduction at full extension in the MCL/POL-ruptured knee. In summary, knees with rupture to both the medial collateral

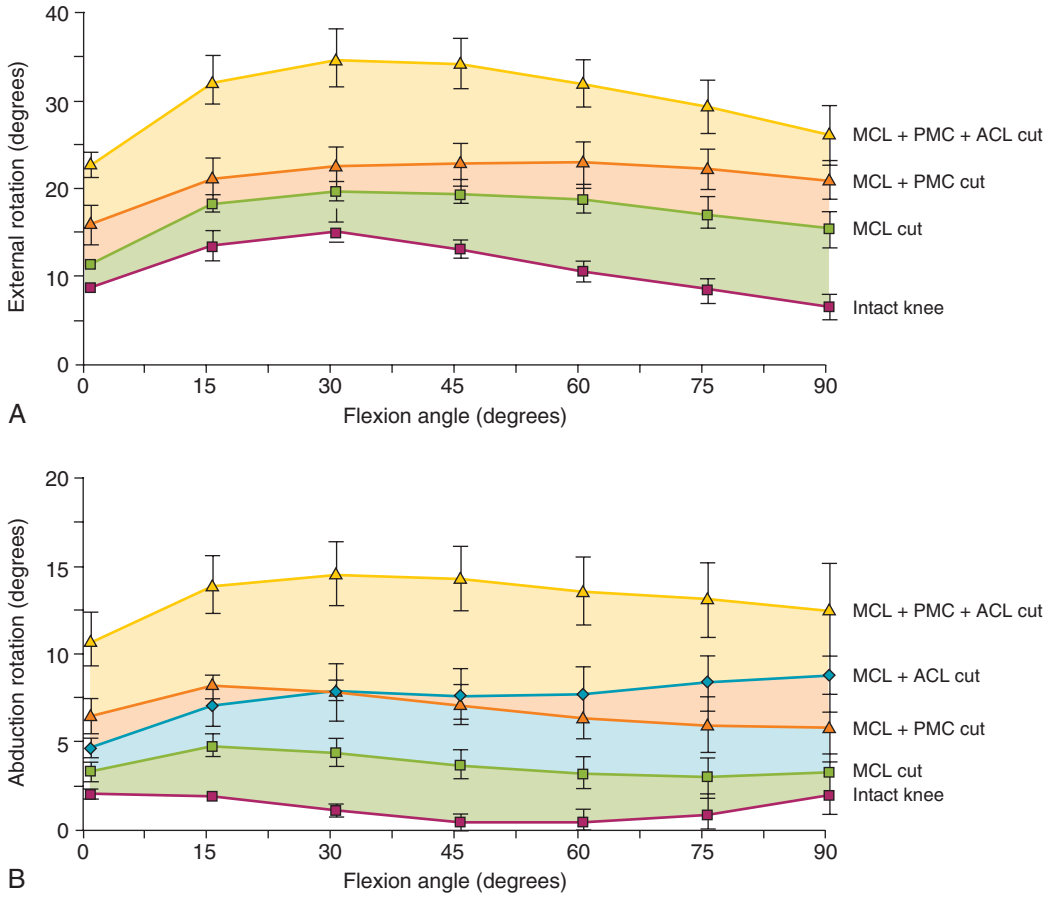


FIG 19-5 A, The external rotation limits in the intact knee first increased with flexion to 30 degrees and then decreased with further flexion (11 donors). Cutting just the superficial MCL increased the external rotation limits (16 donors). Further cutting of the PMC produced a further increased in the external limit at all flexion angles, but the increase was again greater in flexion than extension. Cutting the superficial MCL, the PMC, and the ACL allowed for a large increase in the external limit, particularly from 15 to 45 degrees of flexion. **B,** The abduction rotation limits (valgus opening) of the intact knee (11 donors). Cutting only the MCL produced a small increase (~2 to 4 degrees) in the abduction limit from 15 to 75 degrees of flexion. Cutting the ACL (MCL + ACL cut) increased the abduction limit (6 donors). Cutting the PMC in addition to the MCL with the ACL intact allowed for a further small but consistent increase (2 to 3 degrees) over the superficial MCL alone (6 donors). When compared with the intact knee, this injury combination increased the abduction limit approximately 6 to 7 degrees at both 15 and 30 degrees of flexion. Subsequently cutting the ACL caused a large increase in the abduction limits at all flexion angles (9 donors). Note that the MCL + ACL cut produced a similar increase in abduction at 15, 30, and 45 degrees of flexion as the MCL + PMC cut, but not at full extension. *ACL,* Anterior cruciate ligament; *MCL,* medial collateral ligament; *PMC,* posteromedial corner. (From Haimes JL, Wroble RR, Grood ES, Noyes FR. Role of the medial structures in the intact and anterior cruciate ligament-deficient knee. Limits of motion in the human knee. *Am J Sports Med.* 1994;22: 402-409.)

ligament (MCL) and POL will demonstrate approximate increases in external tibial rotation (average of 9 degrees at 30 degrees of flexion), internal tibial rotation (average of 9 degrees at 30 degrees of flexion), and abduction testing at 0 and 30 degrees of flexion (averages of 5 degrees and 7 degrees, respectively).

The increase in medial joint opening and external tibial rotation shown in Figure 19-5 provides an indication of an associated ACL tear when these motion limits are distinctly abnormal. In these knees, there is a large increase in anterior tibial translation and the pivot shift test is in the grade III category.

The results show the importance of performing the dial tibial rotation test (see Chapter 17) to determine the anterior subluxation of the medial tibial plateau with medial ligament injuries.[18] With a combined MCL/POL injury, there will be a noticeable increase in internal and external tibial rotation (see Fig. 19-5 and Fig. 19-6).

The medial structures resisting external rotation in the dial test show the SMCL is the primary restraint; however, the increase in external rotation is small (4.6-8.7 degrees at 30 and 90 degrees of flexion) and may not be clinically detectable. The increase in external tibial rotation approximately doubles when the SMCL and PMC are injured (9-15 degrees at 30 and 90 degrees of flexion), resulting in a qualitative detectable positive dial test. An even greater increase occurs with ACL rupture. It should be noted that Griffith and associates[18] reported even larger increases in the dial test with SMCL sectioning, suggesting that some knees may have a positive dial test with this injury.

TABLE 19-2 Increases in Motion Limits Relative to the Intact Knee That Occurred When the Indicated Structures Were Sectioned

Motion Limit	0 Degrees of Flexion	15 Degrees of Flexion	30 Degrees of Flexion	60 Degrees of Flexion	90 Degrees of Flexion
Anterior (mm)					
ACL	5.8 ± 0.9*	9.4 ± 1.0†	8.4 ± 1.9*	4.7 ± 2.1‡	3.5 ± 1.6‡
ACL & MCL	6.1 ± 2.0*	10.0 ± 2.4*	11.0 ± 2.9*	10.6 ± 3.5*	10.1 ± 4.2‡
MCL & POL/PMC	–0.5 ± 1.1	–0.3 ± 1.1	–0.5 ± 0.9	–0.1 ± 0.7	0.4 ± 1.1
ACL & MCL & POL/PMC	8.7 ± 3.2†	12.8 ± 4.3†	14.4 ± 4.9†	14.6 ± 5.7†	12.5 ± 5.6*
External Rotation (Degrees)					
ACL	1.2 ± 1.4	0.7 ± 0.8	0.7 ± 0.6	0.7 ± 0.4	0.5 ± 0.5
MCL	2.5 ± 1.1‡	3.3 ± 1.5‡	4.6 ± 1.3*	8.0 ± 2.2*	8.7 ± 3.2‡
POL/PMC	1.6 ± 0.9	1.2 ± 1.2	0.9 ± 1.7	0.8 ± 2.5	0.8 ± 2.4
ACL & MCL	2.3 ± 0.4†	3.2 ± 1.1*	4.6 ± 1.6*	7.3 ± 2.3*	7.5 ± 2.0*
MCL & POL/PMC	6.8 ± 2.5‡	7.2 ± 1.9*	9.0 ± 2.0*	13.6 ± 3.0*	15.0 ± 3.6*
ACL & MCL & POL/PMC	10.9 ± 5.8*	12.7 ± 6.2*	14.7 ± 6.5*	16.7 ± 5.9†	15.3 ± 5.1†
Internal Rotation (Degrees)					
ACL	2.9 ± 1.0*	2.2 ± 0.9‡	0.8 ± 0.9	0.5 ± 0.8	2.0 ± 2.6
MCL	0.5 ± 0.5	1.4 ± 0.7	2.1 ± 1.2	1.8 ± 0.3†	1.5 ± 0.4*
POL/PMC	3.4 ± 2.4	4.0 ± 2.3	2.7 ± 1.7	1.3 ± 0.7	1.4 ± 1.4
ACL & MCL	3.6 ± 1.5‡	3.5 ± 1.4‡	2.3 ± 1.3	2.4 ± 0.8*	2.1 ± 1.4
MCL & POL/PMC	6.3 ± 5.8	11.6 ± 3.4*	9.3 ± 2.2*	3.9 ± 2.4	2.9 ± 1.5
ACL & MCL & POL/PMC	12.7 ± 6.5*	13.2 ± 3.3§	10.4 ± 2.1§	4.5 ± 1.1§	3.3 ± 1.2†
Abduction (Degrees)					
ACL	0.4 ± 0.2‡	0.8 ± 0.5	0.6 ± 0.6	0.1 ± 0.3	0.0 ± 0.3
MCL	1.5 ± 0.9	3.3 ± 0.8*	4.1 ± 0.8†	4.5 ± 0.8†	3.8 ± 1.0*
POL/PMC	0.4 ± 0.3	0.2 ± 0.6	0.4 ± 0.3	0.0 ± 0.9	0.4 ± 0.5
ACL & MCL	2.5 ± 1.1‡	5.4 ± 2.6‡;	7.1 ± 3.6‡	8.1 ± 4.0‡	7.1 ± 2.8‡
MCL & POL/PMC	4.6 ± 1.9‡	6.0 ± 1.4*	6.6 ± 0.9§	5.8 ± 1.2†	4.8 ± 1.1*
ACL & MCL & POL/PMC	9.1 ± 4.6*	12.7 ± 4.8†	14.4 ± 5.0†	14.2 ± 4.5†	12.1 ± 4.0†

*$P < .01$.
†$P < .001$.
‡$P < .05$.
§$P < .0001$.
ACL, Anterior cruciate ligament; *MCL*, superficial medial collateral ligament; *POL*, posterior oblique ligament; *PMC* posteromedial capsule.

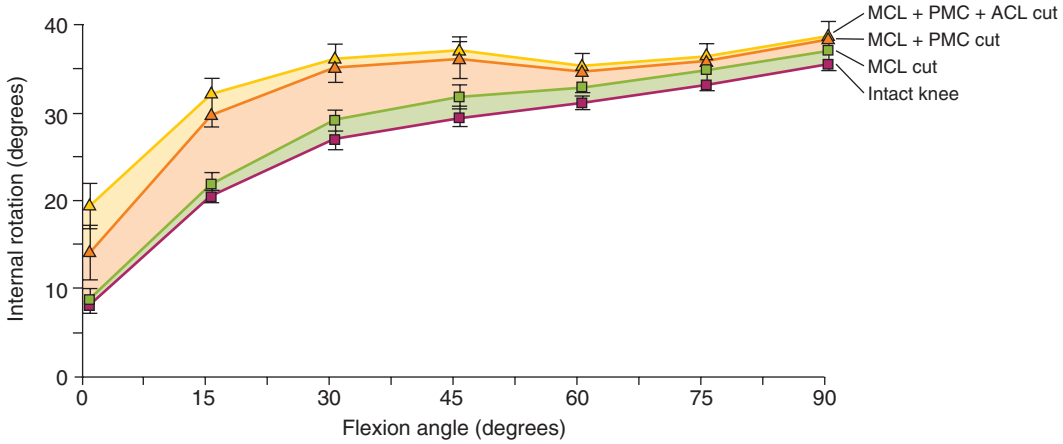


FIG 19-6 The internal rotation limits of the intact knee increased progressively as the knee was passively flexed (11 donors). Cutting the superficial MCL produced only a small increase in the internal rotation limits (6 donors). Cutting the MCL and PMC caused large increases in the internal rotation limits from 0 to 45 degrees of flexion (6 donors). Cutting the MCL, the PMC, and the ACL caused similarly large increases in the internal limits from 0 to 45 degrees of flexion relative to the intact knee (6 donors). However, these increases were not significantly different from those seen with the MCL and PMC cut. *ACL,* Anterior cruciate ligament; *MCL*, medial collateral ligament; *PMC*, posteromedial corner. (From Haimes JL, Wroble RR, Grood ES, Noyes FR. Role of the medial structures in the intact and anterior cruciate ligament-deficient knee. Limits of motion in the human knee. *Am J Sports Med.* 1994;22:402-409.)

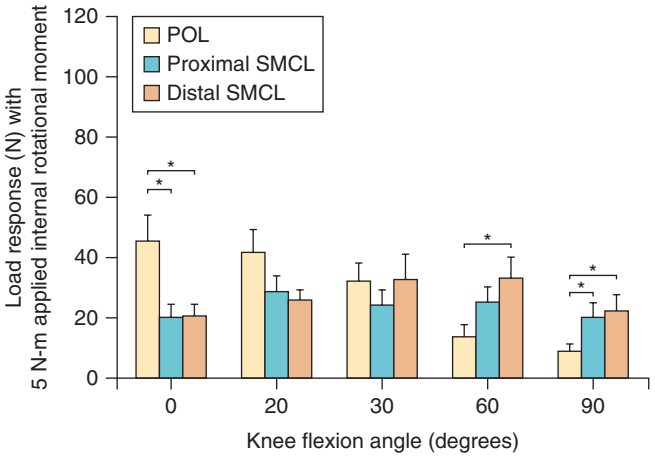


FIG 19-7 Forces measured on the posterior oblique ligament (POL) and the proximal and distal superficial medial collateral ligament (SMCL) divisions during application of a 5 N-m internal rotation torque. *$P < .05$. Error bars indicate the standard error of the mean. (From Griffith CJ, Wijdicks CA, LaPrade RF, et al. Force measurements on the posterior oblique ligament and superficial medial collateral ligament proximal and distal divisions to applied loads. *Am J Sports Med.* 2009;37:140-148.)

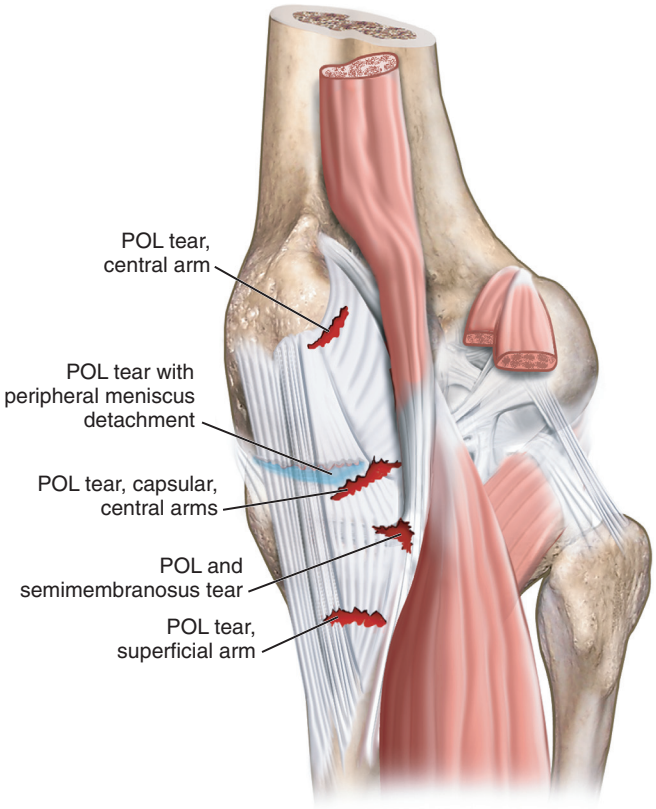


FIG 19-8 Three major acute injury patterns (injury to the posterior oblique ligament [POL] are common to all): (1) injury to the POL with semimembranosus disruption, (2) injury to the POL with complete peripheral meniscocapsular detachment, and (3) POL injury with semimembranosus injury and peripheral meniscocapsular detachment. Disruption at any level is capable of disabling the dynamic function of the semimembranosus.[68]

The medial structures resisting internal tibial rotation involve two primary restraints: the PMC/POL and SMCL, with the SMCL having a higher resistance in force measurements at 90 degrees and the PMC/POL having a higher resistance at 0 degrees of flexion (Fig. 19-7).[19] In the dial test for internal rotation, there are discrepancies in ligament sectioning studies regarding the magnitude of internal tibial rotation that occurs. In addition, there are no studies on the amount of anterior or posterior tibiofemoral compartment translation that occurs with medial ligament injuries. In general, sectioning the SMCL or PMC/POL individually produces only small increases in internal rotation whereas sectioning both structures results in an approximate 10 degrees increase in internal rotation at 30 degrees of flexion, with a lesser increase at 90 degrees of flexion. One study showed a similar amount of increased internal tibial rotation at both 30 and 90 degrees of flexion.[18]

Sims and Jacobson[68] reviewed 93 knees that underwent operative treatment for acute MCL injuries. These authors reported that 93% had associated injury to the POL following the description of Hughston and Eilers.[32] The authors emphasized the importance of identification and repair of the POL and tears of the semimembranosus capsular attachment (present in 70% of knees) and associated peripheral detachment of the medial meniscus (present in 30% of knees, Fig. 19-8). The authors postulated that a dynamic function of the semimembranosus attachments exists for knee stability, but this is unproven experimentally. Although some authors describe rupture and surgical repair of the POL alone (anteromedial rotatory instability), the biomechanic data show that the POL is not a primary restraint for medial joint opening or external tibial rotation.

CLINICAL EVALUATION

History and Physical Examination

A detailed history is taken that includes any previous knee injury and the mechanism of the current injury. The CKRS is used to evaluate the subjective, objective, and functional categories. In acute knee injuries, there may be a swollen knee, with a tense joint effusion and skin ecchymosis that is difficult to examine. Still, it is possible to rule out a multiligament injury with gross instability and complete a neurovascular examination, which includes assessment of signs of a deep venous thrombosis (DVT). The limb is immobilized and the acute injury appropriately treated (ice, compression, elevation, gentle range of motion [ROM], and early muscle activation) and the examination repeated after other diagnostic tests (radiographs, magnetic resonance imaging [MRI]) in 3 to 5 days.

The comprehensive examination of the knee joint required to detect all abnormalities includes (among other items) assessment of (1) range of knee flexion and extension, (2) knee joint effusion and swelling, (3) the knee motion limits and subluxations compared with the contralateral knee,[54] (4) alignment of the patellofemoral joint, (5) patellofemoral and tibiofemoral crepitus, (6) tenderness along the medial joint line and along the entire course of the SMCL from proximal to distal, (7) overall lower limb alignment, (8) neurovascular status, and (9) gait.

The palpation of the medial joint is particularly important to determine if the SMCL tear is more proximal at the femoral attachment, diffuse, or more distal at the tibial attachment. These findings are correlated with MRI. In a young athlete with open physes, palpation at the femoral physis is usually painful and careful radiographic stress views are always obtained to rule out a physeal fracture. A MRI is always helpful to confirm the diagnosis.



FIG 19-9 Demonstration of manual knee stability tests. **A** and **B**, Posterior drawer test at 90 degrees of knee flexion. **C**, Lachman test. **D**, Pivot shift test. **E**, Valgus test, palpating for medial joint opening at 30 and 0 degrees of flexion. **F**, Varus manual test, palpating for lateral joint opening, at 30 and 0 degrees of flexion. **G** to **I**, External rotation-internal rotation dial test. **G**, Starting position (performed at 30 and 90 degrees of flexion. **H**, Maximum at 30 degrees of flexion. **I**, Maximum at 90 degrees of flexion. **J** and **K**, Hyperextension and varus recurvatum tests supine and standing positions.

Diagnostic Clinical Tests

The clinical tests for the assessment of ligament injuries are shown in Figure 19-9. SMCL disruption is determined by manual valgus stress testing at 0 and 30 degrees of knee flexion. The surgeon estimates the amount of joint opening (in millimeters) between the initial closed contact position and open position of each tibiofemoral compartment (avoiding internal or external tibial rotation). The result is recorded according to the approximate increase in the tibiofemoral compartment of the injured knee compared with that of the opposite normal knee. This estimated increase in medial joint opening is easily confirmed at a later time by the gap test if arthroscopy is indicated, as in cases of associated ACL injury.

The integrity of the ACL is determined by Lachman and pivot shift testing. The result of the pivot shift test is recorded on a qualitative scale of 0 to III, with a grade of 0 indicating no pivot shift; grade I, a slip or glide; grade II, a jerk or clunk with the subluxation-reduction; and grade III, gross subluxation with impingement of the posterior aspect of the lateral side of the tibial plateau against the femoral condyle. A KT-2000 (MEDmetric) arthrometer test may be done at 20 degrees of flexion (134-N force) to quantify total anteroposterior (AP) displacement. The medial posterior tibiofemoral step-off on the posterior drawer test is done at 90 degrees of flexion.

The tibiofemoral rotation dial test is done at 30 and 90 degrees of knee flexion with the patient in the supine position to determine whether increases in external tibial rotation occur with anterior subluxation of the medial tibial plateau (and not posterior subluxation of the lateral tibial plateau, indicating a posterolateral ligament injury).[54] An increase in internal rotation may occur with MCL/POL disruptions (maximum 15 to 45 degrees of flexion). Associated lateral and posterolateral disruptions are determined by varus stress testing at 0 and 30 degrees of knee flexion.

A careful observation of the patient's standing alignment and gait is performed to determine whether there is a lower limb valgus alignment and valgus thrust during ambulation.

Radiographs and Imaging Studies

Radiographs taken during the initial examination include standard AP, lateral at 30 degrees of flexion, weight-bearing posteroanterior (PA) at 45 degrees of flexion, and patellofemoral axial views. Medial stress

radiographs may be required of both knees (20 degrees of flexion, neutral tibial rotation, 67-N valgus force). The difference in millimeters of medial tibiofemoral compartment opening between knees is documented. Stress views are usually too painful in acute knee injuries and are obtained more frequently in knees with chronic injuries.

Posterior stress radiographs are obtained in patients with PCL ruptures, especially those in whom the distinction of a partial versus complete PCL tear is difficult to determine on clinical examination (see Chapter 16).[25] Lateral stress radiographs may be required in knees with lateral ligament injury (see Chapter 17). Full standing radiographs of both lower extremities, from the femoral heads to the ankle joints, are done in knees with varus or valgus lower extremity malalignment (see Chapter 26). The mechanical axis and weight-bearing line are measured.[12] Of concern is to exclude a knee with lower extremity valgus alignment and increased medial soft tissue tensile forces with a valgus thrust, indicating the need for a corrective osteotomy in chronic medial injuries.

MRI is required to reveal the location of ligament anatomic disruptions, bone contusions, other ligament ruptures, and meniscus tears (Fig. 19-10). A high rate of concurrent lateral meniscus tears has been reported with MCL ruptures, making MRI an important adjunct for an accurate diagnosis.[52,65] Ligament avulsion or osteochondral injuries requiring treatment within the initial 7- to 10-day period after injury may exist.

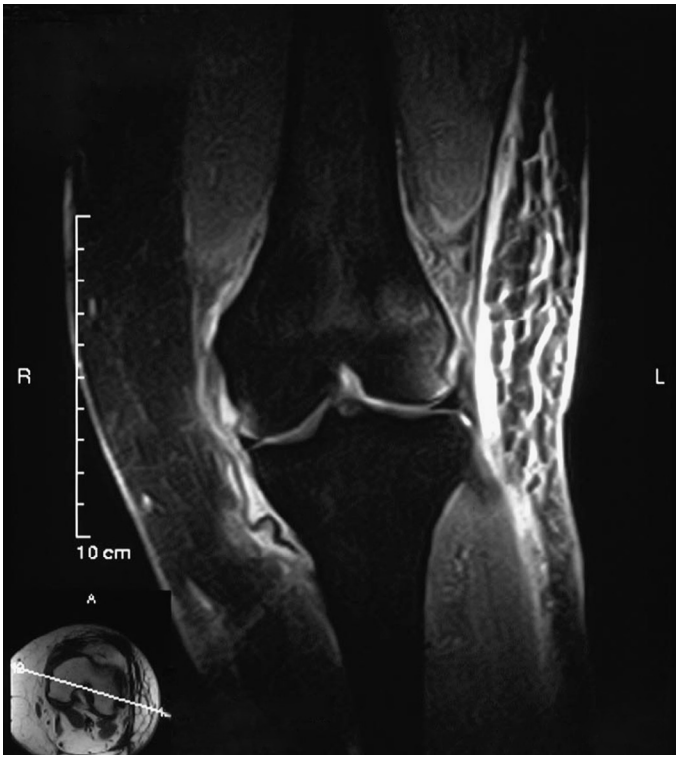


FIG 19-10 Magnetic resonance imaging (MRI) demonstrates extensive damage to the medial ligamentous structures. The superficial medial collateral ligament (SMCL) is disrupted from its proximal attachment and there is disruption of meniscus attachments and the posterior oblique ligament (POL). MRI provides important information on the injury severity. The finding of a coiled lax SMCL, particularly close to an attachment site, is a relative indication for surgery because immobilization would not be expected to allow for approximation of the SMCL/POL injury. An open operative repair was performed in this athlete, along with an anterior cruciate ligament reconstruction.

CONSERVATIVE VERSUS OPERATIVE TREATMENT: RULES AND PLANNING

Acute Medial and Posteromedial Ligament Ruptures

The treatment rationale for patients with acute medial ligament ruptures is shown in Figure 19-4. The algorithm is divided into three major sections based on the extent of injury to the SMCL and PMC/POL. The first- and second-degree injuries are treated initially with a functional brace, weight bearing as tolerated, and rehabilitation as detailed in Chapter 20. Some second-degree injuries may have considerable medial pain and swelling; in these cases, an extension brace is used for the initial 1 to 2 weeks after the injury.

The rule for conservative treatment of all third-degree medial ligament injuries involves the necessity for short-term immobilization to allow the medial ligament structures to heal with the least elongation or laxity by limiting medial joint opening and external tibial rotation. In addition, meniscotibial attachment tears requiring protection for healing may exist. The lower limb is placed in a cylinder cast to allow *stick-down* of the disrupted medial soft tissues. Fiberglass immobilization is required because a soft hinged or functional brace, even if maintained at 0 degrees of extension, does not provide sufficient protection to maintain medial joint line closure to allow close approximation of the disrupted medial ligament and meniscus attachment soft tissues. Patients are allowed toe-touch weight bearing and perform quadriceps isometrics every hour, palpating the muscle tension and increase in thigh volume with their hand. Electrical muscle stimulation is also used. These modalities are important because thigh atrophy can occur even with short-term immobilization.

At 7 to 10 days, the cylinder cast is split into an anterior and posterior shell (Fig. 19-11) and the therapist assists the patient with ROM from 0 to 90 degrees in a figure-four position (Fig. 19-12) with the hip joint externally rotated to protect the healing medial tissues, described in detail in Chapter 38. This protected ROM program is taught to the patient and performed three to four times a day. The split-cylinder cast protection in extension is maintained for three to four weeks, followed by a soft hinged brace. The rehabilitation and crutch-weaning program is detailed in Chapter 20. It must be stressed that the senior author (F.R.N.) has commonly encountered knees referred for treatment in which a complete SMCL injury (and partial-to-complete POL injury) was treated with a soft functional brace where the golden period of the first few weeks after the injury was lost. A residual symptomatic increased medial joint opening and



FIG 19-11 A cylinder cast split into an anterior and posterior shell to allow the patient to perform range of motion exercises.



FIG 19-12 Flexion overpressure exercise in a figure-four position.

external tibial rotation required a chronic medial and posteromedial reconstruction.

It is possible to treat almost all medial ligament injuries (with or without concomitant ACL ruptures) using this conservative stick-down program. Operative treatment is recommended for select cases, as discussed next. A displaced meniscus tear on MRI would indicate the necessity to perform a meniscus repair. When there is an associated ACL tear, the stick-down protocol is followed to treat the medial injury. Then an ACL reconstruction may be performed at an elective time. In high-performance athletes with gross disruption of the SMCL and POL (with or without ACL tear), the senior author prefers to perform an anatomic repair to restore anatomic continuity and function. In addition, in these gross medial disruptions, the repair of the medial meniscus attachments is always required. In select knees with acute SMCL, POL, and ACL injuries, the medial meniscus may be partially dislodged from the joint, and the distal SMCL so extensively displaced or coiled with a reduced chance of protected immobilization, would result in functional medial ligament structures (see Fig. 19-10). An example is the illustrative case described later in this chapter. In our experience, these knees do better with operative repair. For ACL reconstruction, a four-strand semitendinosus-gracilis (STG) autograft may be selected if there is an indication to decrease the morbidity of a bone-patellar tendon-bone (B-PT-B) autograft. We prefer an autograft over allografts for reasons discussed in detail in Chapter 7.

In select acute PCL tears with gross disruption of the SMCL and POL that do not have excessive soft tissue swelling and edema, the senior author prefers an all-inside arthroscopic PCL reconstruction and open medial repair. These knees have a gross amount of medial joint opening and posterior subluxation and surgical stabilization is preferred in younger active patients. Sedentary patients are treated with the stick-down cast program, with a posterior calf pad added to prevent posterior subluxation (confirmed with a lateral radiograph). An SMCL femoral or tibial avulsion may exist in which operative reattachment is indicated through a limited medial approach.

In knees considered for operative intervention, the knee is rehabilitated for 7 days, motion to 90 degrees is obtained, and early quadriceps muscle function is restored. The joint and extremity soft tissue swelling must not be excessive. A routine venous ultrasound is conducted before surgery. In acute medial injuries, it is usually not necessary to perform an augmentation of the repair (described later for chronic reconstructions), because the suture fixation methods restoring ligament continuity and healing after surgery is prompt. However, in select knees, this augmentation option may be required. All knees are treated with an immediate ROM figure-four program as detailed in Chapter 20. Proximal medial ligament disruptions with extensive edema and soft tissue swelling are at risk for ectopic calcification and limitation of joint motion in the first 2 to 3 weeks after surgery. Indomethacin (Indocin) treatment is not routinely administered; however, observation is warranted because indomethacin is effective only if given within the early postoperative course.

Acute Medial Ligament Ruptures With Knee Dislocation

A traumatic knee dislocation with involvement of the medial ligament structures along with the ACL and PCL represents a difficult treatment entity. Too often, these knees have a high incidence of arthrofibrosis after surgery.[71] In our opinion, it is prudent to treat these knees with the stick-down conservative program and manage the associated ACL or PCL injuries at a later time. A posterior calf pad is added to the cylinder cast to maintain a gentle posterior loading and prevent posterior tibial subluxation. Again, a lateral radiograph is obtained to verify tibiofemoral reduction. It is possible for the physical therapist to begin a careful ROM program with the bivalved cylinder cast at the second week as detailed in Chapter 38. In select athletes, under ideal circumstances, operative intervention may be considered; these knee injuries are evaluated and treated on a case-by-case basis. Issues related to evaluation of the vascular system are discussed in Chapter 22. The surgery is delayed for 7 days and the initial rehabilitation program begun, as previously discussed. Consultation is always obtained with exclusion of a vascular injury by repeated evaluation and appropriate diagnostic tests including ankle-brachial indices. A venous ultrasound is obtained. At surgery, the foot and ankle are positioned to allow vascular checks including Doppler, and tourniquet use is avoided or limited to only the initial open exploration to define the injury pattern and is then deflated for the repair procedure.

Chronic Medial and Posteromedial Ruptures

Patients with chronic knee injuries who present with severe muscle atrophy require preoperative rehabilitation and patient education before consideration of surgical reconstruction. Frequently, patients who undergo MCL reconstruction (Fig. 19-13) require a concomitant ACL or PCL reconstruction. The appropriate grafts for the cruciate procedures should be determined, as detailed in separate chapters, and autogenous tissues are preferred. However, the surgeon should ensure that B-PT-B and Achilles tendon-bone allografts are available in multiligament reconstructions if needed and advise the patient of this possible choice.

INTRAOPERATIVE EVALUATION

All knee ligament subluxation tests are performed after the induction of anesthesia in both the injured and contralateral limbs. The amount of increased anterior tibial translation, posterior tibial translation, lateral joint opening, medial joint opening, and external-internal tibial rotation is documented. With ACL and/or SMCL/POL disruptions, the lower portion of the bed is flexed (retroflexion to flex the hip joint and eliminate femoral nerve tension) and flexion of the knee portion is performed as required for the arthroscopic and open approaches (Fig. 19-14, *A*). A leg holder is used for the initial arthroscopic and meniscus procedures and is then removed. An alternative approach used in multiligament and PCL disruptions is to position the lower extremity with the foot in an Alvarado holder or thigh post and foot rest to allow the desired amount of knee flexion during surgery (Fig. 19-14, *B*). The arthroscopic pressure is maintained at a low setting with adequate outflow at all times to prevent fluid extravasation and popliteal and calf swelling, which is documented throughout the case. A thorough

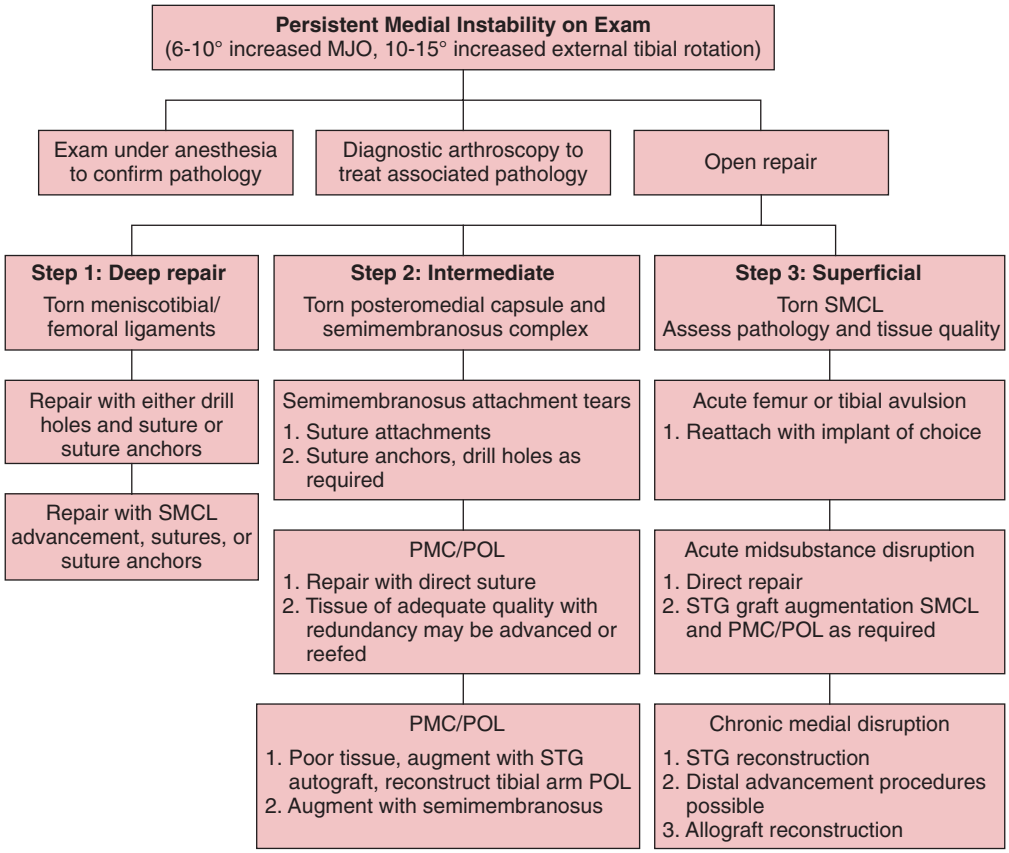


FIG 19-13 Surgical algorithm. *PMC*, Posteromedial capsule; *POL*, posterior oblique ligament; *SMCL*, superficial medial collateral ligament; *STG*, semitendinosus-gracilis.

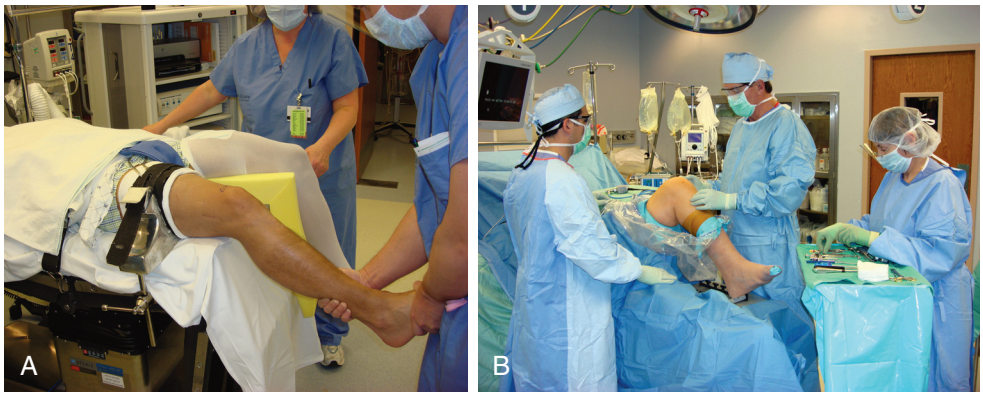


FIG 19-14 **A,** Initial operating room setup and patient positioning. Use of thigh holder to achieve tibiofemoral joint opening, particularly for meniscus repairs. The thigh holder is removed after the arthroscopic procedure. The foot of the bed is placed at 90 degrees of flexion, the bed is placed at 15 degrees for hip flexion, and a soft support is placed under the proximal thigh for the operative approach. **B,** In multiligament injuries with gross instability, a lower extremity leg holder may be used if required to control knee position during the arthroscopic anterior/posterior cruciate ligament reconstruction and associated medial dissection. The medial ligament repair/reconstruction is performed with the knee at 15 to 30 degrees of flexion and a soft tissue pad beneath the thigh.

arthroscopic examination is conducted, documenting articular cartilage surface abnormalities and the condition of the menisci. It is rare to have the complication of fluid extravasation if these precautions are taken; however, if extravasation occurs, an open approach is used throughout the remainder of the procedure.

Medial and lateral tibiofemoral gap tests are done during the arthroscopic examination. The knee is flexed to 30 degrees and a varus and valgus load of approximately 89 N applied. A calibrated nerve hook is used to measure the amount of lateral and medial tibiofemoral compartment opening. Knees with 12 mm or more of absolute joint opening at the periphery of the medial or lateral tibiofemoral compartment indicate gross disruption of all the ligament structures. An absolute opening of 10 mm (~7 mm increase over the contralateral limb) also indicates significant injury to the SMCL and PMC and, along with

increased external tibial rotation, usually represents a problem for athletic patients in twisting and cutting activities.

Appropriate arthroscopic procedures are performed as indicated, including meniscus repairs or partial excision, debridement, and articular cartilage procedures.

SELECTION OF GRAFTS FOR MEDIAL LIGAMENT RECONSTRUCTION

Robinson and associates[62] conducted a cadaveric study in eight unpaired knees (mean age, 77 years; range, 72 to 89 years). The ultimate failure loads of the medial structures were 534 N for the SMCL, 194 N for the DMCL, and 425 N for the PMC (including the central POL arm). Wijdicks and colleagues[72] reported on the failure properties of the medial ligament structures in 20 unpaired cadaveric knees (mean age, 54 years; range, 27 to 68 years). The mean failure loads were 557 N for the SMCL, 88 N for the femoral-to-proximal tibial portion of the MCL, 101 N for the DMCL, and 256 N for the POL. These data provide approximate failure load conditions that are useful for graft substitute decisions.

Noyes and colleagues[53] reported the first biomechanic study of properties of tendons and fascia lata used as ligaments grafts in 18 unpaired knees in younger donors (mean age, 26 ± 6 years) under high strain rate conditions. The mean failure loads of the semitendinosus tendon and the gracilis tendon were 1216 ± 50 N and 838 ± 30 N, respectively. These data imply that a semitendinosus tendon graft would have more than adequate load properties at time zero compared with the patient's native SMCL. It is possible that all of these studies may underestimate the ultimate failure load of the native SMCL because of asymmetric laboratory loading conditions in uniaxial tendons that do not simulate in vivo loading conditions. From a practical standpoint, we use a STG autograft, to be described.

In regard to graft fixation strength for SMCL and POL reconstructions, many different methods have been described.[2,43,69,76] There is a concern for the adequacy of tunnel fixation of a soft tissue graft at the distal SMCL attachment owing to the lack of cancellous tissue. A tibial tunnel Endo Button technique may be selected. Another option keeps the distal STG insertion intact by placing sutures to locate the tendons within the center portion of the distal SMCL fibers. This avoids a nonisometric anterior graft placement and is the senior author's preferred technique. The estimated fixation strength of soft tissue interference screws in the distal tibial SMCL in humans is unknown. In a porcine model, Wijdicks and associates[72] estimated the fixation strength of interference screws in the distal tibial SMCL to be 445 ± 72 N.

There is a lack of consensus in the published literature regarding the selection of grafts to reconstruct the SMCL and POL. Some investigators reconstruct the SMCL alone. The senior author advocates that POL function must always be restored either by plication using the vest-over-pants technique described by Hughston and Eilers[28] or with a graft reconstruction when POL tissues are deficient. Studies that reconstructed only the SMCL have reported acceptable results, to be described later (see Results From Other Clinical Studies). Even so, at surgery, the opportunity exists to repair or reconstruct all of the medial ligament structures and not take the chance that insufficient, unrestored POL function could compromise the overall result. It is relatively straightforward to restore POL function either by plication (in mild to moderate injuries) or graft substitution in cases of gross medial instability. What remains controversial is whether a separate femoral graft tunnel is required for POL reconstruction,[9] or if the femoral graft used for the SMCL can be fixated at a single femoral SMCL attachment and then directed to the POL tibial attachment where it is fixated with either suture, a tunnel and interference screw, or a screw and spiked washer. In multiligamentous reconstructions where operative time needs to be carefully monitored, a single femoral fixation of an STG graft by screw and spiked washer and fixation of the remaining STG graft at the POL tibial attachment site by screw and spiked washer (adjacent to the anterior medial arm of the ST tendon) avoids the complexity of two femoral and tibial tunnels.[41]

OPERATIVE TREATMENT

Acute Medial and Posteromedial Ligament Repairs

The key to the operative procedure is a thorough understanding of the medial anatomy (see Figs. 19-1 to 19-3), because the integrity and injury to the SMCL, POL, semimembranosus attachments, and meniscus attachments (DMCL) need to be identified. The goal is to restore normal anatomy and function of all of these structures. The surgical dissection uses a layered approach[70] following the description provided in Chapter 1 (Fig. 19-15).

Before surgery, the operative extremity is signed by the patient and surgeon with nursing personnel present. A time-out is performed with

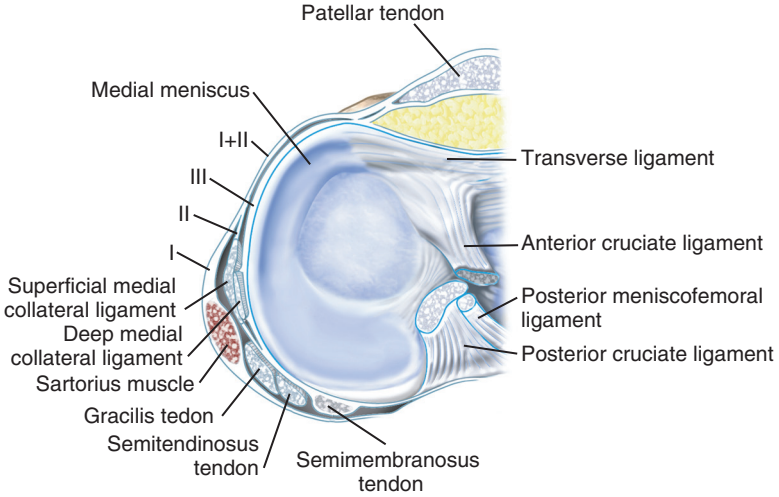


FIG 19-15 Medial layers of the knee. The gracilis and semitendinosus lie between layers I and II.

TABLE 19-3 Operative Steps for Acute Medial Ligamentous Ruptures

1. Use a limited medial approach, dissection of skin flaps beneath fascia and not in subcutaneous tissue to preserve blood supply to overlying skin.
2. Approach carefully avoids superficial nerve structures, protects infrapatellar nerve branches to limit a postoperative neuroma or loss of cutaneous sensation.
3. Incision anterior sartorial fascia extending to anterior border of SMCL, identify pes bursae, posterior retraction of pes tendons, proceed proximal to VMO.
4. Limited medial dissection at the site of injury, but not beyond, with preservation of vascular and nerve supply.
5. Identification of SMCL tear site preoperatively on MRI and confirmation at surgery including medial patellofemoral ligament, which may require repair.
6. Identification of PMC tear site on MRI and operatively at anatomic attachments. There may be an interstitial tear or disruption at femoral or tibial attachments.
7. Identification of semimembranosus attachments and tears at POL and meniscus attachments.
8. Identification of deep MCL and meniscal attachments requiring repair.
9. Appropriate repair of all disrupted structures using nonabsorbable and absorbable sutures to decrease overall suture load. Initial repair proceeds deep to superficial with meniscus attachments meticulously first repaired, usually by sutures or suture anchors.
10. SMCL repairs performed next to provide stable medial column. Repair frequently requires baseball-type sutures fixed to a suture post at attachment site, which provides high-tensile strength for immediate postoperative motion. Avulsion at femur or tibia fixed by screw and soft tissue washer. Suture anchors may be used to supplement repair.
11. Assess need for STG reconstruction of SMCL and POL when extensive medial disruption exists with poor tissue quality for primary repair; will allow increased tissue strength and immediate range of knee motion.
12. Avoid shortening SMCL at the tibial attachment site by fixation too proximal, goal is to restore normal anatomic attachment locations.
13. Avoid placement of tibial staples or other large metallic fixation devices, which frequently are painful and require subsequent repeat surgery.
14. POL repair performed next, frequently requires suture anchor fixation at respective tear site. Anterior portion of POL sutured to posterior SMCL after femoral or tibial attachment repaired. Avoid constraint to full knee extension, which is tested after POL repair.
15. Perform final full knee extension and flexion at operative table to make sure that suture fixation of all soft tissue structures has not constrained normal joint motion.
16. Medial patellofemoral ligament and retinaculum closed with knee at 20 degrees, avoiding overtensioning with a normal lateral patellar glide of approximately one quadrant (25% patellar width) to avoid "capture" of the patellofemoral joint and limited knee flexion.
17. Close sartorial fascia over SMCL, medial repair.
18. Meticulous hemostasis and closure of dead spaces beneath skin flaps to avoid hematoma.
19. Routine closure, double compression bandage with cotton, ice bladder, and soft hinged postoperative brace.

MCL, Medial collateral ligament; *MRI*, magnetic resonance imaging; *PMC*, posteromedial capsule; *POL*, posterior oblique ligament; *SMCL*, superficial medial collateral ligament; *STG*, semitendinosus-gracilis; *VMO*, vastus medialis obliquus.

the patient's name, procedure, allergies, and preoperative antibiotics, special precautions given and agreed upon by the surgeon, anesthetist, and nursing personnel.

The operative steps are outlined in Table 19-3 and Figure 19-13. It is important to perform a careful limited dissection to avoid further disruption of the neurovascular supply of tissues (Fig. 19-16). Based on preoperative MRI and limited medial dissection, it is possible to identify the tear site of the soft tissue structures for the operative repair. A tourniquet is used for the initial exploration and then deflated during the repair portion of the procedure. A limited cosmetic incision along the anteromedial aspect of the tibia provides good exposure for both ACL and medial repairs and is favored over a two-incision approach (Fig. 19-17).

During the initial dissection, an incision is made into the sartorius fascia just anterior to the SMCL and the fascia and pes tendons are reflected posteriorly to allow identification of the medial structures. The tear site of the SMCL is usually easily identified. However, it may be more difficult to recognize the tear site for the PMC capsular arms referred to as the POL divisions (see Fig. 19-2). There may be interstitial tearing of capsular tissues without a definite tear, or the POL may be torn off its femoral or tibial attachment, requiring reattachment. The first goal is to restore normal anatomy. The SMCL, POL, and meniscus sutures are placed to restore anatomic attachment sites (see Table 19-3). After the DMCL and SMCL are repaired, the POL is repaired at 10 to 15 degrees of flexion and the knee is taken to full extension to ensure the sutures are not overtensioned to constrain knee extension and produce a flexion contracture.

The second goal is to perform a meticulous anatomic repair of sufficient strength to allow immediate knee motion following the protocol provided in Chapter 20. Numerous ligament fixation devices are available, and a low-profile screw and soft tissue washer or four-prong staple and screw are favored, along with suture anchors. Standard baseball locking sutures of two to three throws are sufficient to tension soft tissues using a combination of nonabsorbable and absorbable sutures. When the medial ligament disruption is extensive, it is necessary to perform an augmentation graft for the SMCL and PMC (POL division B; see Fig. 19-2) following the techniques outlined in a chronic medial reconstruction with either an STG autograft or allograft approach, as discussed next.

Chronic Medial and Posteromedial Ligament Repairs

The operative steps are the same as outlined for acute medial repairs in terms of the initial surgical approach and dissection. The specific additional steps that apply are provided in Table 19-4.

Based on the extent of injury and integrity of the medial ligament structures, the surgeon has three options that require judgment at surgery. These are (1) advancement of the SMCL and plication of the POL using existing tissues, (2) advancement and plication of existing tissues and graft reconstruction of the SMCL and POL, and (3) onlay SMCL/POL graft reconstruction without use of existing tissues for severe cases of medial ligament disruption.

In Figure 19-17, the cosmetic medial skin incision is shown for a patient who had a combined ACL and MCL reconstruction. The standard ACL skin incision is extended proximally to provide adequate exposure for the medial ligament procedure. Advancement procedures are used only when there has been a robust healing response in the medial ligament structures, with good integrity noted of these tissues that are moderately lax, but otherwise intact. The meniscus

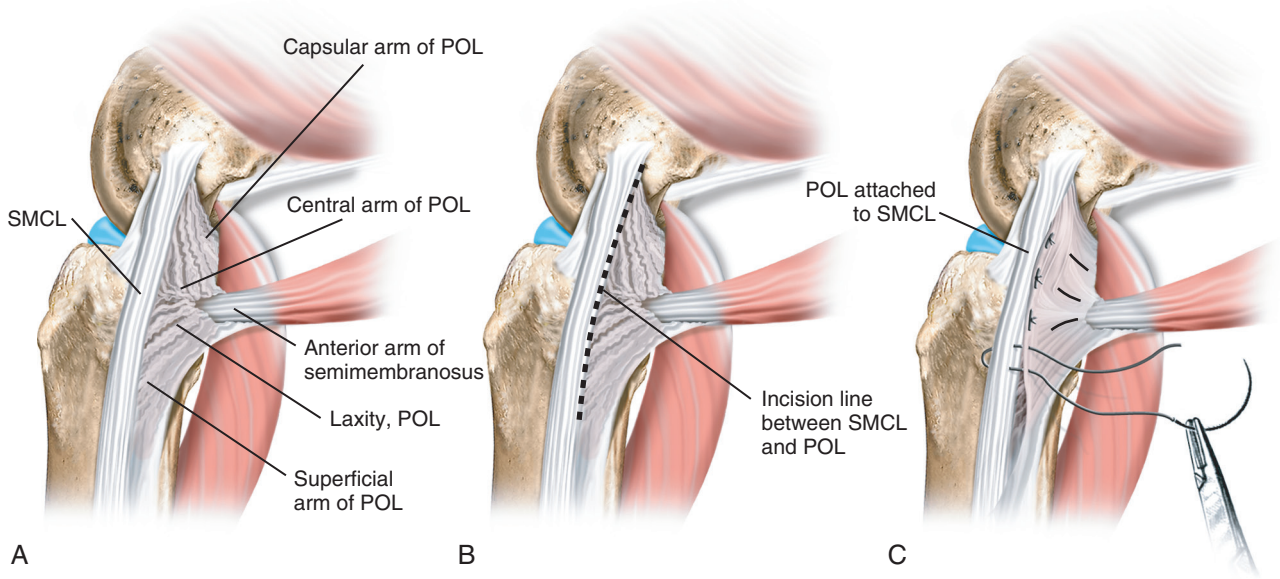


FIG 19-16 Surgical plication procedure for the posterior oblique ligament (POL). **A,** Identification of laxity and redundant POL that involves all three components. In the majority of knees, there will exist concurrent laxity of the superficial medial collateral ligament (SMCL), which also requires surgical reconstruction as described (not shown). **B,** Incision into POL just behind the SMCL, avoiding medial meniscus tibial attachments. Confirm the POL is not avulsed from femoral or tibial attachments because reattachment may be required. **C,** Suture plication vest-over-pants technique to restore tension in the POL, performed at 20 degrees of flexion to avoid overtensioning that would limit full knee extension.



FIG 19-17 **A** and **B,** Cosmetic skin incision of the knee joint in an expert skier, 6 months after bone-patellar tendon-bone anterior cruciate ligament (ACL) autograft and superficial medial collateral ligament, posterior oblique ligament, and displaced medial meniscus repair followed by an immediate motion program. In this knee with a gross medial disruption and a medial meniscus that was displaced into the joint, the decision was made to proceed with a combined arthroscopic and open repair of all structures. An ACL autograft (semitendinosus-gracilis) reconstruction is preferred over an allograft.

TABLE 19-4 Operative Steps for Chronic Medial Ligamentous Ruptures

1. Follow initial exposure steps provided in Table 19-3.
2. Identify integrity and healing of remaining SMCL and POL to select knees in which these structures may be incorporated into reconstruction or in which complete graft replacement of the SMCL and POL is indicated.
3. Place incision along anterior POL border, just posterior to SMCL fibers. Confirm femoral, tibial attachments intact or require reattachment.
4. Identify semimembranosus, attachments, need for reattachment or repair.
5. Place incision along anterior border of SMCL, identify meniscus tibial and femoral attachments that require repair.
6. In some knees when distal SMCL advancement is possible, place fixation at distal attachment site not to shorten SMCL length. It will be first necessary to reattach meniscotibial attachments with suture anchors. Arthroscopy before procedure indicates need for meniscus peripheral repair based on proximal-distal meniscus displacement.
7. PMC plication procedures performed when capsular attachments to femur and tibia are intact and goal is to remove redundancy. Plication to posterior portion of SMCL accomplishes goal of restoring normal PMC tension as knee approaches extension.
8. STG autograft reconstruction of the SMCL and POL is the senior author's preferred choice in chronic cases with poor medial ligament structures that have undergone injury and scar replacement. Harvest STG with closed-end tendon stripper leaving tibial attachments intact. Relocate distal STG to middle of SMCL. Locate isometric point at femur with guide pin and suture, followed by screw and spiked washer fixation. Proceed with remaining STG for POL reconstruction. Suture STG graft to remaining SMCL and POL tissues.
9. Severe loss of all medial tissues requiring complete SMCL replacement treated with long B-PT-B allograft for secure bone fixation at tibial and femoral attachments. Alternative option is Achilles tendon-bone allograft reconstruction with bone placed at femoral attachment and collagenous portion of graft at tibial attachment. Another option is anatomic double-graft SMCL and POL reconstruction.
10. Careful adjustment of medial patellofemoral ligament and medial retinaculum at 30 degrees of knee flexion to restore normal tension and allow normal lateral patellar glide.
11. Closure as detailed in Table 19-3.

B-PT-B, Bone-patellar tendon-bone; *PMC*, Posteromedial capsule; *POL*, posterior oblique ligament; *SMCL*, superficial medial collateral ligament; *STG*, semitendinosus-gracilis.

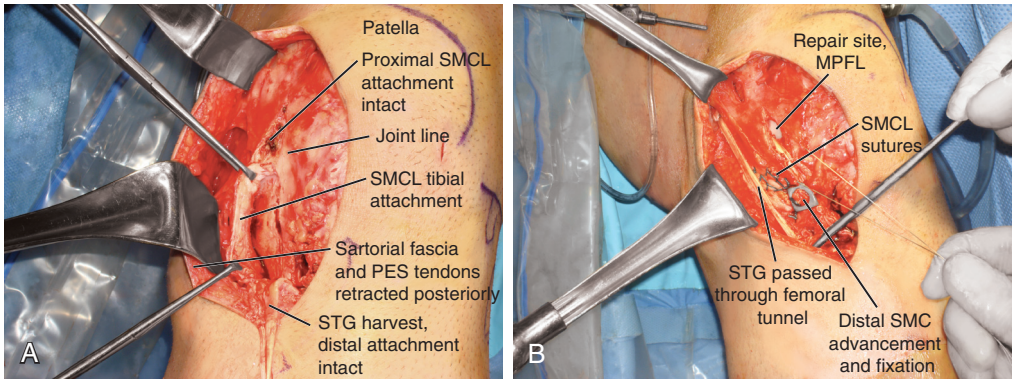


FIG 19-18 Demonstration of distal advancement of the superficial medial collateral ligament (SMCL) with semitendinosus-gracilis (STG) reconstruction for chronic MCL insufficiency. **A,** The SMCL is dissected at its distal attachment and proximally to the joint. Arthroscopic examination showed the medial meniscus attachments would be restored by reattachment of the meniscus tibial attachments, which was performed (not shown). **B,** Distal SMCL advancement supplemented with nonabsorbable baseball sutures through distal SMCL to provide secure fixation. A plication of the posteromedial corner (PMC) to the posterior edge of the SMCL has been performed. The STG tendons are passed through a small-diameter tunnel just anterior to the SMCL attachment and brought out posterior to the attachment and in line with the posterior oblique ligament (POL). The STG tendons are sutured anteriorly to the SMCL and posteriorly to the POL. In some cases, a screw and washer are used for added fixation at the tibial POL attachment (see Illustrative Case). The use of the remaining SMCL provides for additional joint stabilization and the STG reconstruction allows for immediate protected knee motion. *MPFL*, Medial patellofemoral ligament.

attachments medially require appropriate suture fixation to restore the meniscotibial attachment, with distal SMCL advancement. In chronic medial injuries that are extensive, a SMCL reconstruction with STG tendons is required. The STG tendons are tensioned based on isometric length-tension behavior with knee flexion-extension at surgery. In addition, after femoral fixation, the distal portion of the STG graft is used for POL reconstruction.

Following the operative principles outlined in Table 19-4, an example of a distal SMCL advancement supplemented with an STG reconstruction for chronic MCL deficiency is shown in Figure 19-18. In Figure 19-19, a more complex medial reconstructive procedure is shown that involved extensive repair of the meniscus attachments and STG tendon reconstruction of both the SMCL and PMC (POL, see Illustrative Case). The operative procedure provides sufficient strength to allow immediate knee motion postoperatively to lessen the risk of a joint contracture.

The correct attachment points for the STG SMCL graft are at the native femoral and tibial attachments (Figure 19-20). The SMCL

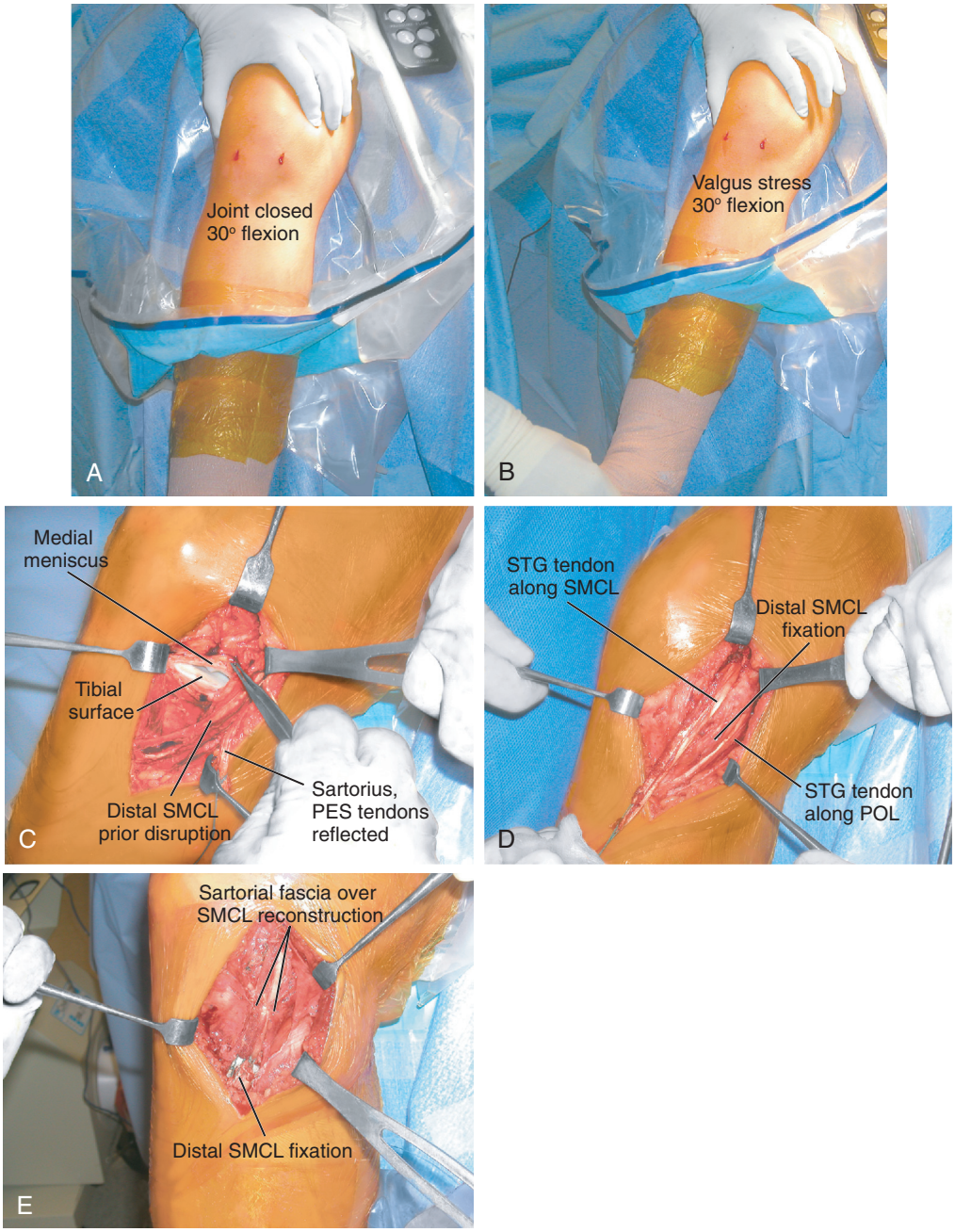


FIG 19-19 A 22-year-old female elite soccer planer referred for treatment for giving-way episodes on cutting movements after a prior partial anterior cruciate ligament and complete disruption of the superficial medial collateral ligament (SMCL) treated conservatively. There was a negative pivot shift and Lachman test; however, there were 12 mm of medial joint opening at 30 degrees, 5 mm of medial joint opening at 0 degrees, and 10 degrees of increased external tibial rotation on the dial test. **A** and **B,** Demonstration of the valgus test at surgery with medial joint opening confirmed on arthroscopic examination. **C,** On surgical exploration, the medial meniscus attachment to the tibia required repair. The proximal SMCL was intact; however, the distal SMCL attachment was the site of the prior disruption. **D,** Semitendinosus-gracilis (STG) tendons left attached distally and advanced to reconstruct the posterior portion of the posterior oblique ligament (POL) were placed through a femoral tunnel from posterior to anterior and brought along the anatomic course of the SMCL. **E,** Final closure; sartorius attachments closed over SMCL that had been advanced distally with STG tendon reconstruction.

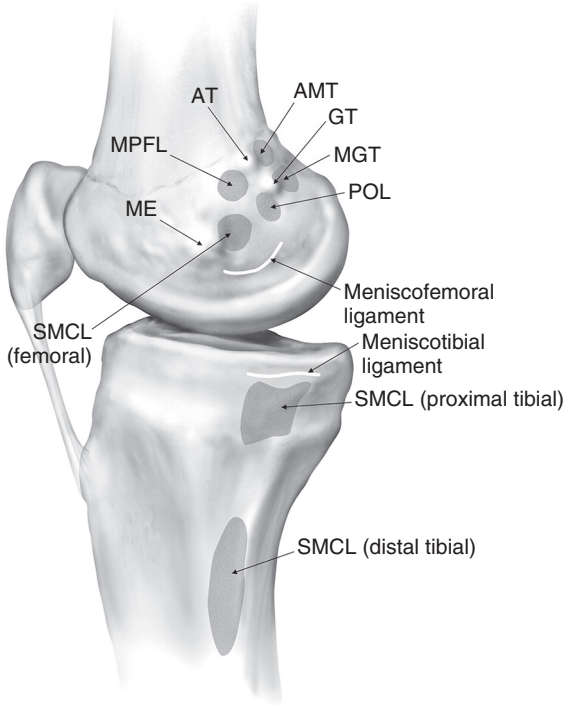


FIG 19-20 The femoral osseous landmarks and attachment sites of the main medial knee structures. *AMT*, Adductor magnus tendon; *AT*, Adductor tubercle; *GT*, gastrocnemius tubercle; *ME*, medial epicondyle; *MGT*, medial gastrocnemius tendon; *MPFL*, medial patellofemoral ligament; *POL*, posterior oblique ligament; *SMCL*, superficial medial collateral ligament. (From LaPrade RF, Engebretsen AH, Ly TV, et al. The anatomy of the medial part of the knee. *J Bone Joint Surg Am.* 2007;89:2000-2010.)

femoral attachment is, on average, 3.2 mm proximal and 4.8 mm posterior to the medial epicondyle. The SMCL has two tibial attachment sites (see Fig. 19-20). Care is taken not to allow the STG graft to be anterior at the SMCL tibial attachment because this portion of the graft is under increased tension with knee flexion. The STG graft is sutured to the middle portion of the SMCL. In some knees, additional screw/washer STG fixation at the distal SMCL attachment may be required. The SMCL femoral graft attachment site is verified by placing a K-wire at the femoral site, attaching suture to the distal tibial site, and taking the knee through a full ROM. A change of 2 to 3 mm in length is acceptable. The POL is reattached to its native femoral or tibial site when proximal or distal disruption has occurred. For capsular redundancy, a plication procedure is performed to the posterior edge of the SMCL graft, which provides the stable medial column for the capsular reconstruction.

In Figure 19-21, the use of a B-PT-B allograft is shown for severe cases of chronic medial ligament disruption. The Achilles tendon is an alternative allograft, with the bone portion placed at the native SMCL femoral attachment and the full-thickness tendon fixed by a screw and soft tissue washer with additional baseball sutures at the native tibial attachment. All of these procedures involve extensive postoperative rehabilitation, which is described in Chapter 20.

COMPLICATIONS

The most frequent complication of medial and posteromedial ligament surgery relates to the approximately 10% of operated knees that will have initial limitations in regaining normal flexion and extension.

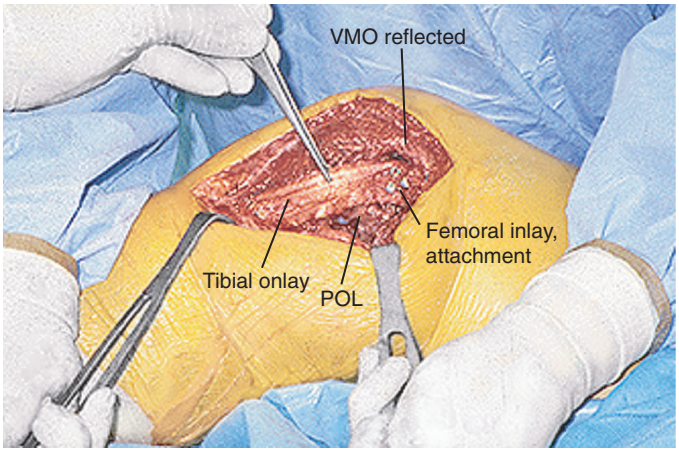


FIG 19-21 Demonstration of the use of a long 25-mm wide bone-patellar tendon-bone (B-PT-B) allograft for a severe medial ligament disruption in which no remaining superficial medial collateral ligament (SMCL) was present. This patient had a prior total knee replacement and presented with complete loss of the SMCL. The bone portions of the graft are placed as an inlay on the femur and as an onlay on the tibia and fixated with cancellous and small fragment screws, respectively. A posterior oblique ligament (POL) plication was performed (see Table 19-4 for operative steps). The procedure was successful and prevented a revision total knee arthroplasty. Because of the large limb and body size, the B-PT-B graft was chosen to provide more secure fixation compared with a semitendinosus-gracilis graft. *VMO*, Vastus medialis oblique.

It is necessary at surgery not to overtighten the POL plication or repair. The repair is performed at 10 to 15 degrees of flexion, and the knee is taken to full extension at the end of the procedure. The SMCL augmentation or replacement is fixated at native femoral and tibial attachments and not overtensioned so as not to constrain the knee joint. The treatment of knee motion limitations, principles of patellofemoral mobilization, and muscle rehabilitation exercises are covered in detail in Chapter 20.

We use a 5-day course of maximum-dose nonsteroidal antiinflammatory medication, which begins the night before surgery. A firm double compression wrap and cotton dressing, ice delivery system, and elevation are used for the first week after surgery. Patients are carefully examined preoperatively and postoperatively for deep venous thrombosis, with ultrasound used on all acutely injured knees before surgery and postoperatively if warranted. After surgery, patients use calf compression venous return devices, and ankle pumps are performed hourly. Aspirin prophylaxis (325 mg 2 ×/day for 7 days) is prescribed. It is important to establish that there is no family history of DVT or blood clot formation, because there is a 2% to 5% incidence of inherited coagulation defects.

The complication of infection is rare with the use of preoperative intravenous antibiotics at appropriate doses, careful handling of tissues, and other precautions as detailed in Chapter 7. A femoral nerve block may be used for pain control.

OUR CLINICAL STUDY

A prospective study was conducted to determine the outcome of 46 knees with acute ACL-MCL ruptures in which all patients received an ACL reconstruction and either conservative or operative management of the medial ligament injury, based on the extent of the injury.[52] The inclusionary criteria were a complete rupture of the ACL, rupture to a

TABLE 19-5 Medial Joint Opening to Manual Valgus Stress Testing at 5 Degrees and 25 Degrees of Knee Flexion (mm)

Difference: Involved–Noninvolved (mm)	GROUP I (*N*)				GROUP II (*N*)			
	PREOPERATIVE		FOLLOW-UP		PREOPERATIVE		FOLLOW-UP	
	5 Degrees of Flexion	25 Degrees of Flexion	5 Degrees of Flexion	25 Degrees of Flexion	5 Degrees of Flexion	25 Degrees of Flexion	5 Degrees of Flexion	25 Degrees of Flexion
0-3	0	0	33	33	12	3	11	11
4-5	19	2	0	0	0	6	0	0
6-10	15	27	0	0	0	3	0	0
11-15	0	5	0	0	0	0	0	0

From Noyes FR. Barber-Westin SD. The treatment of acute combined ruptures of the anterior cruciate and medial ligaments of the knee. *Am J Sports Med.* 1995;23:380-391.

portion or all of the medial ligamentous structures, no rupture to the other knee ligaments, and reconstruction performed within 10 weeks of the original knee injury.

Group I consisted of 34 patients who sustained a complete rupture to the SMCL and PMC that had acute repair and ACL reconstruction. The medial meniscus was repaired in 12 knees and the lateral meniscus was repaired in seven knees. The patients were followed a mean of 5.7 years (range, 2-8.9 years) postoperatively.

Group II consisted of 12 patients who sustained a complete rupture to the SMCL/PMC who were treated without surgery for the medial ligament injury, followed by a staged ACL reconstruction. The medial meniscus was repaired in three knees and the lateral meniscus was repaired in six knees. The patients were followed a mean of 4.1 years (range, 2.2-5.6 years) postoperatively.

At follow-up, no patient had more than 2 to 3 mm of increase in medial joint opening (Table 19-5). Healing was demonstrated in both the surgically repaired complete medial ligament disruptions and in the conservatively treated knees with SMCL disruption. The ACL reconstructions were rated (based on knee arthrometer and pivot shift testing) as normal in 61% in group I and in 82% in group II; nearly normal in 21% in group I and in 18% in group II; and failed in 18% of group I.

Before the injury, all patients except one were participating in sports activities (Table 19-6). At follow-up, all except three patients in group I had returned to athletics, although over half had returned to a lower level of participation. Seven patients in group I had significant difficulty squatting or kneeling. More patients in group I had swelling and pain with sports activities than those in group II (Fig. 19-22).

The rehabilitation program and early treatment of knee motion limitations successfully restored at least 0 to 135 degrees of knee motion in 96% of the patients. The treatment program of knee motion limitations, described in Chapter 38, was instituted in 24% of the knees (26% of group I and 17% of group II). Patients with ruptures at or proximal to the medial joint line had a higher incidence of motion complications (7 of 15 patients, 47%) than those with ruptures located distal to the joint line (2 of 18 patients, 11%). Similar findings were reported by Robins and associates.[61]

The overall rating scores for group I, based on the CKRS, were excellent/good in 19 patients, fair in seven, and poor in seven. For group II, the overall ratings were excellent/good in 10 patients and fair in one. Seven of the patients with a fair or poor rating had failure of the ACL allograft reconstruction; we advocate autogenous B-PT-B grafts for this procedure. At the time of the study, we used irradiated allografts and, as discussed in Chapter 7, the irradiation process appeared to increase the rate of failure compared with other studies in which fresh-frozen allografts were selected. The results of this study and other investigations[5,48,50,57,67] promoted a worthwhile reevaluation of the recommendation for operative management of both ACL and medial ligament ruptures.

TABLE 19-6 Sports Activities Before Injury and at Follow-up

Sport	PREOPERATIVE		FOLLOW-UP	
	Group I, *n* (%)	Group II, *n* (%)	Group I, *n* (%)	Group II, *n* (%)
Jumping, pivoting, cutting	21 (62)	8 (67)	9 (26)	4 (33)
Running, twisting, turning	9 (26)	4 (33)	10 (29)	5 (42)
Swimming, cycling	3 (9)	0	12 (35)	3 (25)
None	1 (3)	0	3 (10)	0
Change in sports activities:				
Same level, no symptoms			8 (23)	3 (25)
Decreased level, no symptoms, knee related			17 (50)	6 (50)
Decreased level, no symptoms, not knee related			3 (9)	3 (25)
Participating with symptoms			3 (9)	0
No sports, knee related			3 (9)	0
No sports, not knee related			0	0

From Noyes FR. Barber-Westin SD. The treatment of acute combined ruptures of the anterior cruciate and medial ligaments of the knee. *Am J Sports Med.* 1995;23:380-391.

RESULTS FROM OTHER CLINICAL STUDIES

Historically, studies have presented various treatment options for MCL injuries. One problem in the analysis of the literature is that the severity of the medial ligamentous injuries varies and, in many instances, is difficult to interpret owing to the ambiguous terminology used to describe the degree or grade of the injury and the lack of data on the estimated (or measured) millimeters of medial joint opening (at both 30 degrees and 0 degrees of knee flexion) before and after treatment.

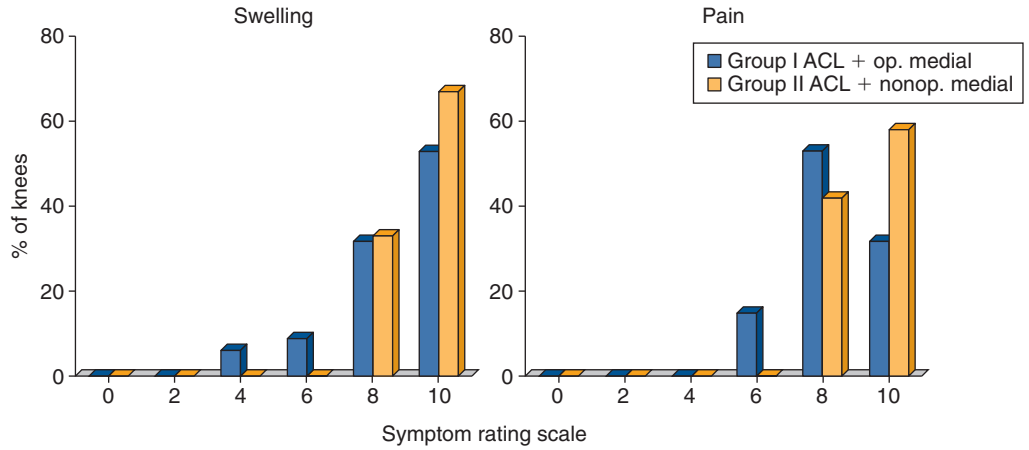


FIG 19-22 The postoperative distributions of swelling and pain scores are shown. 0, Severe symptoms with activities of daily living; 2, moderate symptoms with activities of daily living; 4, no symptoms with activities of daily living but symptoms with sports; 6, no symptoms with swimming or cycling but symptoms with other sports activities; 8, no symptoms with running, twisting, or turning, but symptoms with jumping, hard pivoting, or cutting; 10, no symptoms with jumping, hard pivoting, or cutting. *ACL*, Anterior cruciate ligament; *nonop.*, nonoperated; *op.*, operated. (From Noyes FR, Barber-Westin SD. The treatment of acute combined ruptures of the anterior cruciate and medial ligaments of the knee. *Am J Sports Med.* 1995;23:380-391.)

Therefore the exact structures that are ruptured (and those that remain intact) in many studies are unknown. In light of this issue, investigators have begun using stress radiography to measure medial joint space opening at 20 to 30 degrees of knee flexion before and after treatment, which is a reliable method to quantify medial tibiofemoral compartment opening.[11,22,38,41,44,74,75] Using valgus stress radiographs, LaPrade and associates[40] reported that a mean increase in medial joint space opening of 3.2 mm occurred at 20 degrees of flexion (10-N valgus load) in cadaver lower extremities with a simulated grade III SMCL injury (versus the intact state). Intraobserver repeatability and interobserver reproducibility intraclass correlation coefficients were 0.99 and 0.98, respectively.

Truly isolated MCL injuries are rare and the few studies published in the 1980s and 1990s showed that reasonable results could be obtained with a program of protective bracing and rehabilitation (Table 19-7).[34,35,45,56,59] During this time period, acute MCL ruptures that occurred with other knee ligament injuries (usually the ACL) were treated by some surgeons with primary suture repair.[3,4,15,26,29,61,64] Other studies reported successful nonoperative management of SMCL ruptures provided the ACL was either intact or reconstructed.[5,24,27,33,34,36,48,57,67] Halinen and coworkers[22] published to date the only study of acute grade III medial ligament ruptures (defined as >10-mm increase in medial joint opening at 25 degrees of flexion and a subtle increase at 5 degrees of flexion) that were randomized to either a primary repair or conservative management group. All 47 patients in the study also had complete ACL ruptures that were reconstructed with a B-PT-B autograft. At follow-up, a mean of 2.2 years postoperatively, stress radiographs revealed a mean increase in medial joint opening of 0.9 mm (range, −0.8 to 3.6 mm) in the SMCL-operatively treated group, and 1.7 mm (range, −0.5 to 6.4 mm) in the SMCL-conservatively treated group. The SMCL-conservatively treated group had a faster restoration of knee flexion and quadriceps muscle power.[21] Halinen and coworkers[22] concluded that SMCL ruptures do not require operative treatment.

The majority of studies published since 2004 recommend initial conservative management of nearly all acute MCL injuries owing to the self-healing capability of this ligament.[17,23,46,48,63,73] Exceptions to this strategy have been discussed in detail earlier in this chapter.

Surgery for MCL ruptures is usually reserved for failure of nonoperative treatment according to symptoms[51] and the severity of medial instability (Table 19-8). A variety of reconstructive procedures have been described for severe and symptomatic medial instability. Although the effectiveness of some operative techniques has yet to be determined clinically,[2,7,43,69] many investigations have reported satisfactory restoration of function of the MCL, with few complications (see Table 19-8).[29,55]

Achilles tendon allografts[11,41,44,47] and semitendinosus[37,38,42] or STG[74] autografts have been used to reconstruct chronic MCL insufficiency. Operative techniques either reconstruct the SMCL alone or also reconstruct or repair the POL. It appears more appropriate to refer to the anatomic structure reconstructed, rather than to reference a technique as either a single- or double-bundle procedure. The major differences among studies are the grafts used and the number of femoral graft site locations (one versus two), addressing the need for further clinical studies. Plication techniques for the POL still have a role along with a SMCL graft reconstruction, as previously discussed. All injured or deficient medial ligament structures should be restored.

Liu and associates[44] found Achilles tendon allografts effectively resolved chronic, symptomatic valgus instability in 16 patients that were followed from 2 to 5.5 years postoperatively. Stress radiographs revealed a mean of 1.1 mm (range, −1.1 to 3.2 mm) of increased medial joint opening compared with the opposite knee. Dong and coworkers[11] performed a double MCL allograft reconstruction in 56 patients, 68% of whom also had anteromedial rotatory instability. The mean amount of medial joint opening on stress radiographs was reduced from 10.1 ± 0.05 mm before surgery to 2.9 ± 1.2 mm ($P < .05$) at follow-up that ranged from 6 to 27 months. There was no difference in results between isolated MCL and combined MCL-ACL injuries. LaPrade and colleagues[41] used two allografts to replace both the SMCL and the POL in 28 patients; both grafts were placed in the anatomic attachment sites of these structures. A mean of 1.5 years postoperatively, stress radiographs showed a mean of 1.3 mm (range, −1 to 2 mm) of increased medial joint opening, which was improved from the mean of 6.2 mm (range, 3.5-14 mm) measured before surgery. We LaPrade et al[41] concluded the procedure was effective in patients with chronic, symptomatic grade III instability.

TABLE 19-7 Results of Treatment of Isolated Medial Collateral Ligament Ruptures

Study	N	Follow-up	MCL Grade, Medial Joint Opening	Treatment of MCL	Follow-up Medial Joint Opening	Follow-up Symptoms, Function, Activity Level	Reinjuries	Recommendations
Lundberg & Messner[45] (1996)	38	10 yr	Grade I: 16 Grade II: 22	Early function rehabilitation, weight bearing as soon as tolerated	No increase: 31 Grade I: 7	Slight reduction knee function and sports activity levels, unknown if knee-related.	4 MCL reinjury, 2 ACL injuries; 5 ACL injuries on other knee	Isolated partial MCL ruptures successfully managed without surgery. Unusually high incidence of subsequent ACL rupture (~20%).
Petermann[56] (1993)	102	86 followed mean 3.6 yr	30 degrees 1+ (≤5 mm): 39 2+ (6-10 mm): 41 3+ (>10 mm): 6	Cast brace 4 wk, ROM 10-90 degrees, weight bearing as tolerated, return to activity 8 weeks	No increase in all except 2 knees with 1+ instability	97% returned to previous activity level	None	Isolated MCL injuries can be successfully managed nonoperatively.
Reider[59] (1994)	36	34 completed questionnaires, 30 examined 2.5-8 yr	Grade III (tenderness over MCL, abnormally increased valgus laxity, soft endpoint in flexion)	Lateral hinged brace, weight bearing as tolerated, ROM, supervised therapy program	No increase: 8 <5 mm: 17 6-9 mm: 5	23 patients had at least 1 residual symptom. 18 patients had mild pain. 11 patients had feeling of looseness. All returned to preinjury sports, 7 at a lower level.	7 new knee injuries, 6 during football	Early functional rehabilitation isolated grade III MCL injuries effective, but residual symptoms common. Unknown correlation with reinjuries; longer follow-up required.
Indelicato et al[34] (1990)	28 football players	21 followed 18-72 mo	Grade III (>10-mm medial opening 30 degrees, soft endpoint)	Immobilized 2 wk, 4 wk brace 30-90 degrees, weight bearing as tolerated, rehabilitation	No increase: 8 1+ (<5 mm): 13	18 returned contact drills mean 9.2 weeks	None	Conservative management for grade III MCL tears is successful as long as there is no damage to ACL or menisci.
Jones[35] (1986)	22 football players	followed mean 6 mo	Grade III	Immobilized 1 wk in brace, then ROM allowed with weight bearing as tolerated, supervised rehabilitation as required	All 0-1+	All returned to football 24-38 days after injury	None; 1 ACL rupture missed at initial diagnosis	Conservative management for isolated grade III MCL injuries gives satisfactory short-term results.

ACL, Anterior cruciate ligament; *MCL*, medial collateral ligament; *ROM*, range of motion.

TABLE 19-8 Results of Operative Treatment of Chronic Combined Medial Collateral Ligament–Anterior Cruciate Ligament Injuries

	DEMOGRAPHICS			LIGAMENT RUPTURES							
Study	N	F/U (yr)	Inj-Surg	MCL	Others	Treatment of Ligament Ruptures	Follow-up Medial Joint Opening*	Follow-up Other Reconstructed Ligaments†	Follow-up IKDC Overall Ratings†	Follow-up Symptoms, Function, Activity Level	Complications
Liu et al[44] (2013)	16	2.8 (2-5.5)	24 d to 84 mo	IKDC grades: 12 C, 4 D	12+ PCL, 5+ ACL, 7+ PL	SMCL: AT-B allograft; all other ligaments reconstructed, grafts NA	Stress x-ray I-N: mean 1.1 mm (–1.1 to 3.2)	KT-1000 I-N: mean 1.8 mm (1-2.8) Pivot shift negative in 4, 1+ in 1 Posterior stress x-ray I-N: mean 3.3 mm (0.2-5.8)	94% A, 6% B	Significant improvement IKDC and Lysholm scores	3 patients lacked 10 degrees of flexion, 1 lacked 20 degrees of flexion
Kitamura et al[38] (2013)	30	2-12.6	3-216 mo	All grade III	16+ ACL, 5+ PCL, 9+ ACL, PCL	MCL: doubled ST autograft ACL: STG or B-PT-B autograft PCL: STG autograft	Stress x-ray I-N: mean 0.05 mm; 87% <3 mm, 13% 3-5 mm	Pivot shift: all IKDC A/B except 1 C PCL KT-1000 70 degrees I-N: mean 2.8	30% A, 56% B, 10% C, 3% D	No preoperative data; Lysholm score mean >94 points in all 3 groups	5 patients lacked 6-15 degrees of flexion, 2 lacked 16-25 degrees of flexion
Dong et al[11] (2012)	56	2.7 (1.5-5)	6-27 mo	IKDC grades: 25% C, 75% D	29+ ACL	MCL: double-bundle allograft ACL: double-bundle allograft	Stress x-ray I-N: mean 2.9 mm Slocum test anteromedial rotatory instability "incidence" 9%	Not given	59% A, 36% B, 5% C	Significant improvement in IKDC subjective score; 91% returned to normal/ near-normal sports activity level	4 patients lacked >6 degrees extension, 2 lacked >25 degrees of flexion; 9 patients had abnormal pain on medial side of knee
Marx & Hetsroni[47] (2012)	14	2-5.1	2-12 mo	All grade 2+ (6-10 mm) or 3+ (>10 mm)	12+ ACL, 1+ PCL, 1+ ACL, PCL, PL	MCL: AT-B allograft; all other ligaments reconstructed, grafts NA	11 patients no increase, 3 patients grade 1+	All normal except 2 grade 2+ pivot shift	None	Symptoms and function inferior in 5 ACL revision knees; 7 ACL primary knees returned to preinjury activity levels; no preoperative data	2 patients lacked 15 degrees of flexion
LaPrade et al[41] (2012)	28	0.05-3	NA	All grade III, stress x-ray I-N: mean, 6.2 mm (3.5-14)	8+ ACL, 9+ PCL, 9+ ACL, PCL	MCL: 2 allografts to reconstruct SMCL & POL	Stress x-ray I-N: mean 1.3 mm (–1 to 2)	No recurrent laxity of cruciate ligament reconstruction	Not given	Improved IKDC subjective score from 43.5 to 76.2	1 infection

Continued

TABLE 19-8 Results of Operative Treatment of Chronic Combined Medial Collateral Ligament–Anterior Cruciate Ligament Injuries—cont'd

	DEMOGRAPHICS			LIGAMENT RUPTURES						
Study	N	F/U (yr)	Inj-Surg	MCL	Others	Treatment of Ligament Ruptures	Follow-up Medial Joint Opening*	Follow-up Other Reconstructed Ligaments†	Follow-up IKDC Overall Ratings†	Follow-up Symptoms, Function, Activity Level	Complications
Canata et al[8] (2012)	36	3 (2-7)	8-136 wk	11 grade II, 25 grade III	All positive external rotation 30, 90 degrees. All complete ACL rupture.	MCL: mini-invasive MCL plasty, sutured MCL/POL proximally to medial epicondyle ACL: B-PT-B autograft	No increase in valgus stress, external tibial rotation	All IKDC A/B, objective evaluation	83% A, 17% B	Significant improvement in KOOS scales; 75% returned to preinjury activity level, 11% no sports fear of reinjury, 14% no sports non-knee-related reasons	None
Lind et al[42] (2009)	50	3.3 (2.1-5.6)	all >2 mo	All IKDC C or D	28+ ACL, 4+ ACL, PL, 3+ ACL, PCL, 1+ PCL, PL, 1+ PCL	MCL: ST autograft (tibial attachment preserved) to reconstruct MCL & POL ACL/PCL/PL: autografts or allografts	98% IKDC A, B; 2% C	MCL: 98% IKDC A, B ACL: 96% IKDC A	83% A, B	6 returned Tegner score to ≥6, 40 returned to recreational sports, 4 had problems with daily activities; 91% satisfied	1 infection, 1 reoperation for arthrofibrosis, 1 total knee arthroplasty
Kim et al[37] (2008)	26	4.3 (2.1-7.7)	3-53 mo	Stress x-ray I-N: mean, 7.8 mm (range, 5-12)	12+ ACL, 6+ PCL	MCL: ST autograft (tibial attachment preserved) to reconstruct MCL & POL ACL: B-PT-B autograft PCL: AT allograft	Stress x-ray I-N: mean 1.1 mm (0-5), 92% <2 mm	ACL: 92% IKDC A, B PCL: 83% IKDC A, B	50% A, 42% B, 8% C	Lysholm 80-100 points; no preoperative data	1 infection
Yoshiya, et al[74] (2005)	24	2.2 (2-4)	4-204 mo	Gross medial instability, no firm endpoint	12+ ACL, 7+ PCL, 3+ ACL, PCL	SMCL: STG autograft ACL/PCL: contralateral B-PT-B or QT autograft	Stress x-ray I-N: mean 0.2 mm (–1 to 2 mm)	ACL KT-1000: 7, <3 mm 5, 3-5 mm PCL stress x-ray: 1, <3 mm 4, 3-5 mm 2, >5 mm	Symptoms: 88% A, B, 12% C	3 patients had pain and instability with light activities	None

*All stress x-rays done at 20 degrees of knee flexion.
†A, normal; B, nearly normal; C, abnormal; D, severely abnormal.
ACL, Anterior cruciate ligament; *AT-B*, Achilles tendon-bone; *B-PT-B*, bone-patellar tendon-bone; *F/U*, follow-up; *IKDC*, International Knee Documentation Committee; *I-N*, involved-noninvolved; *Inj- Surg*, interval between injury and surgery; *KOOS*, Knee Injury and Osteoarthritis Outcome Score; *MCL*, medial collateral ligament; *NA*, not available; *PCL*, posterior cruciate ligament; *PL*, posterolateral; *POL*, posterior oblique ligament; *QT*, quadriceps tendon; *SMCL*, superficial medial collateral ligament; *ST*, semitendinosus; *STG*, semitendinosus-gracilis.

Both Lind and colleagues[42] and Kim and coworkers[37] used an ST autograft, whose tibial attachment was left intact, to reconstruct both the MCL and POL. Lind and colleagues[42] followed 50 patients from 2.1 to 5.6 years postoperatively and reported that all but one had normal or nearly normal restoration of medial stability. Kim and coworkers[37] included 26 patients in their series who were followed from 2.1 to 7.7 years after surgery. Medial joint space opening on stress radiographs improved from a mean of 7.8 mm (range, 5-12 mm) preoperatively to 1.1 mm (range, 0-5 mm) postoperatively. Yoshiya and associates[74] used an STG autograft to restore the anterior longitudinal portion of the SMCL in 24 patients with chronic, gross medial instability who were followed from 2 to 4 years postoperatively. Stress radiographs showed a mean of 0.2 mm (range, −1 to 2 mm) of increased medial joint opening at follow-up, which was significantly improved from a mean of 4.1 mm (range, 3-6 mm) measured before surgery ($P < .05$).

In summary, these studies show that different types of medial surgical procedures have very similar success rates. However, the studies are level IV, with no investigation to date having a sufficient number of patients to perform a level I study.

ILLUSTRATIVE CASE

Acute Combined ACL, PCL, SMCL, POL Ligament Disruption With Staged Medial Ligament Reconstruction

A 52-year-old real estate executive fell from a ladder and sustained a knee dislocation with gross disruption of the medial ligaments, ACL, and PCL. The neurovascular examination that included a computed tomography angiogram was intact. He was referred 10 days after the injury and physical examination showed moderate swelling of the extremity, a positive Lachman, 8 mm of increased posterior tibial translation at 90 degrees of flexion, and 15 mm of valgus opening at 0 degrees and 30 degrees of flexion. After a negative venous Doppler was obtained, reconstruction and repair of all of the medial ligament structures was performed (Fig. 19-23 to 19-25). Rehabilitation was begun the first postoperative day with ROM (0 to 90 degrees 3 times/day for 3 weeks) and was progressed as described in Chapter 20. In view of the

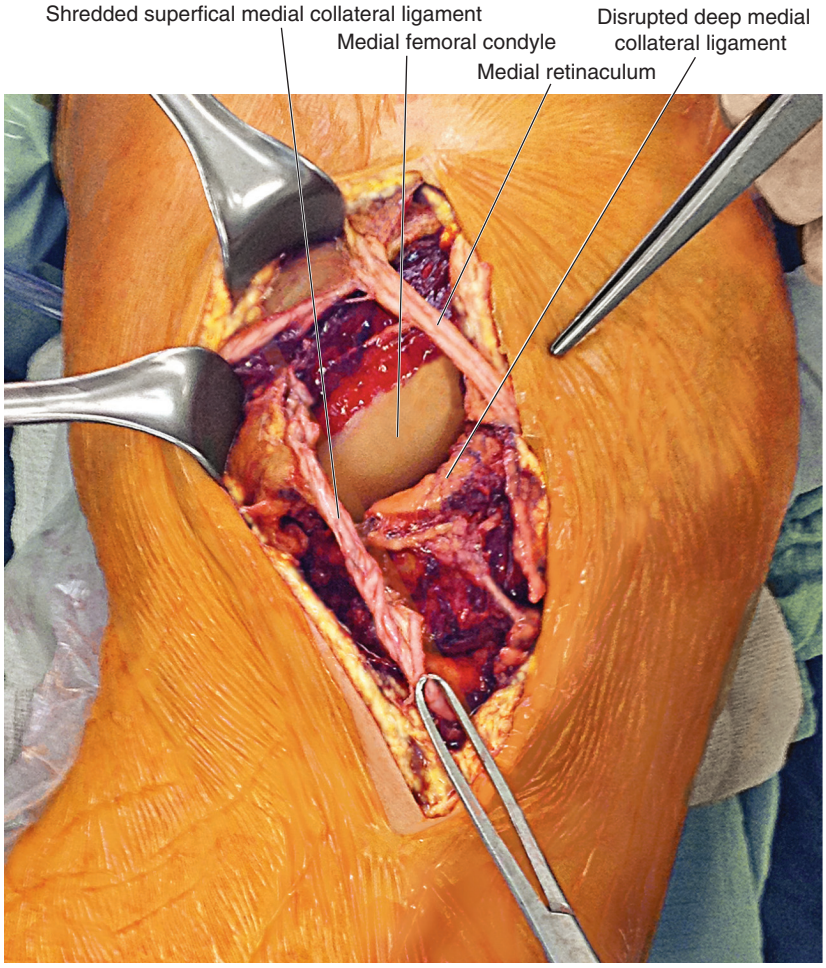


FIG 19-23 Exploration at surgery shows a shredded superficial medial collateral ligament and deep medial collateral ligament. The posterior oblique ligament is disrupted from its tibial attachment. Note the prominent infrapatellar nerve, which was saved.

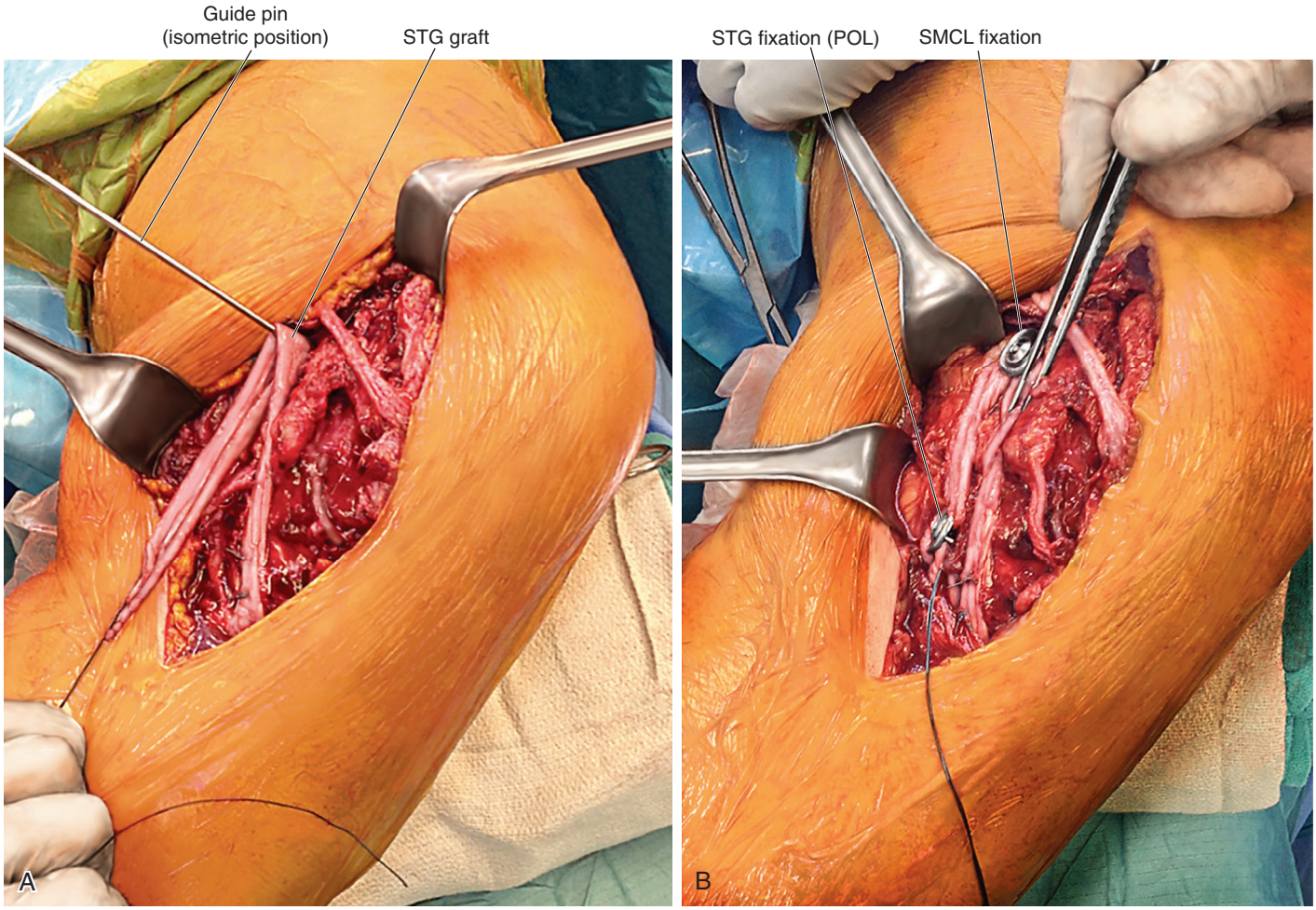


FIG 19-24 A, Repair is performed of the remaining fibers of the posterior oblique ligament (POL), deep medial collateral ligament, and superficial medial collateral ligament (SMCL) to the tibia. Then, a large-diameter semitendinosus-gracilis (STG) graft is passed over a pin just proximal and slightly posterior to the medial epicondyle to determine the correct isometric femoral point that is then fixated with a screw and spiked washer at 30 degrees of flexion, neutral tibial rotation. The STG is fixated at the middle of the distal SMCL fibers. **B,** The remaining STG is brought to the POL tibial attachment for screw and spiked washer fixation at 10 degrees of flexion, neutral tibial rotation.

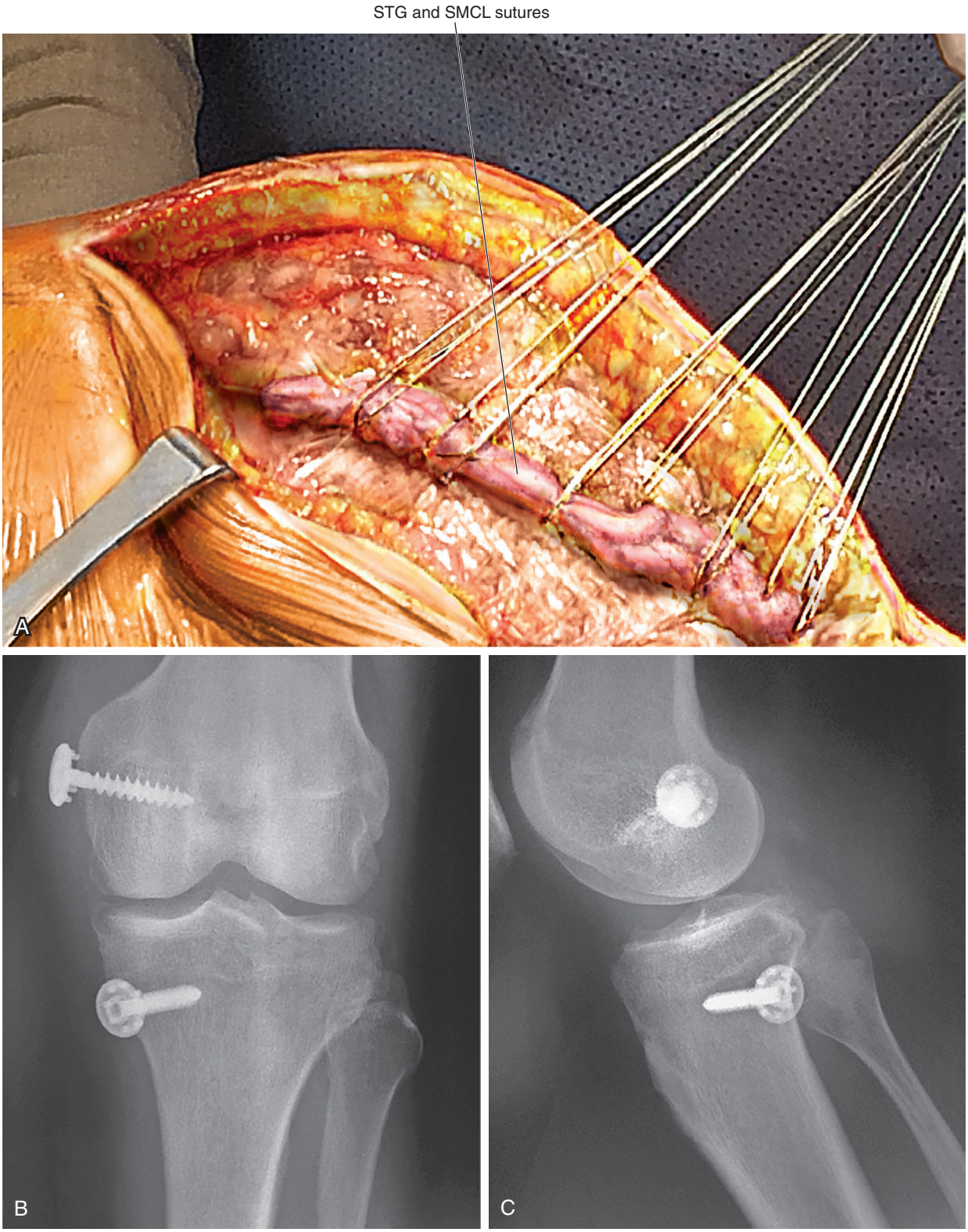


FIG 19-25 A, After the semitendinosus-gracilis (STG) graft and the superficial medial collateral ligament (SMCL) and posterior oblique ligament reconstruction, the remaining SMCL is sutured to the STG graft along the distal and proximal tibial attachments. The sartorial fascia is reflected under the retractors and later brought over the STG reconstruction. Anteroposterior **(B)** and lateral **(C)** radiographs show femoral STG fixation and POL-STG tibial fixation.

medial soft tissue swelling and edema, the decision was made to reconstruct all of the medial ligamentous structures, followed by a period of healing and rehabilitation, and staged elective ACL and PCL reconstruction. An exception would be if there was gross posterior subluxation in which a PCL reconstruction would be required concurrently with the medial reconstruction. The patient regained full range of movement and restoration of normal medial ligament stability.

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Video Content

Video 1-1
Video 3-1

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20

Rehabilitation of Medial Ligament Injuries

Timothy P. Heckmann, Sue D. Barber-Westin, Frank R. Noyes

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VIDEO CONTENT

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CLINICAL CONCEPTS

Medial ligament injuries are among the most frequently treated problems of the knee joint. Whereas isolated superficial medial collateral ligament (SMCL) ruptures are common, concomitant damage to the anterior cruciate ligament (ACL) occurs in many cases, especially in younger active patients.[1,2,6] The majority of isolated acute injuries that involve damage to the SMCL alone, or to the SMCL and posteromedial capsule (PMC), do not require surgery.[8] Patients who have medial ligament tears classified as first-degree (tear involving a few fibers), second-degree (partial tear, no instability, ≤3 mm of increased medial joint opening), or third-degree (complete rupture) who demonstrate either a mild to moderate increase in medial joint opening at 30 degrees of flexion and no increase at 0 degrees do not require acute medial ligament reconstruction. These knees are treated with the conservative rehabilitation program; if concomitant injury exists to other ligaments, the decision of whether to reconstruct those structures is based on the extent of the injury, patient goals, and other issues addressed for the ACL in Chapter 7, the posterior cruciate ligament (PCL) in Chapter 16, and the posterolateral ligament structures in Chapter 17.

An acute third-degree injury consisting of gross major disruption of all of the medial structures (SMCL, deep medial collateral ligament, meniscus attachments, PMC, posterior oblique ligament [POL], and semimembranosus attachments), either alone or in combination with cruciate ligament tears, often requires surgical intervention. In these knees, large increases in medial joint opening are present at 30 degrees of flexion, and at least 5 mm of increased medial joint opening exists at 0 degrees. In addition, repair of medial meniscus attachments is indicated to retain meniscus function. Chronic deficiency of the medial ligament structures that causes partial giving-way during athletic activities may require reconstruction. In these knees, partial or complete ACL deficiency is frequently noted. The indications for medial ligament surgery and the appropriate candidates are discussed in detail in Chapter 19.

CONSERVATIVE TREATMENT OF MEDIAL LIGAMENT INJURIES

The goals of rehabilitation of medial ligament injuries are as follows:

- Provide appropriate protection initially after the injury to allow the disrupted medial ligament structures to "stick-down" and heal with the least amount of residual ligament elongation or abnormal medial joint opening.
- Control joint pain, swelling, and hemarthrosis.
- Regain a normal range of knee motion.
- Restore a normal gait pattern and neuromuscular stability for ambulation.
- Recover normal lower limb muscle strength.
- Regain normal proprioception, balance, coordination, and neuromuscular control for desired activities.
- Achieve optimal functional outcome based on orthopedic and patient goals.

The treatment rationale for patients with acute medial ligament ruptures is shown in Figure 20-1. The algorithm is divided into three

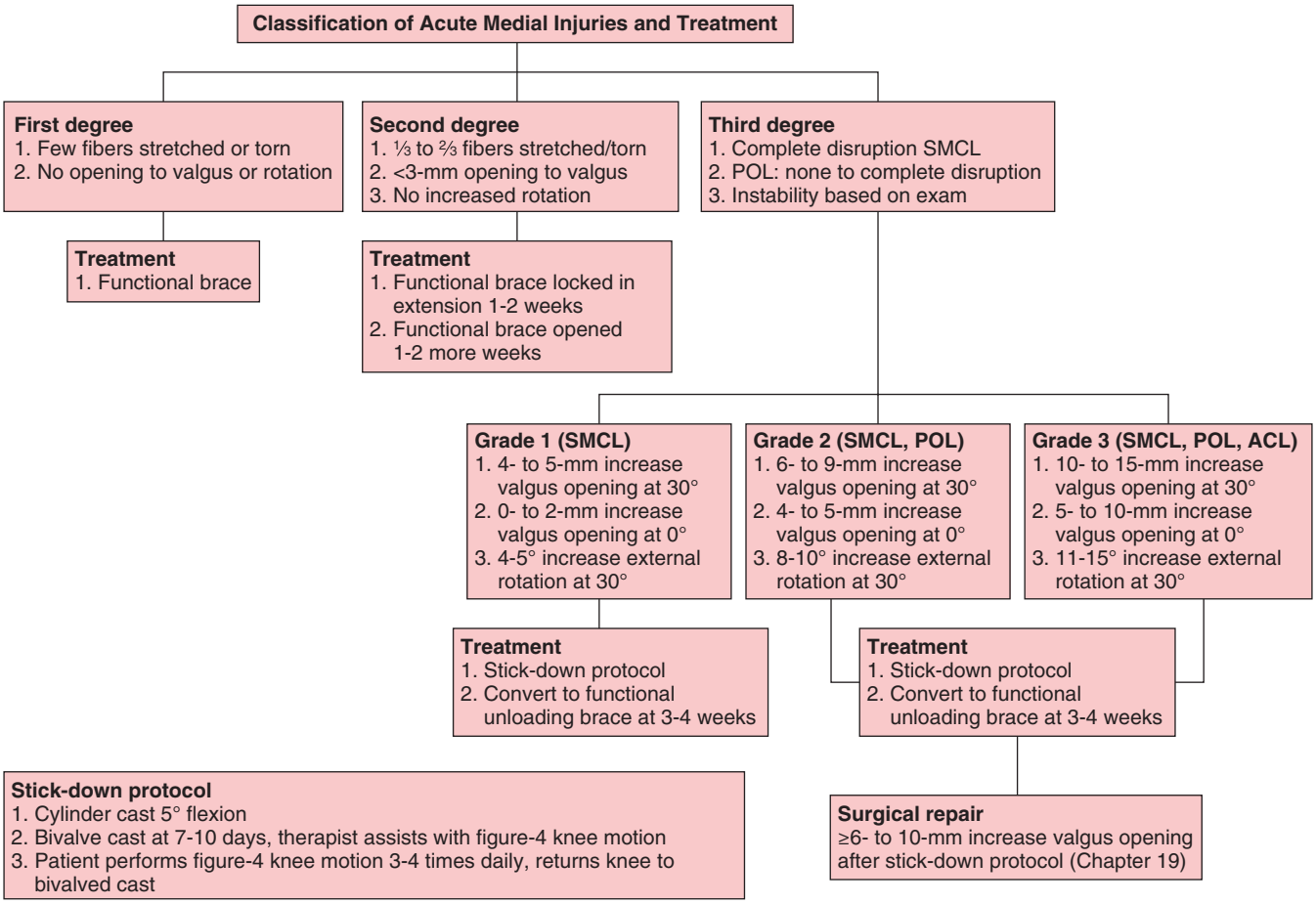


FIG 20-1 Treatment rationale for patients with acute medial ligament ruptures. *ACL,* Anterior cruciate ligament; *POL,* posterior oblique ligament; *SMCL,* superficial medial collateral ligament.

TABLE 20-1 Conservative Management of First-Degree Medial Ligament Injuries

Weight bearing as tolerated with assistive device if required.
Functional brace for protection for 3-4 weeks postinjury.
Active ROM exercises to achieve full ROM as tolerated.
Strengthening exercises: open and closed kinetic chain as tolerated.
Progress to agility, proprioceptive, neuromuscular, sports-specific activities as tolerated.
Return to full activities when strength is equal to the opposite side and all symptoms have resolved.

ROM, Range of motion.

major sections based on the extent of injury to the SMCL and PMC/POL. The first- and second-degree injuries are treated initially with a long-leg hinged brace, weight bearing as tolerated, and the rehabilitation program summarized in Tables 20-1 and 20-2. Some second-degree injuries may have considerable medial pain and swelling and, in these cases, the brace is used locked in extension with assistive ambulatory devices for the initial 1 to 2 weeks after the injury. The brace is then opened and used for another 2 to 4 weeks.

Third-Degree Injuries: Weeks 1 to 3

The treatment of third-degree medial ligament injuries involves short-term immobilization to allow the medial ligament structures time to heal, with the least elongation or laxity, by limiting medial joint opening and external tibial rotation. The lower limb is placed in a cylinder cast positioned in slight varus and internal rotation for 1 week to allow the disrupted medial soft tissues to "stick-down." Fiberglass cast immobilization is required because a long-leg hinged brace, even if locked at 0 degrees, does not provide sufficient protection to maintain medial joint line closure to allow close approximation of the disrupted medial ligament and meniscus attachment soft tissues. The patient is instructed to maintain the leg in an elevated position with the limb supported to control lower extremity swelling. The patient is also instructed to stay off of the lower limb as much as possible. In addition, ankle-pumping exercises are performed to maintain lower extremity circulation, and quadriceps isometrics are done hourly. Electrical muscle stimulation (EMS) is used to augment the voluntary quadriceps contraction. Windows may be cut into the cast to observe the electrodes to ensure they do not irritate the skin or to determine whether or not they need to be replaced. EMS is used approximately six times per day for 15-minute sessions. A cocontraction should occur between the stimulator and the patient's voluntary contraction. Hamstring and gastrocnemius flexibility exercises are also encouraged to promote posterior muscle relaxation.

At 7 to 10 days, the cylinder cast is split into an anterior and posterior shell (Fig. 20-2) to allow the patient to begin passive range of motion (ROM) exercises, which are initially assisted by the therapist. The cast is used for an additional 2 weeks to allow for early stick-down of the medial ligament structures. The patient is allowed to bear 25%



FIG 20-2 Cylinder cast bivalved (split) into an anterior and posterior shell.

TABLE 20-2 Conservative Management of Second-Degree Medial Ligament Injuries

Weight bearing as tolerated with assistive device if required.
Functional brace locked in extension for 1-2 weeks postinjury if excessive medial compartment pain and swelling.
Functional brace opened for next 4-6 weeks.
Active ROM exercises to achieve full ROM as tolerated.
Electrical muscle stimulation and straight-leg raises begun immediately.
Strengthening exercises: open and closed kinetic chain as tolerated.
Progress to agility, proprioceptive, neuromuscular, sports-specific activities upon resumption of full weight bearing as tolerated.
Return to full activities when strength equal to the opposite side and all symptoms have resolved.

ROM, Range of motion.

of her or his body weight as long as the cast is in place. ROM exercises are initiated in a figure-four position from 0 to 90 degrees to avoid valgus and external rotation loads on the healing ligaments (Fig. 20-3). A 4-inch tubular stocking is double-wrapped around the foot and ankle to allow the patient under her or his own power to flex the knee. This protected ROM program is performed three to four times a day for 10 to 15 minutes per session. Quadriceps strengthening exercises including isometrics and flexion straight-leg raises are emphasized. TheraBand resistance for plantar flexion is used to maintain gastrocnemius tone. Ice, compression, and elevation are used for pain and swelling control.

Third-Degree Injuries: Weeks 4 to 6

At the end of the first 3 to 4 weeks, the bivalved cast is discontinued and the patient is placed into a functional unloading brace depending on the extent of the knee effusion and residual tenderness to medial soft tissue pressure. Weight bearing is progressed approximately 25%



FIG 20-3 Patient performs range-of-motion exercises from 0 to 90 degrees in a figure-four position with the hip joint externally rotated to protect the healing medial tissues.

each week to discontinue crutches by the sixth week. Gait retraining is encouraged to allow for return of the normal reciprocal gait pattern (sufficient push-off during toe-off, midstance quadriceps contraction, hip and knee flexion during swing, and an upright posture).

Cryotherapy and EMS are continued to maintain control of pain and swelling as well as quadriceps reeducation. Exercises include quadriceps isometrics and straight-leg raises in the flexion and prone positions through the fourth week. Abduction and adduction leg raises may then be initiated as long as there is sufficient quadriceps control to limit varus/valgus loading. Any resistance in a side-to-side fashion is kept above the knee through at least the sixth week. Closed-chain exercises such as standing calf raises and wall-sitting isometrics are encouraged. ROM is progressed with figure-four protection continued through the fourth to sixth week.

Emphasis during this time period focuses on ligament protection during gait and exercise. The progression of exercise allows knee motion to be restored within normal limits. Muscle strengthening includes both closed-chain and table exercises (straight-leg raises). Emphasis is placed on hip and core control, plus progression of quadriceps strengthening (Table 20-3).

Third-Degree Injuries: Weeks 7 to 9

The brace is continued for ambulation. Gait and ROM should be normal or nearly normal, with restoration to normal as soon as possible. Pain and swelling should be within normal limits. Emphasis during this phase of treatment is on returning lower extremity strength to normal and to begin cross-training for cardiovascular endurance. Balance and proprioception exercises are also important components of this phase (see Chapter 11).

Straight-leg raises in multiple planes with ankle weights are used for hip control. Ten pounds of resistance represents the target goal for these exercises. Progression of the closed-chain program includes performing calf raises off the edge of a step or with weight added for resistance. Isometric wall-sits are done with a gradual increase in hold time and then with handheld weights added. TheraBand resistance is used with minisquats and terminal knee extension. Gait retraining is done with a heavy elastic band positioned about the thighs. In addition, the patient is progressed to a machine-oriented program for leg press (80 to 10 degrees), knee extension (90-30 degrees), seated hamstring curls (0-90 degrees), hip abduction/adduction, and calf presses.

Text continued on p. 645

TABLE 20-3 Cincinnati Sports Medicine and Orthopaedic Center Rehabilitation Protocol for Medial Ligament Repair or Reconstruction

	POSTOPERATIVE WEEKS					POSTOPERATIVE MONTHS			
	1-2	3-4	5-6	7-8	9-12	4	5	6	7-12
Brace:									
Long-leg hinged postoperative	X	X	X						
Functional unloader				X	X	X	X	X	X
ROM minimum goal (degrees):									
0-90	X								
0-110		X							
0-120			X						
0-130				X					
Weight bearing:									
None	X								
Toe touch, 25% body weight		X							
25%-50% body weight			X						
100% body weight				X					
Patellar mobilization	X	X	X	X	X				
Modalities:									
Electrical muscle stimulation	X	X	X	X					
Pain/edema management (cryotherapy)	X	X	X	X	X	X	X	X	X
Stretching: hamstring, gastrocnemius-soleus, ITB, quadriceps	X	X	X	X	X	X	X	X	X
Strengthening:									
Quadriceps isometrics, straight-leg raises	X	X	X	X	X				
Active knee extension		X	X	X	X				
Closed-chain: gait retraining, toe raises, wall-sits, minisquats	X	X	X	X	X	X	X	X	
Knee flexion hamstring curls (90 degrees)					X	X	X	X	X
Knee extension quads (90-30 degrees)		X	X	X	X	X	X	X	X
Hip abduction-adduction, multihip					X	X	X	X	X
Leg press (70-10 degrees)				X	X	X	X	X	X
Balance/proprioceptive training:									
Weight shifting, cup walking, BBS			X	X					
BAPS, perturbation training, balance board, minitrampoline					X	X	X	X	X
Conditioning:									
UBC		X	X	X					
Bike (stationary)			X	X	X	X	X	X	X
Aquatic program					X	X	X	X	X
Elliptical machine					X	X	X	X	X
Swimming (kicking)					X	X	X	X	X
Walking					X	X	X	X	X
Stair machine					X	X	X	X	X
Ski machine						X	X	X	X
Running: straight*							X	X	X
Cutting: lateral carioca, figure-8s*							X	X	X
Plyometric training*								X	X
Full sports*								X	X

PHASE 1: WEEKS 1-2 (VISITS 2-4)

General Observation

Non–weight bearing, maximum protection
Brace locked at 0 degrees (motion exercises 3-4 times/day) or cast
Avoid valgus loads, abnormal external tibial rotation

Evaluation (Goals)

Pain (controlled)
Hemarthrosis (mild)
Patellar mobility (good)
ROM minimum (0-90 degrees)
Quadriceps contraction and patellar migration (good)
Soft tissue contracture (none)

Continued

TABLE 20-3 Cincinnati Sports Medicine and Orthopaedic Center Rehabilitation Protocol for Medial Ligament Repair or Reconstruction—cont'd

PHASE 1: WEEKS 1-2 (VISITS 2-4)		
Goals	ROM 0-90 degrees Adequate quadriceps contraction Control of inflammation, effusion	
	Frequency	**Duration**
ROM	3-4 ×/day, 10 min	
Passive, 0-90 degrees, figure-four protection		
Patellar mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion)		3 sets × 10 reps
Active quadriceps isometrics		1 set × 10 reps
Knee extension (active assisted, 90-30 degrees, per quad control)		3 sets × 10 reps
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
PHASE 2: WEEKS 3-4 (VISITS 2-4)		
General Observation	Partial weight bearing: toe touch to 25% body weight Brace unlocked (motion exercises 3-4 times/day) or cast Avoid valgus loads, abnormal external tibial rotation	
Evaluation (Goals)	Pain (controlled) Effusion (mild) Patellar mobility (good) ROM minimum (0-90 degrees) Quadriceps contraction and patellar migration (good) Soft tissue contracture (none)	
Goals	ROM 0-110 degrees Control of inflammation, effusion Muscle control	
	Frequency	**Duration**
ROM	3-4 ×/day, 10 min	
Passive, 0-110 degrees, figure-four protection		
Patellar mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2-3 ×/day, 20 min	
Straight-leg raises (flexion)		3 sets × 10 reps
Isometric training: multiangle (0, 60 degrees)		1 set × 10 reps
Knee extension (active, 90-30 degrees, per quad control)		3 sets × 10 reps
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

TABLE 20-3 Cincinnati Sports Medicine and Orthopaedic Center Rehabilitation Protocol for Medial Ligament Repair or Reconstruction—cont'd

PHASE 3: WEEKS 5-6 (VISITS 1-2)

General Observation	Partial (25%-50%) weight bearing when: • Pain controlled without narcotics • Hemarthrosis is controlled • Muscle control through ROM ROM 0-120 degrees Avoid valgus loads		
Evaluation (Goals)	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-120 degrees) Muscle control (3/5) Inflammatory response (none)		
Goals	ROM 0-120 degrees Control of inflammation, effusion Muscle control Early recognition of complications (motion, CRPS, patellofemoral changes) 50% weight bearing		
		Frequency	**Duration**
ROM		3 ×/day, 10 min	
Passive, 0-120 degrees			
Patellar mobilization			
Hamstring, gastrocnemius-soleus stretches			5 reps × 30 sec
Strengthening		2 ×/day, 20 min	
Straight-leg raises (ankle weight, not to exceed 10% of body weight)			3 sets × 10 reps
Isometric training: multiangle (90, 60, 30 degrees)			2 sets × 10 reps
Closed-chain: minisquats			3 sets × 20 reps
Knee extension (active, 90-30 degrees)			3 sets × 10 reps
Aerobic Conditioning		2 ×/day, 10 min	
UBC			
Stationary bicycling			
Gait Retraining			
Muscle control of quadriceps and hamstrings			
Walking with toe-in gait; avoid toe-out valgus position			
Observe gait for any tendency for valgus thrust or external tibial rotation			
Smooth stance phase flexion pattern			
Modalities		As required	
EMS			20 min
Cryotherapy			20 min

PHASE 4: WEEKS 7-8 (VISITS 1-2)

General Observation	Full weight bearing Functional unloading brace ROM 0-130 degrees
Evaluation (Goals)	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-130 degrees) Muscle control (4/5) Inflammatory response (none)

Continued

TABLE 20-3 Cincinnati Sports Medicine and Orthopaedic Center Rehabilitation Protocol for Medial Ligament Repair or Reconstruction—cont'd

PHASE 4: WEEKS 7-8 (VISITS 1-2)		
Goals	Full weight bearing Muscle control Control of inflammation, effusion ROM 0-130 degrees	
	Frequency	**Duration**
ROM	2 ×/day, 10 min	
0-130 degrees		
Patellar mobilization		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (flexion, extension, abduction, adduction)		3 sets × 10 reps
Straight-leg raises with rubber tubing		3 sets × 30 reps
Knee extension (active, 90-30 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue × 3
Minisquats (with rubber tubing, 0-45 degrees)		3 sets × 20 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Cup walking		
BBS		
Aerobic Conditioning	1-2 ×/day, 15 min	
UBC		
Stationary bicycling		
Gait Retraining		
Progress program		
Continue to observe for valgus thrust, external tibial rotatin		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
PHASE 5: WEEKS 9-12 (VISITS 1-2)		
General Observation	Full weight bearing Functional unloading brace ROM 0-130 degrees	
Evaluation (Goals)	Pain (minimal) Manual muscle test (hamstrings, quadriceps, hip abductors/adductors/flexors/extensors) (4/5) Swelling (minimal) Patellar mobility (good) Crepitus (none/slight) Gait (symmetric)	
Goals	Increase strength and endurance ROM 0-130 degrees Normal gait without valgus or external tibial rotation	

TABLE 20-3 Cincinnati Sports Medicine and Orthopaedic Center Rehabilitation Protocol for Medial Ligament Repair or Reconstruction—cont'd

PHASE 5: WEEKS 9-12 (VISITS 1-2)

	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Patellar mobilization		
Strengthening	2 ×/day, 20 min	
Straight-leg raises		3 sets × 10 reps
Straight-leg raises with rubber tubing		3 sets × 30 reps
Hamstring curls (week 12, active, 0-90 degrees)		3 sets × 10 reps
Knee extension (with resistance, 90-30 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue × 3
Minisquats (with rubber tubing, 0-45 degrees)		3 sets × 20 reps
Lateral step-ups (2- to 4-inch block)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Cup walking, BBS, BAPS, perturbation training		
Aerobic Conditioning (Patellofemoral Precautions)	1 ×/day, 15-20 min	
Water walking		
Elliptical machine		
Stationary bicycling		
Stair-climbing machine (low resistance and stroke)		
Swimming (kicking)		
Walking		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

PHASE 6: WEEKS 13-26 (VISITS 2-3)

General Observation	No effusion, painless ROM, joint stability Performs activities of daily living, can walk 20 min without pain ROM 0-130 degrees Functional unloading brace
Evaluation (Goals)	Pain (minimal) Manual muscle test (4/5) Swelling (minimal) Patellar mobility (good) Crepitus (none/slight) Gait (symmetric)
Goals	Increase strength and endurance

	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises with rubber tubing (high speed)		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (with resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Closed-chain: minisquats (with rubber tubing, 0-45 degrees)		3 sets × 20 reps

Continued

TABLE 20-3 Cincinnati Sports Medicine and Orthopaedic Center Rehabilitation Protocol for Medial Ligament Repair or Reconstruction—cont'd

PHASE 6: WEEKS 13-26 (VISITS 2-3)

	Frequency	Duration
Balance Training	1-3 ×/day, 5 min	
Balance board, two legged		
Single-leg stance		
Aerobic Conditioning (Patellofemoral Precautions)	3 ×/wk, 20 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Elliptical machine		
Stair-climbing machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Modalities	As required	
Cryotherapy		20 min

PHASE 7: WEEKS 27-52 (VISITS 2-3)

General Observation	No effusion, painless ROM, joint stability Performs activities of daily living, can walk 20 min without pain Functional unloading brace
Evaluation (Goals)	Isokinetic test (% difference between quadriceps and hamstrings, 180 degrees/sec, 300 degrees/sec) (10-15) Swelling (none) Patellar mobility (good) Crepitus (none/slight)
Goals	Increase function Maintain strength and endurance Return to previous activity level

	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	1 ×/day, 20-30 min	
Straight-leg raises with rubber tubing (high speed)		3 sets × 30 reps
Hamstring curls (active, 0-90 degrees)		3 sets × 10 reps
Knee extension (with resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Closed-chain: minisquats (with rubber tubing, 0-45 degrees)		3 sets × 20 reps
Balance Training	1-3 ×/day, 5 min	
Balance board, two legged		
Single-leg stance		
Aerobic Conditioning (Patellofemoral Precautions)	3 ×/wk, 20-30 min	
Stationary bicycling		
Water walking		
Swimming (kicking)		
Walking		
Elliptical machine		
Stair-climbing machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		

TABLE 20-3 Cincinnati Sports Medicine and Orthopaedic Center Rehabilitation Protocol for Medial Ligament Repair or Reconstruction—cont'd

PHASE 7: WEEKS 27-52 (VISITS 2-3)

	Frequency	Duration
Running Program (5 mo Minimum, <30% Deficit Isokinetic Test	3 ×/wk, 15-20 min	
Jog		¼ mile
Walk		⅛ mile
Backward run		20 yards
Cutting Program (5 mo Minimum, 20% Deficit Isokinetic Test)	3 ×/wk	
Lateral, carioca, figure 8s		20 yards
Plyometric Training (6 mo Minimum, Completion of Running/Cutting Programs	3 ×/wk	
Box hops, level, double leg		4-6 sets, 15 sec
Sport-Specific Drills	3 ×/wk	
Modalities	As required	
Cryotherapy		20 min

*Does not include combined anterior cruciate ligament/medial collateral ligament injuries; these require a longer period of protection and training. See text for criteria required to begin these activities.
BAPS, Biomechanical Ankle Platform System (Patterson Medical); *BBS*, Biodex Balance System; *CRPS*, complex regional pain syndrome; *EMS*, electrical muscle stimulation; *ITB*, iliotibial band; *ROM*, range of motion; *UBC*, upper body cycle.

Endurance training includes a stationary bicycle, elliptical cross-trainer, and/or aquatics for 20 to 30 minutes at least three times per week. Activities such as cutting or twisting that place valgus and external rotation torques on the lower extremity are still limited. Proprioception and balance training includes unidirectional exercises balancing on a rocker board and multidirectional activities such as a wobble board or balance board. Balance activities at home progress from tandem balance positioning to single-leg stance. In select patients, isokinetic testing is performed to measure quadriceps and hamstrings muscle strength. The goals for initiating a running program are at least 70% on bilateral comparison for quadriceps and hamstrings at 180 degrees/sec and 300 degrees/sec, torque/body weight ratios (based on age and gender), and a hamstring-quadriceps ratio of 60%.

Third-Degree Injuries: Weeks 10 to 12

The focus of this final phase is on return to activity. By this time, gait, ROM, activities of daily living, and symptoms should be within normal limits. The exercise progression advocates return of isokinetic muscle strength parameters within 70% and 90% for straight-ahead running and more strenuous turning/cutting drills, respectively. The cross-training program is advanced to a full running program that then allows for sports-specific training. Distance and direction-specific running and agility drills are incorporated. Heavy strength training occurs on opposite days of the running program. Injury prevention and neuromuscular retraining programs include jump training activities with emphasis on technique, position, alignment, and repetition as discussed in detail in Chapter 14. Isokinetic testing is performed, with the goal of achieving a 90% bilateral comparison for quadriceps and hamstrings at 180 degrees/sec and 300 degrees/sec, torque/body weight ratios (corrected for age and gender), and a hamstring/quadriceps ratio greater than 60%. Patients continue brace use for activity only. Follow-up treatment is based on either the need for symptom control and/or functional progression for unrestricted return to activity.

Concomitant Cruciate Ligament Injuries

Patients who have a concomitant ACL rupture and third-degree medial ligament rupture undergo the initial stick-down program and treatment described. According to the severity of the medial ligament injury, sufficient time is required to stick down the medial structures, allow for figure-four ROM, protect with partial weight bearing, and initiate early quadriceps exercises. Initial knee motion goals are 0 to 90 degrees. Normally, 3 to 6 weeks of conservative management is required before the patient undergoes ACL reconstruction. The progression of exercises and weight bearing is consistent with that described above.

Patients who have concomitant PCL and medial ligament ruptures also undergo the initial stick-down program with a posterior calf pad to prevent posterior tibial subluxation. The cast is bivalved at 2 to 4 weeks, allowing protected passive ROM exercises to be performed initially by the therapist and then by the patient. Figure-four ROM exercises with an anterior drawer support allow for protection of both ligaments. Two weeks later, the bivalved cast is replaced with a long-leg hinged brace with a posterior pad, which is used for another 4 weeks. Weight bearing, ROM, and quadriceps exercises are all progressed as tolerated. The initial knee motion goal is 0 to 90 degrees, which is then gradually progressed to a full 6 weeks after the cast is discontinued. Full weight bearing is permitted at this time, with emphasis on quadriceps control. Hamstring contractions are not allowed for the initial 6 weeks, and are then permitted in the active mode only for an additional 6 weeks. The patient's gait, knee motion, quadriceps control, and symptoms should be back to normal limits to consider surgical intervention. Knee injuries with combined third-degree medial ligament ruptures and PCL ruptures often require operative repair; the postoperative course is described in Chapter 18.

POSTOPERATIVE REHABILITATION OF MEDIAL LIGAMENT REPAIRS/RECONSTRUCTIONS

The surgical treatment of acute third-degree medial ligament ruptures involves anatomic repair to restore continuity and function, including repair of the medial meniscus attachments. Knees with chronic deficiency of the medial ligament ruptures often require a graft reconstruction using a semitendinosus-gracilis autograft or allograft, discussed in Chapter 19. The operative procedure is designed to provide sufficient tensile strength to the reconstructed medial tissues to allow immediate knee motion and restore early limb function. The goal is to provide 4 weeks of maximum protection, using either a long-leg hinged postoperative brace or bivalved cast in cases where the surgical repair was tenuous, extensive disruption occurred, the patient is obese, or compliance with brace wear is questionable. After this period, the rehabilitation program progresses, as soft tissue healing provides sufficient strength for ambulatory activities.

The postoperative protocol (see Table 20-3) is divided into seven phases according to the time period postoperatively (e.g., phase 1 comprises postoperative weeks 1-2). Each phase has four main categories that describe the factors evaluated by the therapist and exercises performed by the patient:

- General observation of the patient's condition.
- Evaluation and measurement of specific variables, with goals identified for each variable
- Treatment and exercise program according to frequency and duration.
- Rehabilitation goals that must be achieved to enter the next phase.

Specific criteria are evaluated throughout the rehabilitation program to determine whether the patient is ready to progress from one phase to the next. The protocol incorporates a home self-management program, along with an estimated number of formal physical therapy visits. For most patients, 11 to 21 postoperative visits are expected to produce a desirable result.

The following signs are continually monitored postoperatively: joint swelling, pain, gait pattern, knee motion, patellar mobility, muscle strength, flexibility, and medial tibiofemoral compartment opening. Any individual who experiences difficulty progressing through the protocol or who develops a complication is expected to require additional supervision in the formal clinic setting.

The first postoperative week represents a critical time period in regard to control of knee joint pain and swelling, return of adequate quadriceps muscle contraction, initiation of immediate knee motion exercises from 0 to 90 degrees, and maintenance of adequate limb elevation. A bulky compression dressing is used for 48 hours and then converted to compression stockings with an additional compression bandage if necessary. Patients are encouraged to stay in bed and elevate the limb above their heart for the first 5 to 7 days, rising only to perform exercises and attend to personal bathing issues. Prophylaxis against deep venous thrombosis includes one aspirin (325 mg) a day for 10 days or, for larger patients, one aspirin twice a day, ambulation (with crutch support) six to eight times a day for short periods of time, ankle pumping every hour the patient is awake, and close observation of the lower limb by the therapist and surgeon. Knee joint hemarthrosis require aspiration. Nonsteroidal antiinflammatories are used for 5 days postoperatively. Appropriate pain medication is prescribed to provide relief and allow the immediate exercise protocol described below to be performed.

Modalities

In the immediate postoperative period, knee effusion must be controlled to avoid the quadriceps inhibition phenomenon. Electrogalvanic stimulation or high-voltage EMS may be used along with ice, compression, and elevation to control swelling. Treatment duration is approximately 20 minutes, the intensity is set to patient's tolerance, and the treatment frequency is three to six times per day.

Once joint effusion is controlled, functional EMS is used for quadriceps muscle reeducation based on the evaluation of quadriceps muscle tone. One electrode is placed over the vastus medialis oblique (VMO) and a second electrode is placed on the central to lateral aspect of the upper third of the quadriceps muscle belly. The treatment duration is 20 minutes. The patient actively contracts the quadriceps muscle simultaneously with the machine's stimulation.

Biofeedback therapy is important to facilitate an adequate quadriceps muscle contraction early postoperatively. The surface electrode is placed over the selected muscle component to provide feedback to the patient and clinician regarding the quality of active or voluntary quadriceps contraction. Biofeedback is also useful in enhancing hamstring relaxation if the patient has difficulty achieving full knee extension owing to knee pain or muscle spasm. The electrode is placed over the belly of the hamstring muscle while the patient performs ROM exercises.

Cryotherapy is begun in the recovery room after surgery. The standard method of cold therapy is an ice bag or commercial cold pack, which is kept in the freezer until required. Empirically, patients prefer motorized cooler units. These units maintain a constant temperature and circulation of ice water through a pad, which provides excellent pain control. Cryotherapy is used from three times a day to every waking hour for 20 minutes at a time depending on the extent of pain and swelling. Cold therapy is typically done after exercise or when required for pain and swelling control and is maintained throughout the entire postoperative rehabilitation protocol.

Postoperative Bracing

Immediately after surgery, patients in whom excellent stability was obtained and are of normal body weight are placed into a long-leg hinged postoperative brace that is locked at 0 degree extension for 2 weeks until the initial postoperative pain has receded and return of lower limb muscle control occurs. At this time, the brace is unlocked and the patient taught to resume a normal gait, with flexion during the stance phase, under 25% body weight. In cases where the surgical repair was tenuous, questionable tissue quality exists even with a graft reconstruction, or in cases of obesity, a bivalved cast is used as described earlier for third-degree injuries. The cast is used for 3 to 4 weeks and then converted to a functional unloading brace. The brace (lateral compartment-medial soft tissues) is prescribed for at least the first year postoperatively in select knees in which extensive surgery was performed and additional protection is indicated.

Weight Bearing

Patients are kept non–weight bearing for the first 2 weeks. Then, toe touch to 25% of the patient's body weight is permitted from weeks 3 to 4. Partial weight bearing is allowed as long as pain and swelling are controlled and a voluntary quadriceps contraction is demonstrated. The patient is taught to walk with a toe-in gait and avoid a toe-out valgus position. The therapist should observe the gait cycle for any tendency for a valgus thrust or external tibial rotation, which requires immediate correction to avoid placing excessive loads on the medial ligament repair or graft reconstruction. Weight bearing is slowly progressed to full by the seventh to eighth week.

Range of Knee Motion

The goal in the first postoperative week is to obtain 0 to 90 degrees. A continuous passive motion machine is not required. Patients perform



FIG 20-4 Early postoperatively, the therapist performs range-of-motion exercises by applying a mild amount of varus and internal tibial rotation stress during flexion to unload the medial compartment.

passive and active ROM exercises in a seated position for 10 minutes a session, approximately four to six times per day. Initially, the therapist performs this exercise by applying a mild amount of varus and internal tibial rotation stress during flexion to unload the medial compartment (Fig. 20-4). Full passive knee extension must be obtained immediately to avoid excessive scarring in the intercondylar notch and posterior capsular tissues. It is important to note that patients undergoing SMCL repair or reconstruction are at an increased risk for developing a knee motion problem postoperatively.[3] Supervision and close monitoring of the patient's progress by the therapist is essential to avoid a potential arthrofibrotic response. If the patient has difficulty regaining at least 0 degrees by the seventh postoperative day, an overpressure program is begun as described in detail in Chapter 11 and Chapter 38. Overpressure exercises and modalities include hanging weight, extension board, and a drop-out cast (Fig. 20-5).

Passive knee flexion exercises are performed initially in the figure-four position for the first 4 to 6 weeks to protect the healing medial ligament tissues (see Fig. 20-3). Knee flexion is then gradually increased to 130 degrees by the seventh to eighth postoperative week. Other methods to assist in achieving flexion include chair rolling, wall-slides, commercial devices (Fig. 20-6), and passive quadriceps stretching exercises.

Patellar Mobilization

Maintaining normal patellar mobility is critical to regain normal ROM. The loss of patellar mobility is often associated with arthrofibrosis and, in extreme cases, the development of patella infera.[4,5,7] Patellar glides are performed beginning the first postoperative day in all four planes (superior, inferior, medial, and lateral) with sustained pressure applied to the appropriate patellar border for at least 10 seconds (Fig. 20-7). This exercise is performed for 5 minutes before ROM exercises. Caution is warranted if an extensor lag is detected because this may be associated with poor superior migration of the patella, indicating the need for additional emphasis on this exercise. Patellar mobilization is performed for approximately 12 weeks postoperatively.

Flexibility

Hamstring and gastrocnemius-soleus flexibility exercises are begun the first day postoperatively. A sustained static stretch is held for 30 seconds and repeated five times. These exercises help control pain caused by the reflex response created in the hamstrings when the knee is kept in the flexed position. In addition, the gastrocnemius-soleus towel pulling exercise can help lessen discomfort in the calf, Achilles tendon, and ankle. Quadriceps and iliotibial band flexibility exercises are initiated at week 9. The flexibility program is maintained throughout the course of the rehabilitation program.

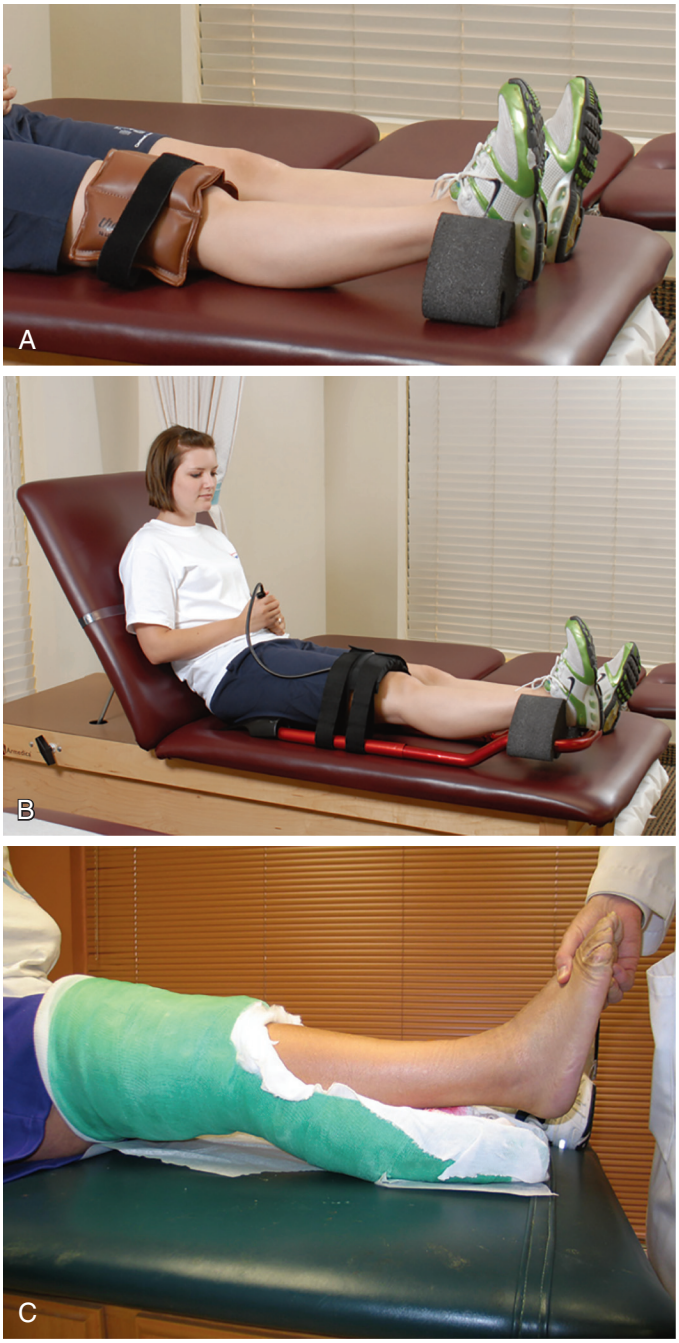


FIG 20-5 Extension overpressure exercises. **A,** Hanging weight. **B,** Extension board (ERMI Knee Extensionater). **C,** Drop-out cast.

Strengthening

The strengthening program is begun on the first postoperative day. Early emphasis on the generation of a good voluntary quadriceps contraction is critical for a successful and safe return to functional activity. Isometric quadriceps contractions, along with a hamstring cocontraction to prevent knee hyperextension, are completed hourly



FIG 20-6 Flexion overpressure exercises. **A,** Rolling stool. **B,** Wall-slides. **C,** Commercial device (ERMI Knee Flexionater).



FIG 20-7 Patellar mobilization.

following the rules of 10 second holds, 10 repetitions, 10 times per day. Adequate evaluation of the quadriceps contraction by both the therapist and patient is critical. If necessary, biofeedback can also be used to reinforce a good voluntary quadriceps contraction.

Straight-leg raises are initiated the first postoperative day in the hip flexion plane. At weeks 7 to 8, the other three planes (adduction, abduction, and extension) are added to this exercise. As leg raises become easy to perform, ankle weights are added to progress muscle strengthening. Initially, 1- to 2-lb weights are used and eventually, up to 10 lb may be added as long as this is not more than 10% of the patient's body weight.

Active-assisted ROM can also be used to facilitate the quadriceps muscle if poor tone is observed during isometric contractions. These exercises are primarily used during the first 8 postoperative weeks where emphasis is placed on controlling pain and swelling, regaining full ROM, achieving early quadriceps control and proximal stabilization, and resuming a normal gait pattern.

Closed kinetic chain exercises are begun when partial weight bearing of at least 50% is tolerated. Patients are instructed to avoid valgus loading during these exercises. These activities initially consist of minisquats from 0 to 45 degrees, toe raises, and wall-sits. During the wall-sitting exercise, the patient may use an elastic band around the distal thigh to produce a varus-directed force to avoid loading the MCL repair/reconstruction, or hold dumbbell weights in his or her hands to increase body weight (Fig. 20-8). The patient can also shift his or her body weight over the involved side to stimulate a single-leg contraction. The wall-sitting position should be held to a maximum burning of the quadriceps and repeated. This is an excellent exercise to mimic a stationary leg press, achieve quadriceps muscle fiber recruitment, and induce muscle fatigue to build strength.

Lateral step-ups are begun when the patient has achieved full weight bearing. The height of the step is gradually increased based on patient tolerance from 2 to 8 inches.

Hamstring curls are begun with Velcro ankle weights between weeks 9 and 12 and eventually advanced to weight machines. The patient exercises the involved limb alone, as well as both limbs together. Weight training is used throughout the program and continues in the return to activity and maintenance phases of rehabilitation.



FIG 20-8 Strengthening exercises. **A,** Wall-sitting while holding hand weights. **B,** Toe raises. **C,** Lateral step-ups.

Open kinetic chain extension exercises are incorporated within the first few weeks to further develop quadriceps muscle strength. Caution is warranted owing to the potential problems these exercises may create for the patellofemoral joint. Resisted knee extension is begun with Velcro ankle weights from 90 to 30 degrees at postoperative weeks 3 to 4. The terminal phase of extension is avoided owing to the forces placed on the patellofemoral joint. The patellofemoral joint must be monitored for pain, swelling, and crepitus to avoid a conversion in which painful patellofemoral crepitus develops with articular cartilage damage. The surgeon should advise the therapist if patellofemoral joint damage was observed at surgery. The therapist should palpate the patellofemoral joint during active knee extension every therapy session to detect pain or an onset of joint crepitus. A patellofemoral conversion to a symptomatic state will occur in select knees, especially those with

preexisting patellofemoral joint damage. In these knees, modification of the entire rehabilitation program is required.

A full lower extremity strengthening program is critical for early and long-term success of the rehabilitation program. Other muscle groups included in this routine are the hip abductors, hip adductors, hip flexors, and hip extensors. These muscle groups may be exercised on either a multihip or cable system machine or a hip abductor-adductor machine. Gastrocnemius-soleus strength is a key component for both early ambulation and the running program. In addition, upper extremity and core strengthening are important for a safe and effective return to work or sports.

Balance, Proprioceptive, and Perturbation Training

Balance and proprioceptive training are initiated when the patient achieves 50% weight bearing. Initially, the patient stands and shifts weight from side to side and front to back. This activity promotes confidence in the leg's ability to withstand the pressures of weight bearing and initiates the stimulus to knee joint position sense. Cup walking is then done to promote symmetry between the surgical and uninvolved limbs by facilitating early midstance quadriceps activation and focusing on sufficient active knee flexion during swing phase (Fig. 20-9).

Double- and single-leg balance exercises in the stance position are beneficial and initiated during phases 5 to 6, depending on patient tolerance. During the single-leg exercise, the foot is pointed straight ahead, the knee flexed 20 to 30 degrees, the arms extended outward to horizontal, and the torso positioned upright with the shoulders above the hips and the hips above the ankles. The patient remains in this position until balance is disturbed. A minitrampoline or unstable platform makes this exercise more challenging. The patient may assume the single-leg stance position and throw/catch a weighted ball against an inverted minitrampoline until fatigue occurs.

Perturbation training techniques are initiated during balance exercises. The therapist stands behind the patient and disrupts her or his body posture and position periodically to enhance dynamic knee stability. The techniques involve either direct contact with the patient or disruption of the platform on which the patient is standing.

Walking on half foam rolls is also used in the gait retraining and balance program. This activity helps the patient develop the balance and dynamic muscular control required to maintain an upright position and be able to walk from one end of the roll to the other. Developing a center of balance, limb symmetry, quadriceps control in midstance, and postural positioning are benefits obtained from this type of training.

Conditioning

Depending on accessibility, a cardiovascular program is begun as soon as the patient can sufficiently tolerate the upright position with an upper extremity ergometer. The surgical limb should be elevated to minimize lower extremity swelling. This exercise is performed as tolerated. Stationary bicycling is begun in the fifth to sixth postoperative week if tolerated.

Water walking, swimming, and the use of an elliptical machine are allowed during the ninth to twelfth postoperative weeks. Then, cross-country ski and stair-climbing machines are permitted. Protection against high stresses to the patellofemoral joint is strongly advocated. During bicycling, the seat height is adjusted to its highest level based on patient body size and a low-resistance level is used initially. Stair-climbing machines are adjusted to produce a short step and low resistance.

To improve cardiovascular endurance, the program should be performed at least three times per week for 20 to 30 minutes, and the exercise performed to at least 60% to 85% of maximal heart rate. It is generally regarded that performing in the higher levels of percentage

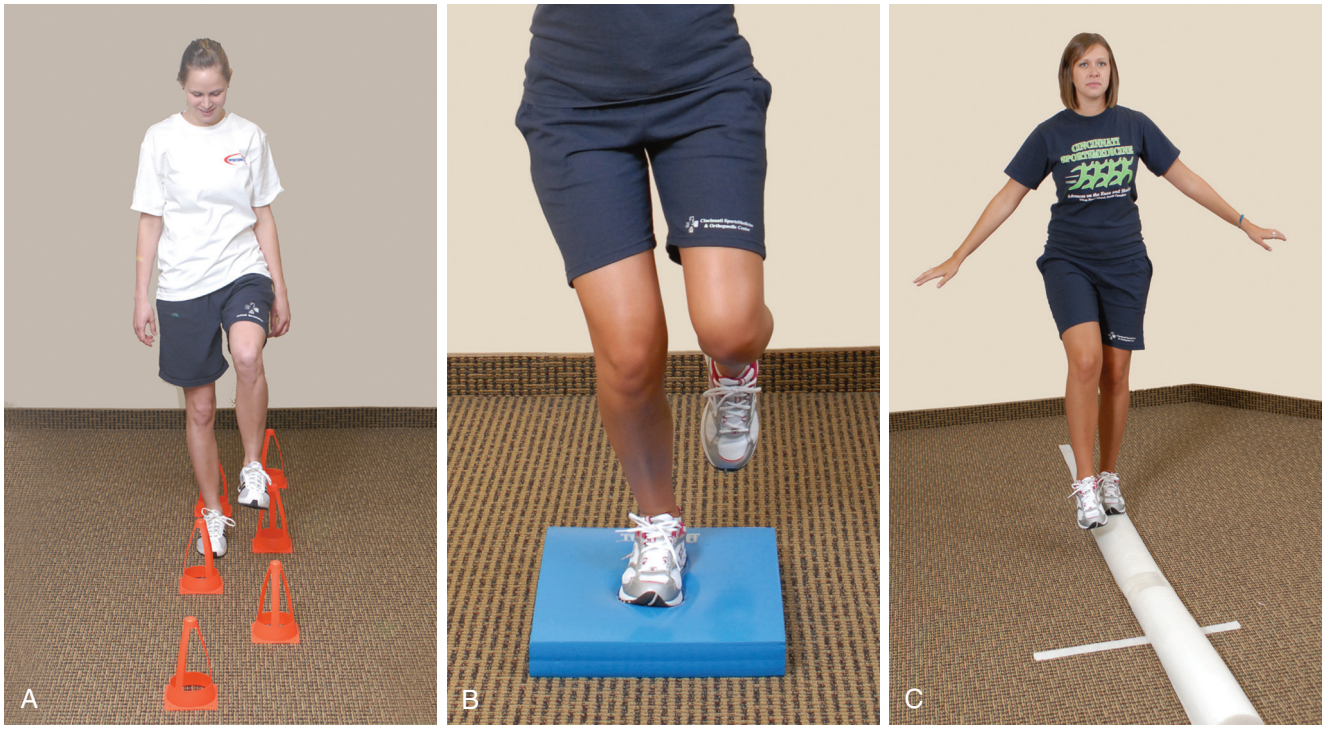


FIG 20-9 Balance and proprioceptive training. **A,** Cup (or cone) walking. **B,** Single-leg balancing on an unstable platform. **C,** Walking on half foam rolls.

of maximal heart rate achieves greater cardiovascular efficiency and endurance.

Running and Agility Program

To initiate the running program, the patient must demonstrate no more than a 30% deficit in average torque for the quadriceps and hamstrings on isokinetic testing and have no more than 3 mm of increase in medial joint opening (30 degrees of flexion). The majority of patients are at least 5 months postoperative.

The running program is based on the patient's athletic goals, particularly the position or physical requirements of the activity, and is described in detail in Chapter 11. The program is performed three times per week, on opposite days of the strength program. Since the running program may not reach aerobic levels initially, a cross-training program is used to facilitate cardiovascular fitness. The cross-training program is performed on the same day as the strength workout. Sports-specific agility drills are an important part of the return to activity program. Patients must be taught proper body alignment and positioning during cutting and pivoting to avoid abnormal and potential dangerous forces, discussed in detail in Chapter 14.

Plyometric Training

Progressive plyometric training is initiated upon successful completion of the running program in patients who desire to return to high-risk sports activities. Important parameters to consider when performing plyometric exercises include surface, footwear, and warm-up. The jump training should be done on a firm, yet forgiving surface such as a wooden gym floor. Very hard surfaces like concrete should be avoided. A cross-training or running shoe should be worn to provide adequate shock absorption, as well as adequate stability to the foot. Checking wear patterns and outer sole wear will help avoid overuse injuries. Beginning plyometric training is done in individual sessions performed in a manner similar to interval training. Initially, a rest period is incorporated that lasts 2 to 3 times the length of the exercise period; this is gradually decreased to 1 to 2 times the length of the exercise period. Plyometrics are also performed 2 to 3 times each week in addition to strength and cardiovascular endurance exercises.

The program begins with level-surface box hopping. A four-square grid of four equally sized boxes is created on the floor with tape. The patient first hops from box 1 to box 3 (front-to-back), and then from box 1 to box 2 (side-to-side). This drill is initially performed using both legs, with the body weight kept on the ball of the foot. The patient hops as fast as possible with the knees bent and lands in flexion to avoid knee hyperextension. It is important for the patient to focus on limb symmetry during this exercise.

The initial exercise time period lasts 15 seconds, with the patient completing as many hops between the squares as possible. Three sets are performed for both directions, and the number of hops is recorded. Progression of the program occurs as the number of hops, as well as patient confidence, improves. This exercise has four levels. The first level includes front-to-back and side-to-side hopping, as previously described. The second level incorporates both of the directions in level one into one sequence and also includes hopping in both right and left directions (box 1 to box 2 to box 4 to box 2 to box 1). Level three progresses to diagonal hops, and level four includes pivot hops in a 180-degree direction. Once the patient can perform level-four double-leg jumps, similar exercises are initiated using single-leg hops.

During the various jumps, the patient is instructed to keep his or her body weight on the balls of the feet. He or she should jump and land with the knees flexed and shoulder-width apart to avoid knee hyperextension and an overall valgus lower limb position. The patient should understand that the exercises are reaction and agility drills and, although speed is emphasized, correct body posture must be maintained throughout the drills.

For patients who undergo a combined ACL-SMCL reconstruction, advanced plyometric training is recommended before release to strenuous high-risk sports activities such as soccer and basketball. Our Sportsmetrics program is described in detail in Chapter 14. The program is applicable for both female and male athletes.

Return to Sports

Once the patient has completed the running and plyometric programs, sport-specific drills and cutting patterns of 45 degrees and 90 degrees angles may be implemented based on their athletic goals. Return to sports activities is based on successful completion of the running and functional training program.

For patients who undergo a combined ACL-SMCL reconstruction, a longer period of protection and training is required. Although in general these patients may be released to full sports around 7 months postoperatively, the following specific criteria are recommended before release is granted:

- Isokinetic test 180 degrees/s and 300 degrees/s quadriceps, hamstrings: 10% or less deficit
- No pain, swelling, patellofemoral crepitus
- Lachman, KT-2000 (MEDmetric) arthrometer test: less than 3-mm increase over opposite side
- Negative pivot shift test
- Single-leg hop tests: less than 15% deficit
- Successful completion advanced plyometric training
- Greater than 60% normalized knee separation distance on video drop-jump test
- No valgus motion or medial-lateral movement of knee on single-leg squat test

A trial of function is encouraged where the patient is monitored for knee swelling, pain, overuse symptoms, and giving-way episodes. Some athletes will experience transient knee swelling upon return to strenuous activities and should be educated on how to recognize this problem and the importance of reducing activities until the swelling subsides. If swelling persists, the athlete is advised to reduce athletics for 2 to 6 weeks, consider use of nonsteroidal antiinflammatories, and use ice and elevation. Upon successful return to activity, the patient is encouraged to continue with a maintenance program. During the in-season, a conditioning program of two workouts a week is recommended. In the off-season or preseason, this program should be performed three times a week to maximize gains in flexibility, strength, and cardiovascular endurance.

During the entire functional progression, the therapist and surgeon should individualize the program based on the initial injury (particularly to the menisci and articular cartilage), magnitude of the operative procedure, and healing response of the patient. Athletes with loss of a meniscus or articular cartilage damage are advised to refrain from high-impact activities and are followed yearly to detect progression of the joint injury. These patients frequently have episodes of joint swelling and pain during the functional progression and are instructed to "play smart" and not be a knee abuser.

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Video Content

Video 1-1
Video 3-1
Video 11-2

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21

Classification of Knee Dislocations

Judd R. Fitzgerald, Dustin L. Richter, Daniel C. Wascher, Robert C. Schenck Jr

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INTRODUCTION

The concept of a dislocated knee has changed markedly over the past few decades. In 1971, Meyers and Harvey[16] predicted that most orthopedists would not see more than one knee dislocation in their entire career. However, evidence indicates that knee dislocations are being seen with increasing frequency for a variety of reasons. Increasing trauma, the growing epidemic of obesity, changes in automotive design, and recognition of spontaneously reduced knee dislocations have all added to the increased incidence.[2,7] The increasing number of knee dislocations has created the need for a classification system that will help guide the management of these complex injuries. Classification systems should be simple and reproducible, provide information to the clinician that will be helpful in making treatment decisions, aid in the communication of similar injuries, and assist in developing prognoses for the injuries. This chapter reviews the shortcomings of older classification systems of knee dislocations and presents an anatomic classification that is simple, accurate, reproducible, and useful.[25-27,35]

DEFINITION OF KNEE DISLOCATION

Classically, a knee dislocation was defined as greater than 100% displacement of the tibiofemoral articulation. This displacement had to be present on either physical examination or on radiographic imaging. Since the 1990s, several authors have recognized the existence of *reduced* knee dislocations. These are knees that present to the treating physician as reduced but have multiple injured ligaments (usually including both cruciate ligaments) and gross instability on stress testing. Some of these injuries represent a spontaneous reduction of a knee dislocation and others are dislocated knees that are reduced in the field before transport to a medical facility. The incidence of this type of reduced knee dislocation may be as high as 50% of all knee injuries classified as a dislocation.[5,35,39] A study from our institution showed that the incidence of vascular injury in reduced dislocations was equal to that of knees that presented as dislocated (Fig. 21-1).[39] Recent studies have shown the risk of arterial injury ranges from 3% to 43% in knees diagnosed as dislocated.[3,15,19,33,40] Clinicians must be alert to the presence of reduced dislocations so as not to miss a limb-threatening arterial injury. A multiligament-injured knee with gross instability must be treated the same as a knee that presents as dislocated.

Although most knee dislocations involve tears of both cruciate ligaments (posterior cruciate ligament [PCL] and anterior cruciate ligament [ACL]), case reports of cruciate intact knee dislocations do exist. A PCL-intact knee dislocation was first described in 1975.[16] Some authors[4,30] have reported on patients with a radiographically documented knee dislocation that, upon reduction, demonstrated an intact, functional cruciate ligament on physical examination or at the time of operative exploration. Although some of these patients were noted to have sustained partial PCL tears, the presence of a functional PCL provides increased stability and changes the management of these PCL-intact dislocations. In most PCL-intact knee dislocations, the tibia is perched anterior on the distal femur (Fig. 21-2). In addition to an ACL tear, there is often complete rupture of either the medial collateral ligament (MCL) or posterolateral structures.

Similarly, ACL-intact knee dislocations have also been reported. These are also extremely rare injuries. The tibia is perched posterior on the femur, and there is a complete tear of the PCL associated with a complete collateral ligament injury. Again, the presence of a functional ACL provides increased stability in the knee and changes the management of these injuries. A classification system for knee dislocations must take into account the presence of both reduced and cruciate-intact knee dislocations.

CRITICAL POINTS Assessment of Knee Dislocations

- Clinicians must be alert to the presence of "reduced" dislocations so as not to miss a limb-threatening arterial injury.
- Although rare, cruciate-intact knee dislocations do occur, adding to the stability of the knee and changing the management of these injuries.
- A classification system for knee dislocations must take into account the presence of both reduced and cruciate-intact knee dislocations.

POSITION CLASSIFICATION SYSTEM

In 1963, Kennedy[14] was the first to classify knee dislocations. He proposed a classification system based on the tibial position with respect to the femur. For example, an anterior knee dislocation implies that

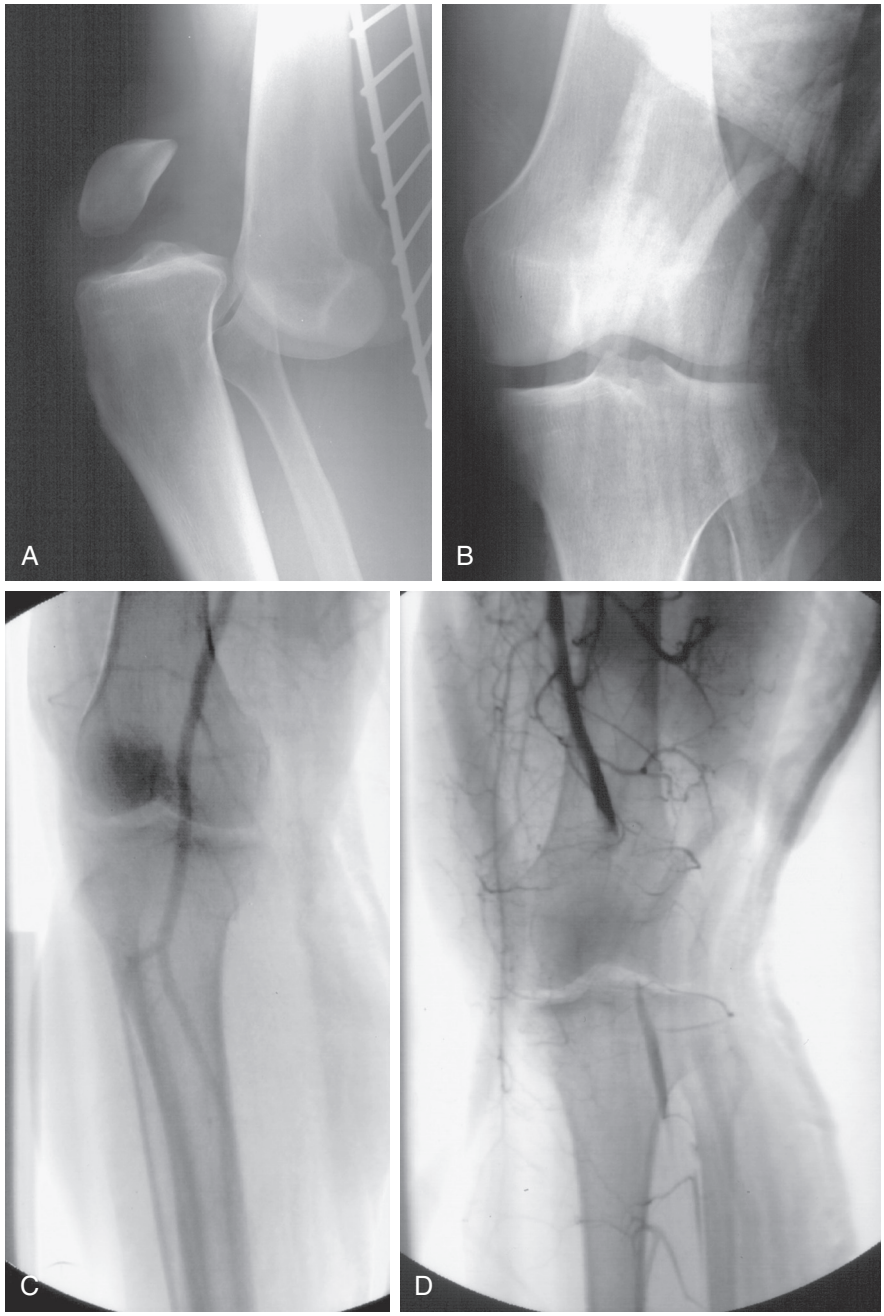


FIG 21-1 Bilateral knee injuries, both classified as dislocation, presenting in the same patient. **A,** A lateral radiograph of the right knee demonstrates an anterior dislocation. On examination, the patient was noted to have sustained an anterior cruciate ligament/posterior cruciate ligament/medial collateral ligament (ACL/PCL/MCL) injury (knee dislocation [KD] III-M). **B,** An anteroposterior view of the left knee on initial presentation shows the knee is reduced. On physical examination, the injury pattern involved the ACL/PCL/fibular collateral ligament (FCL) (KD III-L-C). **C,** An arteriogram of the right knee reveals good flow through the popliteal artery. **D,** An arteriogram of the reduced left knee demonstrates complete occlusion of the left popliteal artery and hence required revascularization. (From Wascher DC. High-energy knee dislocations. In: Drez D Jr, DeLee JC, eds. *Operative Techniques in Sports Medicine*, vol 11. Philadelphia: Saunders; 2003: 235-245.)

the tibia is positioned anterior to the femoral condyles. Kennedy identified five types of knee dislocation: anterior, posterior, lateral, medial, and rotatory. Rotatory dislocations were further subdivided into four groups: anteromedial, anterolateral, posteromedial, and posterolateral.[8,10,20,21] This classification system has been widely used in the literature.[6,8,13,16,20-22,29,31,32,34]

The position classification system can help the physician plan a reduction maneuver for the dislocated knee. However, most knee dislocations can be easily reduced with longitudinal traction. The position classification system can also be useful to alert the clinician to the possibility of coexisting injuries. For example, studies have shown a higher incidence of popliteal artery injury in anterior dislocations.[14]



FIG 21-2 This patient presented with a posterior cruciate ligament–intact knee dislocation. Note how the tibia is perched anterior on the distal femur. This type of injury would be classified as KD I according to the anatomic classification system, to be discussed later.

CRITICAL POINTS Position Classification System

The position classification system is based on the tibial position with respect to the femur.

Uses

- For a posterolateral knee dislocation, the position classification alerts the clinician to the injured structures and the means of treating the injury.
- The position classification system can help the physician to plan a reduction maneuver for the dislocated knee, although most knee dislocations can be easily reduced with longitudinal traction.
- The position classification system can alert the clinician to the possibility and type of co-existing injuries (neurovascular), although vascular injury can occur with any position of knee dislocation.

Limitations

- Up to half of knee dislocations are unable to be classified.
- Reduced knees cannot be described within the structure of the position classification system.
- The position classification system does not give any information about what structures (ligamentous, neurovascular) have been injured and what treatment is required, with the exception of the posterolateral dislocation.

Knowledge of the position of dislocation along with an understanding of the biomechanics of the knee may also provide the clinician with useful information regarding the type of arterial injury. Anterior dislocation often causes arterial stretch injuries and resultant intimal tears, with possible delayed progression to thrombosis and limb-threatening distal ischemia. Posterior dislocations predispose to popliteal artery disruptions largely because of the popliteal artery's fixed tethers proximally at the adductor hiatus and distally at the fascial arch of the soleus.[7] However, any type of vascular injury can occur with any position of knee dislocation and one must have a high index of suspicion for associated acute and delayed vascular injuries in any dislocated knee, regardless of position. Although knowing that anterior dislocation carries an increased risk of vascular injury and that arterial stretch injuries may have a delayed clinical presentation is helpful to the clinician, information is not provided regarding which structures (ligamentous, neurovascular) have been injured and what treatment is required.

Another example of the use of the position classification is the rare but important posterolateral dislocation (Fig. 21-3). The mechanism of injury is an abduction force to a flexed knee coupled with internal rotation of the tibia. This force causes the medial femoral condyle to "buttonhole" through the medial capsule and the MCL invaginates into the knee joint. The trapped condyle and MCL prevent closed reduction. The clinical hallmark of the posterolateral dislocation is a transverse furrow seen on the medial aspect of the knee.[10,21] Peroneal nerve palsy, theoretically resulting from a traction injury to the nerve over the lateral femoral condyle, is frequently associated with this type of dislocation. Skin necrosis secondary to pressure from the medially displaced femur has also been reported. For a posterolateral knee dislocation, the position classification system alerts the clinician to the injured structures (ACL, PCL, or MCL) and the means of treating the injury (open reduction).

The major limitation of the position classification system is that up to half of knee dislocations are unable to be classified. Knees that present with a spontaneous reduction or that have been reduced in the field cannot be described. The clinician does not have information regarding damaged ligaments nor of the possibility of coexisting vascular or nerve injury. Even more dangerous is the fact that because this injury is not included in the position classification system, the inexperienced physician may not recognize the reduced knee dislocation as a significant ligamentous injury and will not undertake the rigorous vascular examination required to detect a popliteal artery injury.

ENERGY OF INJURY CLASSIFICATION SYSTEM

Knee dislocations have also been classified by the degree of energy imparted to the knee joint. Most commonly, knee dislocations result from high-energy mechanisms such as motor vehicle wrecks, industrial accidents, and falls from a height (Fig. 21-4). The injury mechanisms in high-energy knee dislocations often cause significant associated head, chest, abdominal, and extremity injuries as well as soft tissue injury about the affected knee. Many of these injuries can be life threatening and their management takes precedent over the knee ligaments. Regardless of the energy of injury, the clinician must remain vigilant about the possibility of a popliteal artery injury in any knee dislocation. The orthopedic surgeon must be alerted to the possibility of other life-threatening trauma in a patient with a knee dislocation. Conversely, trauma surgeons must include a gross assessment of knee stability in all patients involved in high-energy injury mechanisms. The risk of vascular and nerve injury is increased in high-energy knee dislocations.[14,18,29,38]

Knee dislocations can also occur from low-energy trauma such as that seen in sports activities or in minor falls from low heights. Sports where knee dislocations are occasionally encountered include football, rugby, horseback riding, and alpine sports such as skiing or snowboarding. Patients who sustain low-energy knee dislocations rarely

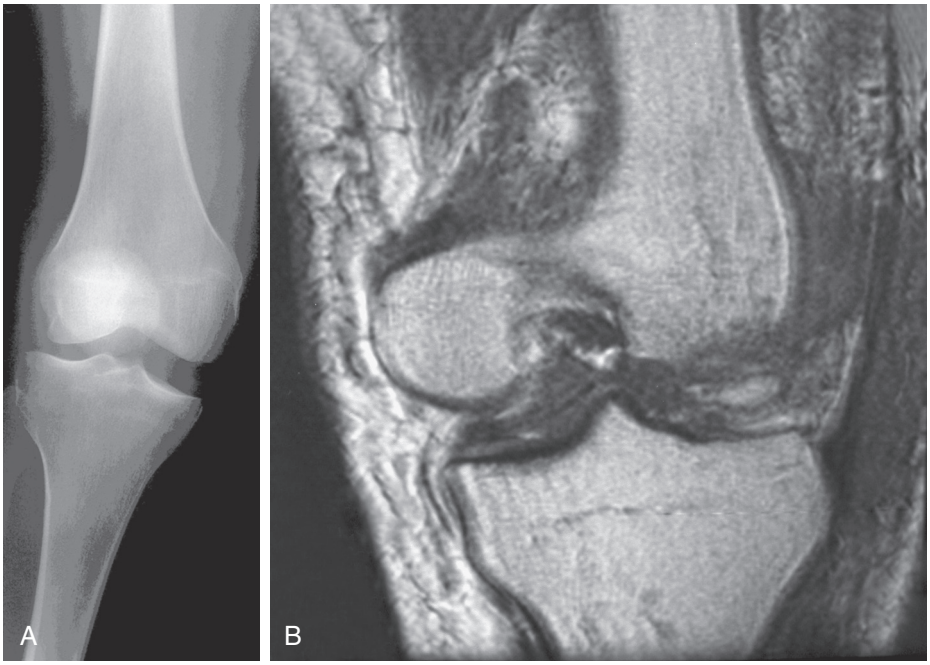


FIG 21-3 Anteroposterior radiograph (**A**) and magnetic resonance image (**B**) of a posterolateral dislocation. The injury pattern involved the anterior cruciate ligament/posterior cruciate ligament/medial collateral ligament and included damage to the peroneal nerve (KD III-M-N).



FIG 21-4 This patient sustained a severe dashboard injury in a high-speed car accident. He presented with a severe open knee dislocation, with rupture of the anterior cruciate ligament/posterior cruciate ligament/fibular collateral ligament and posterolateral capsule (KD III-L). (From Wascher DC. High-velocity knee dislocation with vascular injury: treatment principles. In Miller MD, Johnson DL., eds. *Clinics in Sports Medicine: The Dislocated Knee*, vol. 19. Philadelphia: Saunders; 2000:467.)

CRITICAL POINTS Energy of Injury Classification System

The energy of injury classification system is based on the degree of energy imparted to the knee joint.

Uses

- The energy of injury classification system often dictates management of the dislocated knee (early versus delayed treatment).
- High-energy knee dislocations (e.g., motor vehicle accident) alert the physician to the increased risk of vascular and nerve injury, although vascular injury can occur regardless of the energy of injury.
- Ultra-low-velocity knee dislocations may act more like high-energy injuries, with a high incidence of vascular injury and poorer clinical outcomes. A high clinical suspicion is required to avoid missed injuries and to optimize management.

Limitations

- The energy of injury classification system categories are somewhat arbitrary.
- The energy of injury classification system does not alert the orthopedic surgeon as to which knee structures (ligamentous, neurovascular) have been injured and what treatment is required.

have associated traumatic injuries. Although the risk of vascular injury is lower in low-energy mechanisms, the physician must still be vigilant in assessing the popliteal artery in all patients with a knee dislocation.

In the past, knee dislocations have been described as low- or high-velocity injuries.[29] Recently, Azar and colleagues[3] proposed a third group of patients presenting to emergency departments with increasing frequency. These are morbidly obese individuals who present with a dislocated knee from a fall from standing height or from stepping awkwardly. They termed this group *ultra-low-velocity (ULV) knee dislocation*.[3,40] These patients tend to have a body mass index (BMI) greater than 48 kg/m^2 and are more commonly female. Because $E_k = 1/2mv^2$, the large mass in these patients can still produce enough energy to dislocate the knee despite the very low velocity involved. Reports regarding this cohort of patients are largely responsible for the increased incidence of vascular injury among knee dislocations because they are much more likely to have associated vascular and neurologic injury than even high-velocity knee dislocations. Recent literature has

reported popliteal artery injury and neurologic injury rates as high as 43% in this population.[3] Initial examination and imaging (magnetic resonance imaging [MRI]) is often limited because of body habitus, and postoperative rehabilitation and bracing are often challenging given body habitus and limited mobility. This group presents specific challenges at presentation and throughout treatment that require clinical diligence to minimize complications and to maximize treatment outcomes.

It is our opinion that the term *energy*, rather than the term *velocity*, more accurately describes the injury mechanism. Notwithstanding the mechanism, the energy of injury often dictates management of the dislocated knee. The associated injuries in high-energy dislocations frequently preclude early operative management of the knee ligaments. Initial management of the knee dislocation in a patient with multiple injuries commonly includes the use of external fixation spanning the knee joint to stabilize the knee in a reduced position and to facilitate patient transport and positioning. The use of an external fixator to maintain reduction and allow some soft tissue healing must be balanced against the risk of arthrofibrosis with prolonged use. Delayed treatment of high-energy dislocations often requires collateral ligament reconstruction in addition to reconstruction of both cruciate ligaments. Conversely, low-energy dislocations can frequently undergo early operative intervention. The collateral ligaments can often be primarily repaired or reconstructed, yielding superior results compared to that obtained with delayed reconstruction. ULV knee dislocations present additional treatment challenges. These patients tend to do poorly with nonoperative treatment, but their size and medical comorbidities (diabetes mellitus, compromised circulation, and cardiopulmonary disease) make surgical treatment difficult and risky. Patients who sustain ULV knee dislocations have been shown to have higher rates of surgical complications, including reoperation rates, wound infection, deep venous thrombosis, vascular claudication, and above-knee amputation. In addition, this cohort has demonstrated poorer outcome scores compared with low-velocity dislocations.[3]

One of the problems with the energy of injury classification system is that the categories are somewhat arbitrary. If a patient sustains a knee dislocation when hit by a slow-speed car in a parking lot, is this a high- or low-energy dislocation? What about a patient who falls off a roof or a high tower? At what weight does a ULV dislocation become high-energy? Although it is useful for the clinician to think in terms of the energy imparted to the knee, ultimately it is the pattern of ligamentous injury, the presence or absence of neurovascular injuries, and the overall clinical assessment that will dictate treatment of the knee dislocation. A morbidly obese patient with a major psychiatric illness who dislocates a knee slipping on a wet bathroom floor (low-energy dislocation) may be treated definitively with external fixation. Conversely, an athletic patient with an isolated knee dislocation from a motorcycle wreck (high-energy dislocation) might be best treated by early ligament repair or reconstruction. Finally, the energy of injury classification system does not assist the orthopedic surgeon in planning which knee structures need to be repaired or reconstructed.

ANATOMIC CLASSIFICATION SYSTEM

A classification system for knee dislocations has been described and is based on which ligamentous structures are torn.[35] The ligament anatomy of the knee is complex, with many injury patterns possible when a knee dislocation occurs.[26,27,39] Conceptually, the knee can be separated into four simply identifiable structures: the ACL, the PCL, the medial ligamentous structures, and the posterolateral corner. The medial structures include the superficial and deep MCL as well as the oblique popliteal ligament, semimembranosus, and posteromedial capsule. The posterolateral corner is primarily composed of the fibular (lateral) collateral ligament, the popliteofibular ligament, the popliteus tendon, and the lateral joint capsule. This simplistic representation of knee anatomy can be useful to the clinician in planning treatment of a dislocated knee.

To classify a knee dislocation by the injured anatomy, it is important to obtain a complete assessment of the injured knee. The clinician must perform a thorough physical examination of the knee on initial presentation to the emergency room or office. At a minimum, this should include a Lachman test, a posterior drawer test, varus and valgus stress testing at 0 degrees and 30 degrees, and a spin or dial test at 30 degrees and 90 degrees in the prone and supine positions.

A thorough neurovascular examination must also be performed and repeated at regular intervals. Vascular evaluation using angiography has previously been recommended for all knee dislocations. In addition to complete arterial transections or occlusions, angiography has the ability to identify intimal flap tears. Because of the morbidity and cost of angiography, Stannard and colleagues[33] have proposed the use of selective angiography. They have suggested a protocol that uses angiography only when triggered by abnormal ankle brachial indices (ABIs) or change/asymmetry in serial examination performed at regular intervals for 48 hours by both nursing staff and the on-call physician.[33] This vascular screening protocol has a very high sensitivity for identifying clinically significant arterial injury.[9] In addition, many patients with high-energy knee dislocations have associated injuries that are evaluated by computed tomography (CT) scanning. In these patients, it is relatively easy to simultaneously perform a CT angiogram to evaluate the popliteal artery. It has been shown that multislice CT angiography is an alternative to the traditional gold standard of catheter-based angiography that is both sensitive and specific for arterial evaluation in the injured lower extremity.[12]

CRITICAL POINTS Anatomic Classification System

The anatomic classification system for knee dislocations is based on the anatomic structures injured.

- The anatomic classification system requires a thorough ligamentous and serial neurovascular assessment of the knee, consisting of three parts: an initial examination in the trauma room or office, a preoperative magnetic resonance imaging study, and an examination under anesthesia at the time of surgery.
- The anatomic classification system describes five major ligamentous injury patterns and associated neurovascular injury (if applicable).

Advantages

- All knee dislocations can be adequately described by the anatomic classification system, even those presenting as reduced.
- No judgment is required for placing a dislocated knee within a specific group.
- The anatomic classification system has the ability to help guide the clinician in treatment by simple and accurate identification of the injured structures and planning of surgical intervention.
- The anatomic classification system rapidly communicates the extent of the injuries among clinicians and allows for comparisons of like injuries in the wide spectrum of knee dislocations.
- The anatomic classification system helps the clinician predict outcomes in the treatment of dislocated knees.

A complete neurologic examination may be difficult in a patient with head trauma, but in most cases, a gross assessment of tibial and peroneal nerve function can be obtained. As soon as the patient's overall condition allows, we recommend obtaining an MRI of the knee to better assess the degree and location of ligament injuries. Authors[23] have commented on the use of MRI in the evaluation of ligament injury in knee dislocations. Certain injuries (e.g., the presence of a PCL peel-off injury or a popliteus tendon avulsion) can only be accurately detected preoperatively by MRI. Knowing preoperatively which ligaments are torn and detecting the presence of avulsions can help the surgeon plan the number and types of allograft required and the fixation devices necessary to restore functional stability to the knee.[25,28,36] The final and most critical assessment of knee ligament function occurs with an examination under anesthesia (EUA) at the time of knee reconstruction. The EUA provides a final assessment of the degree of translation, the presence of an endpoint on ligament stress testing, and the overall functionality of the specific ligamentous structure. Although MRI can identify which ligaments are injured, the EUA gives an accurate assessment of the functional status of the injured knee ligaments.[1,11,27,30,37] In the dislocated knee, partial ligament tears can sometimes be treated nonoperatively. To summarize, the assessment of the dislocated knee consists of four parts: an initial examination in the trauma room or office, vascular imaging or serial neurovascular exams, a preoperative MRI, and an EUA at the time of surgery.

The anatomic classification of knee dislocation (KD) is a simple system based on which ligaments are torn. Five major injury patterns may occur (Table 21-1). Injuries are classified by roman numerals; in general, higher-number injuries have sustained greater trauma than lower-number injuries. A *KD I* injury is a cruciate-intact knee dislocation and includes both PCL-intact and ACL-intact injuries (see Fig. 21-2). A *KD II* injury is a bicruciate injury with functionally intact collateral ligaments (Fig. 21-5). *KD III*, the most common injury pattern, involves tears of both cruciate ligaments and one of the collateral ligaments. These injuries are further subdivided into medial (KD III-M; Fig. 21-6) or lateral (KD III-L; Fig. 21-7) injuries. A *KD IV* injury involves complete disruption of all four major knee ligaments (Fig. 21-8). Finally, the *KD V* injury group involves a knee dislocation with the presence of a major periarticular fracture and is described by other authors as a fracture-dislocation of the knee (Fig. 21-9).[17,28] Fracture-dislocations of the knee involve a ligamentous injury to the knee in association with a major fracture of the tibial plateau or femoral condyles that further destabilize the knee joint. Although avulsion injuries are frequently seen in purely ligamentous knee dislocations (arcuate avulsion fractures, tibial spine avulsions, or Segond fractures), they should be classified as a ligamentous injury in one of the first four categories, despite the small fracture present.[6,32]

TABLE 21-1 Anatomic Classification of Knee Dislocations

Class*	Injury
KD I	PCL- or ACL-intact KD, variable collateral involvement
KD II	Both cruciate ligaments torn, collaterals intact
KD III	Both cruciate ligaments torn, one collateral torn, subset M or L
KD IV	All four ligaments torn
KD V	Periarticular fracture-dislocation

*Subtypes are C for arterial injury and N for nerve injury.
ACL, Anterior cruciate ligament; *KD*, knee dislocation; *L*, lateral; *M*, medial; *PCL*, posterior cruciate ligament.

The final component of the anatomic classification is the use of additional labels to identify associated neurovascular injuries. A subtype C indicates a significant arterial injury and alerts the clinician to the need for revascularization of the limb. A subtype N indicates a peripheral nerve injury, either the tibial nerve or, more commonly, the peroneal nerve. This N subtype is used for any neurologic deficit (neurapraxia, neurotmesis, or axonotmesis). For example, a dislocated knee with complete tears of the ACL, PCL, and posterolateral corner with an associated popliteal artery injury and a peroneal nerve palsy would be classified as a *KD III-L-CN*.

The anatomic classification has significant advantages over older classifications. Unlike the position classification, all knee dislocations can adequately be described by the anatomic classification system. Even knee dislocations presenting as reduced can be classified after a physical examination and MRI have identified the torn ligaments and associated injuries. In contrast to the energy of injury classification system, no judgment is required for placing a dislocated knee within a specific group. If a ligament is injured and functionally incompetent, it is "torn" for the purposes of the anatomic classification system. Most important, however, is the ability of the anatomic classification system to help guide the clinician in treatment. The surgeon can readily identify the injured structures and can then proceed to plan how best to "fix what is torn." The anatomic classification rapidly communicates among clinicians the extent of the injuries and allows for comparisons of similar injuries in the wide spectrum of knee dislocations. At our institution, residents and attending physicians quickly describe the ACL/PCL/MCL knee injury as a KD III-M. The injury diagnosis and ligamentous involvement are easily communicated. Here are a few additional examples of the usefulness of the anatomic classification: The C subtype quickly alerts the physician to the need for urgent vascular surgery to restore flow to the ischemic limb. A KD II injury has functionally intact collateral ligaments and can be treated just as successfully with either an early or a delayed reconstruction of the cruciate ligaments. Studies of the degree of injury show that KD III-M



FIG 21-5 Lateral radiograph demonstrating a bicruciate injury with functionally intact collateral ligaments (KD II).

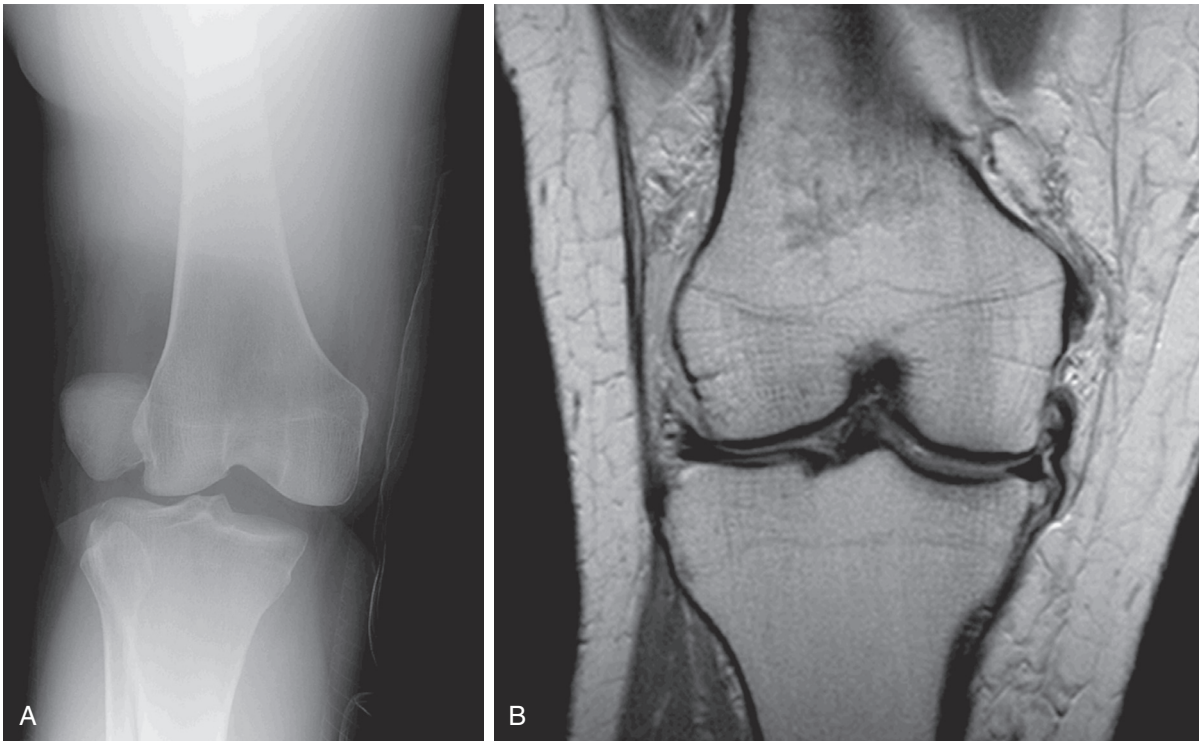


FIG 21-6 Anteroposterior radiograph (**A**) and magnetic resonance imaging (**B**) of a bicruciate injury with involvement of the medial collateral ligament (KD III-M).

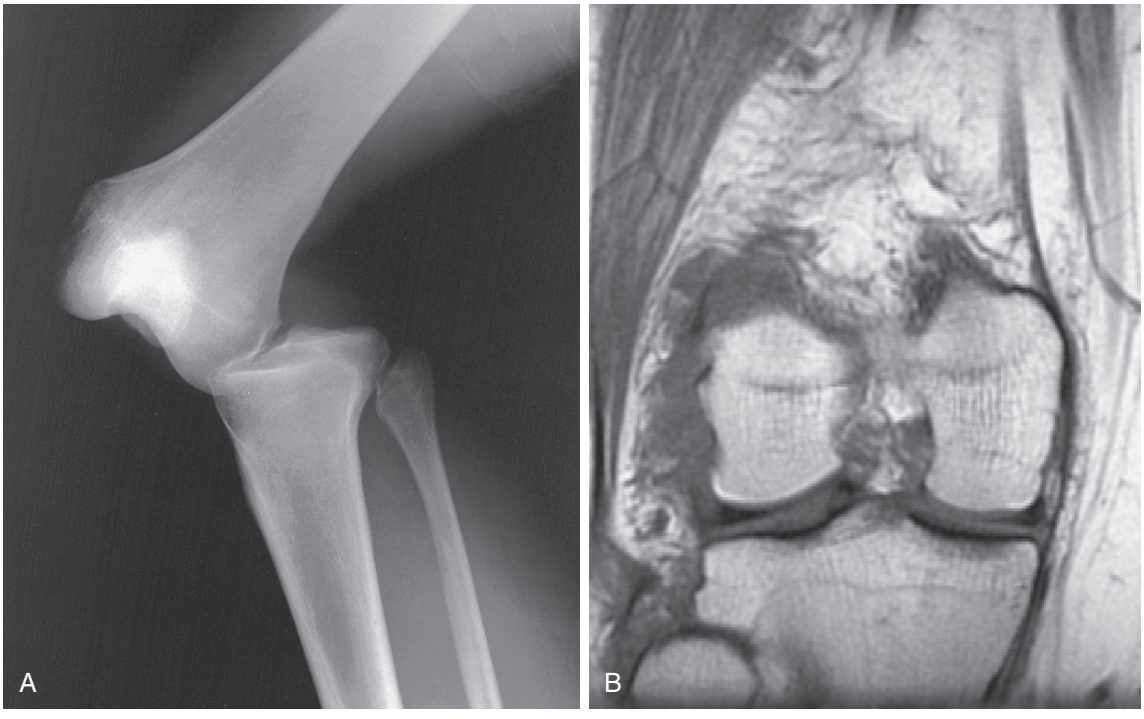


FIG 21-7 Lateral radiograph (**A**) and magnetic resonance imaging (**B**) of a bicruciate injury with involvement of the fibular collateral ligament (KD III-L).

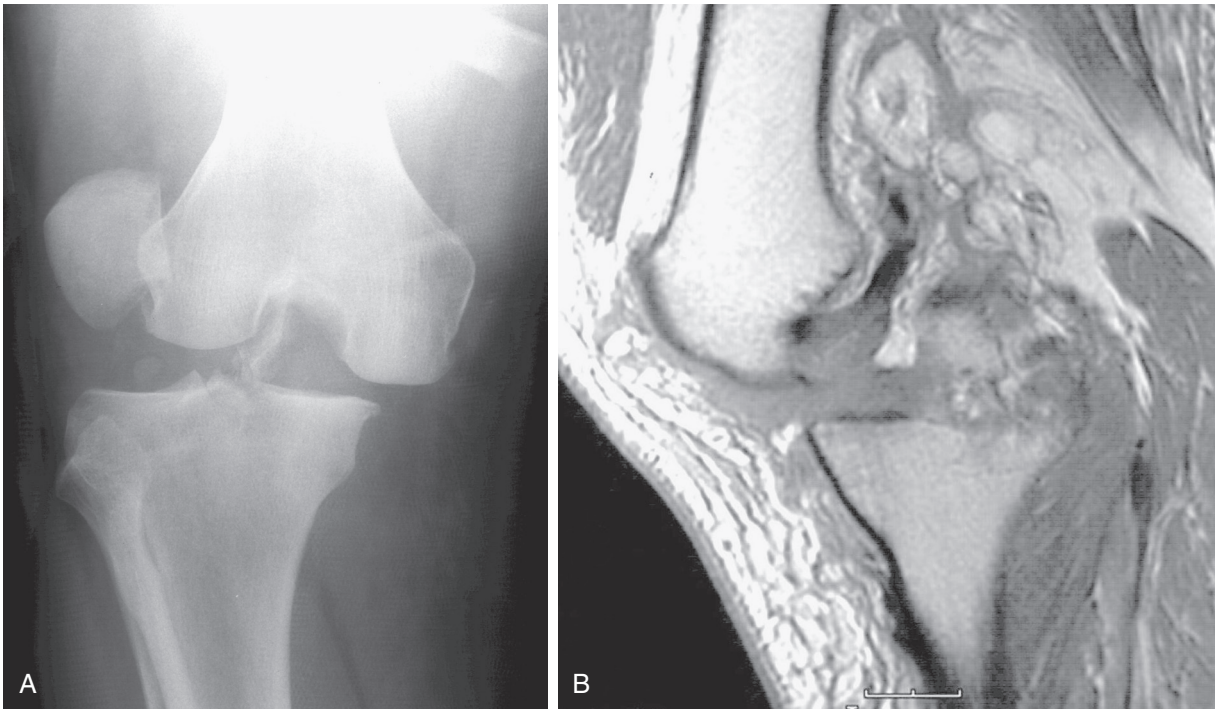


FIG 21-8 Anteroposterior radiograph (**A**) and magnetic resonance imaging (**B**) demonstrating complete disruption of all four major knee ligaments (KD IV).



FIG 21-9 Anteriorposterior radiograph demonstrates a knee dislocation with the presence of a major periarticular fracture (KD V). In this case, the patient has a femoral-sided fracture-dislocation, which includes a fracture of the medial epicondyle. (Courtesy Robert Schenck Jr.)

injuries more frequently have complete deep MCL tears and posterior oblique ligament tears compared with KD IV injuries, which may aid in the decision of medial-side reconstruction versus nonoperative management.[41] A KD IV injury identifies a knee with severe instability that may require external fixation to maintain joint reduction before ligament reconstruction.

Finally, the anatomic classification system will help the clinician predict outcomes in the treatment of dislocated knees. On average, knees with higher roman numeral classification will have inferior outcome scores. For example, KD III-M knees have better Lysholm scores than KD IV knees.[41] Likewise, it has been shown that KD III-L injuries fare worse than KD III-M injuries.[5,35] Knee dislocations with neurovascular injuries (subtypes C or N) are also more likely to have unsatisfactory outcome measurements. KD V injuries are associated with a high complication rate related to the increased incidence of arterial injury, inadequate fracture reduction, or difficulty in achieving a satisfactory ligament reconstruction.

CONCLUSION

Successful treatment of the dislocated knee requires a thorough understanding of the knee injury. Older classification systems are not able to categorize all knee dislocations, do not guide treatment, and are not predictive of outcome. The anatomic classification we have used for the past 20 years readily allows the physician to classify all knee dislocations on the basis of the injured structures identified by physical examination and imaging studies. This simple system helps the surgeon plan treatment of the dislocated knee and has been predictive of outcomes in published reports. Hopefully, more widespread use and reporting of this classification system in future series of knee dislocations will yield additional insight into the optimal treatment of these uncommon yet challenging injuries.

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22

Management of Acute Knee Dislocation Before Surgical Intervention

K. Linnea Welton, Geoffrey A. Bernas, Edward M. Wojtys

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INTRODUCTION

Knee dislocations are uncommon but serious injuries. These injuries not only pose a potential threat to the limb involved, but often result in long-term pain and functional disability. What was thought to be an injury pattern caused by high-energy collision in motor vehicles or in collision sports, has also emerged as a common diagnosis in the ever-increasing obese population. Although diagnosis and initial management principles have progressed over the past several decades, ultimate treatment strategies remain controversial. Having a high index of suspicion and taking the right steps in initial evaluation and management are paramount to maximize potential outcomes and avoid disastrous consequences associated with these complex injuries.

EVALUATION

Knee dislocations are typically the result of high-energy, violent trauma. Therefore the initial evaluation should always begin in the same fashion as that for a polytrauma patient. Where appropriate, a primary survey consisting of assessment of the patient's airway, breathing, and circulation (ABCs) is performed first. The secondary survey seeks life-threatening injuries and conditions. Polytrauma patients require a thorough neurologic and vascular examination, followed by an assessment of the chest, abdomen, and pelvis in addition to a detailed musculoskeletal examination of the extremities and spine. Whenever possible, the medical history should be reviewed while the patient is assessed for common polytrauma conditions, such as hypovolemia and concussion. Once the basics of trauma care have been attended to, the injured extremity should be carefully examined.

The vascular and neurologic examinations are of utmost importance and are detailed in the following sections. Starting with visual inspection, all open injury sites should be identified and cleansed. Palpation of bony prominences, areas of soft tissue swelling, and key insertion sites provides important information. If possible, the extensor mechanism should be tested to ensure the status of the quadriceps and patellar tendon. If the patient is unconscious or cannot cooperate, these structures should undergo magnetic resonance imaging (MRI) followed by a physical examination, when possible. Lastly, a complete ligament examination is conducted to assess the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), fibular collateral ligament (FCL), medial collateral ligament (MCL), and posterolateral and posteromedial structures using translation and rotation testing. Stress view imaging may be helpful, but may not be appropriate in the acute setting.

CRITICAL POINTS Evaluation

- Polytrauma patients require a thorough neurologic/vascular examination followed by an assessment of the chest, abdomen, and pelvis along with a detailed musculoskeletal examination of the extremities and spine.

CLASSIFICATION

A patient with two or more torn major ligaments may have sustained a knee dislocation.[78] This definition accounts not only for those knees that are dislocated at the time of evaluation but also for those that have spontaneously reduced. Clinically, the degree of ligament disruption can be misleading. Because ligaments may not appear completely disrupted, especially on MRI, the severity of these injuries can be easily underestimated.

The following variables are the basis for classification and complete description of a dislocated knee: (1) direction of dislocation, (2) open or closed, (3) high- or low-energy trauma, and (4) time from dislocation.[25] Schenck[72] has also recommended that the extent of ligamentous injury be included in the classification of knee dislocations (see Chapter 21).

The direction of dislocation may be unidimensional (anterior, posterior, medial, or lateral) or a rotatory combination. If the knee has spontaneously reduced, classification is based on direction of instability.[67] Anterior dislocations caused by hyperextension of the knee are the most common, occurring in 40% according to Green and Allen's review[26] of 245 knee dislocations. Posterior dislocations, often caused by a high-energy dashboard mechanism, accounted for 33% of the cases. Medial and lateral dislocations were present in 18% and 4% of the cases, respectively.

CRITICAL POINTS Classification

- A patient with two or more torn major ligaments may have sustained a knee dislocation.
- Because ligaments can stretch and may not appear completely disrupted, especially on magnetic resonance imaging, the severity of these injuries can be easily underestimated.

In 1963, Kennedy's biomechanic study[38] in cadavers elucidated the mechanisms for both anterior and posterior dislocations. This investigation demonstrated that by progressively hyperextending the knee, the posterior capsule ruptured followed by the posterior cruciate ligament (PCL) and the anterior cruciate ligament (ACL). Without adequate ligamentous restraint, the knee dislocated in an anterior direction. A high posteriorly directed force on the proximal tibia in knee flexion caused a posterior dislocation.

Posterolateral dislocations are the most common type of rotatory dislocations. The flexed and weight-bearing knee undergoes a sudden rotatory moment that abducts and internally rotates the lower leg on the femur.[65] This causes the medial femoral condyle to "buttonhole" through the anteromedial capsule, which may be irreducible. Inspection of the knee will reveal a transverse groove in the skin along the medial joint line secondary to invagination of the medial capsule. This "dimple sign" becomes more prominent with attempted reduction and is pathognomonic of the irreducible posterolateral dislocation.[25,59,66,69,71]

Open dislocations of the knee are emergencies that require antibiotics and urgent irrigation and debridement in the operating room. Open injuries, present in 19% to 35% of knee dislocations, are most commonly seen with anterior and posterior mechanisms.[54,79]

VASCULAR INJURIES

Knee dislocations associated with arterial trauma are limb-threatening injuries. The incidence of popliteal artery disruption during a knee dislocation is 32% to 45%.[26,35] Delay in diagnosis longer than 6 to 8 hours is associated with an increasing amputation rate.[26,35] Because of the high rate of injury and the devastating consequences associated with a delay in diagnosis, it is imperative to recognize vascular injuries early.

It is not clear yet how many vascular injuries require surgery, but several recent studies have sought to answer this question. In a nationwide population-based study in Finland between 1998 and 2011, the occurrence of popliteal injury requiring surgical interventions was 1.6%.[80] Using the Finnish Hospital Discharge Register and International Classification of Diseases, Tenth Revision (ICD-10) diagnoses, this study extracted all adult patients who were admitted to Finnish hospitals with an acute knee dislocation and characterized them further based on the presence and type of operation performed. A total of 837 patients over this 14-year period were hospitalized with a primary or secondary diagnosis of acute knee dislocation and 84% required some form of surgical intervention. Of the 1.6% (13) of patients who had a vascular injury requiring surgical repair, all involved the popliteal artery. The surgeries performed included bypass surgery from the femoral artery to the distal popliteal artery (nine cases), direct repair of the popliteal artery (one case), and a nonspecified bypass operation (three cases).[80]

Another recent study, with differing results was a systematic review by Medina et al.[51] After an initial Medline search for "knee dislocation" and "multiligament knee," 15 studies met the final inclusion criteria, totaling 862 patients. The frequency of vascular injury was 20% (171 of 862), and 84% (134 of 160) underwent surgical intervention. Seventy-six percent of the studies reported injury to only the popliteal artery; other vessels included the medial genicular artery, anterior tibial artery, posterior tibial artery, superficial femoral artery, and common femoral artery. Of the 134 vascular injuries requiring surgical repair, 22 underwent amputation, yielding an amputation frequency of 12% for those with popliteal artery injury. The majority (73%, 16 of 22) of amputations were performed because of infection or ischemia subsequent to failed vascular repair, while the remainder of amputations were performed at presentation because of prolonged ischemia or complete neurovascular disruption. The Schenck and Kennedy[38,74] knee dislocation classifications with the highest vascular injury prevalence involved the ACL, PCL, and lateral collateral ligament (KD III-L, 32%) and posterior dislocation (25%).[51]

CRITICAL POINTS Vascular Injuries

- Arterial trauma associated with knee dislocations are limb-threatening injuries. The incidence of popliteal artery disruption during a knee dislocation is 32% to 45%. Delay in diagnosis longer than 6 to 8 hours is associated with an increasing amputation rate.
- The diagnosis of a vascular injury should be made on the assimilation of a variety of clinical and diagnostic tests: physical examination, ankle/brachial index (ABI), and arteriography.
- The presence of pulses with a warm foot is not a guarantee that an arterial injury is not present.
- An ABI of less than 0.90 is abnormal and should prompt arteriography. A selective angiography algorithm has become the gold standard in vascular injury assessment and management in the setting of acute knee dislocations.
- Hard signs for emergent surgical exploration with or without angiography include absent distal pulses, active hemorrhage, and/or expanding pulsatile hematoma.
- Clinicians should be aware that not all arterial trauma is detectable with arteriography. Stretch injuries of the intimal wall and small intimal flap tears may not be visualized on the arteriogram but may subsequently clot and result in arterial occlusion.

Despite the continued discrepancy in the true frequency of vascular injuries requiring surgical intervention, an abnormal vascular examination should prompt imaging and/or an immediate vascular surgery consultation.

The popliteal artery is at risk of injury during a knee dislocation owing to its anatomic location (Fig. 22-1). The popliteal artery is tethered proximally by the adductor hiatus and distally by the soleus arch. The artery bifurcates into the anterior and posterior branches at the soleus arch. Collateral circulation in the form of the genicular arteries originates within the popliteal fossa. The geniculate arterial system is usually not sufficient to perfuse the limb should there be obstruction or transection of the popliteal artery.[25,61] Anterior dislocations of the knee can place significant traction on the popliteal artery, leading to extensive intimal injury and/or vasospasm (Fig. 22-2).[26] Posterior dislocations can result in complete transection of the artery (Fig. 22-3).[62]

The diagnosis of a vascular injury should be made on the assimilation of a variety of clinical and diagnostic tests including physical examination, ankle/brachial index (ABI), and arteriography. The dorsalis pedis arterial pulse is palpated on dorsum of the foot, and the posterior tibial arterial pulse is palpable posterior to the medial malleolus. The presence of these pulses with a warm foot is not a guarantee that an arterial injury is not present. There are multiple reports of vascular occlusion or intimal tears with normal distal pulses; the incidence is 5% to 15%.[1,35,49,87] In 2004, Barnes and coworkers[6] performed a meta-analysis that included 284 multiligamentous knee injuries in

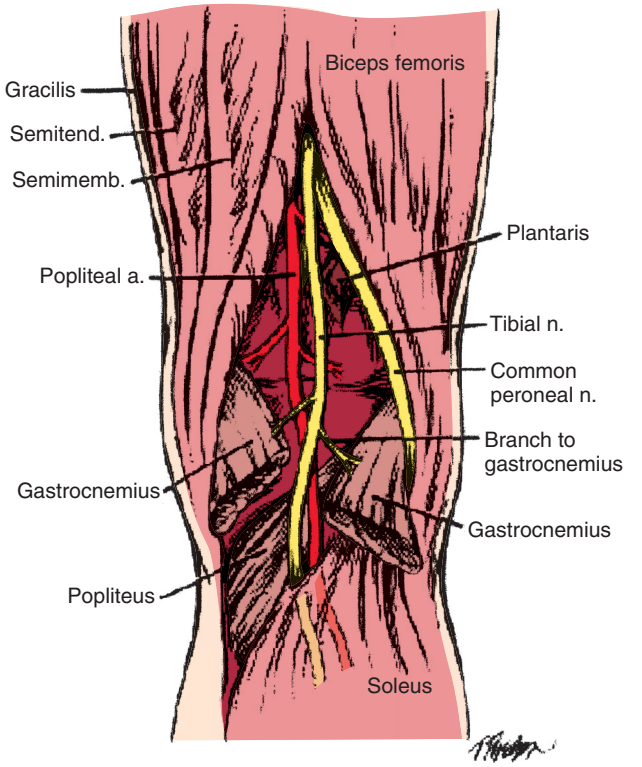


FIG 22-1 Schematic diagram of the sciatic, tibial, and common peroneal nerves and their relationship to the other structures in the popliteal fossa. *a,* Artery; *n.*, nerve; *semimemb.*, semimembranosus; *semitend.*, semitendinosus. (From Kim TK, Savino RM, McFarland EG, Cosgarea AJ. Neurovascular complications of knee arthroscopy. *Am J Sports Med.* 2002;30:619-629.)



FIG 22-2 Angiogram demonstrates diffuse irregularity in the popliteal artery with intimal dissection.

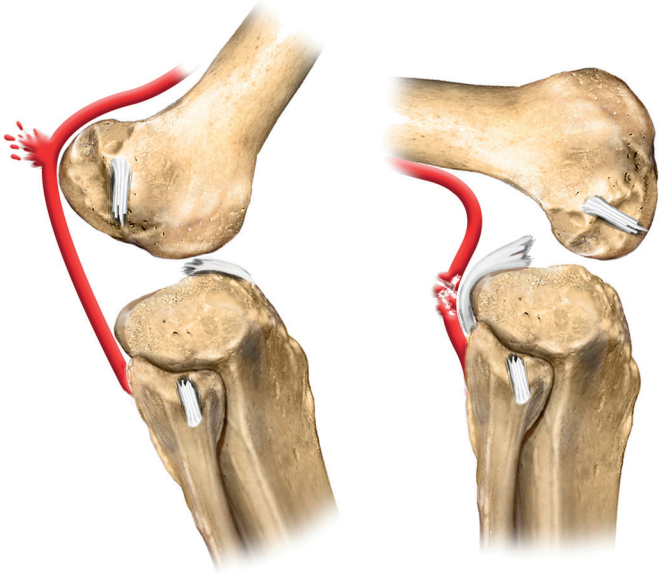


FIG 22-3 *Left,* An anterior knee dislocation demonstrates a traction injury to the popliteal artery. *Right,* A posterior dislocation demonstrates a transaction injury to the popliteal artery.

seven studies. Seven of 52 patients requiring vascular surgery had normal pulses on presentation. Thirteen of 140 patients with normal pulses who underwent arteriography had nonocclusive intimal defects that were safely observed. Abnormal pulses had a sensitivity rate of 0.79 (95% confidence interval [CI], 0.64-0.89), specificity rate of 0.91 (95% CI, 0.78-0.96), positive predictive value of 0.75 (95% CI, 0.61-0.83), and a negative predictive value of 0.93 (95% CI, 0.85-0.96). The low sensitivity and specificity may be associated with hypotension in the acutely traumatized patient, as well as intimal lesions that may initially present with normal pulses.

The ankle brachial index (ABI) is the second diagnostic tool that should be used and requires little technology. It is easy to perform, readily available, and capable of detecting serious vascular injuries and conditions. ABIs are determined by measuring the systolic blood pressure for all four extremities using a Doppler probe and a standardized blood pressure cuff. For the lower extremity, the systolic pressure is measured at the posterior tibial and dorsalis pedis arteries. The ABI is then calculated by dividing the highest measured pressure in the ankle or foot by the higher of the brachial arterial pressures. An ABI of less than 0.90 is considered abnormal and should prompt arteriography. In 2004, Mills and associates[55] demonstrated that 11 of 11 patients with ABIs less than 0.90 required a reverse saphenous vein graft for popliteal artery injury (3 popliteal artery transections, 6 popliteal artery occlusions, 1 common femoral and peroneal artery thrombosis, and 1 high-grade superficial femoral artery occlusion with intimal flap altering popliteal artery flow). None of the 27 patients with ABIs greater than 0.90 had evidence of vascular injury by serial examination or duplex ultrasonography. The sensitivity and specificity was 100%, making this an outstanding diagnostic test for serious vascular injuries and/or conditions.[55] In 1998, Cole and colleagues[11] evaluated 70 consecutive patients with blunt trauma and found no arterial injury with ABI greater than 0.90, whereas an ABI lower than 0.90 had a positive predictive value of 88%. Lynch and Johansen[46] studied blunt and penetrating trauma in 100 consecutive patients and found an ABI less than 0.90 predicted vascular surgery with a sensitivity of 87%, specificity of 97%, and positive predictive value of 91%.

Arteriography, developed in the 1960s, has improved outcomes and reduced the number of negative explorations. Many authors have

advocated routine use of arteriography to evaluate the limb after a suspected knee dislocation.[1,13,26,37,38,44,48,49,94] The routine use of arteriograms for suspected knee dislocations is justified by the relative low morbidity of the test, the high incidence of popliteal injury, and the devastating consequences of a delay in diagnosis.[67] However, clinicians should be aware that not all arterial trauma is detectable with arteriography. Stretch injuries of the intimal wall and small intimal flap tears may not be visualized on the arteriogram but may subsequently clot and result in arterial occlusion. Those patients whose conditions worsen usually do so within the first 3 months, but more commonly, within a week after injury. McDonough and Wojtys[50] reported on three patients with normal initial arteriograms. Two patients who had a loss of pulse after tourniquet release during ligament reconstruction were found to have chronic intimal flaps with thrombi at immediate revascularization. One patient developed a pseudoaneurysm, which was recognized by a second arteriogram undertaken after significant postoperative swelling.[50] These "silent injuries" should be a consideration in the evaluation of a patient for acute surgical repair and/or the use of a tourniquet.

Arteriograms can be performed in the operating room if there are obviously diminished pulses or if the delay in obtaining a formal arteriogram in the angiography suite would compromise limb survival. Six to 8 hours of warm ischemic time will significantly compromise a lower extremity.[26] Formal angiography is performed with a femoral artery puncture followed by insertion of a pigtail catheter. Next, a bolus of contrast is injected and an angiographic unit is used to capture images. The length of the segment to be imaged determines the number of acquisitions needed. Intraoperative arteriogram can be performed by injecting 45 mL of contrast through an 18-gauge catheter with a single film exposure[52] or a vascular fluoroscopic unit.

Unfortunately, arteriography is not without risks, costs, and false-negative results. The complication rate has been reported to be 1.7% and includes thrombosis, arteriovenous fistulae, bleeding, renal failure, reaction to contrast material, and pseudoaneurysm formation.[3,39,55,87,93] The reported false-positive results have ranged from 2.4% to 7%, which could lead to unnecessary surgical intervention.[3,84,87,93] The cost of the arteriograms ranged from $750 to $1500 per study in 1990; a more recent figure was $5240 in 2003.[3,84,87]

The recent systematic review and meta-analysis performed by Medina et al.[51] revealed that the most frequently (61%) used diagnostic modality for vascular injury is selective angiography. Although protocols vary with respect to the time of observation required, frequency of physical examination, and whether adjunctive tests are used, they can rule out a clinically significant vascular injury.[37,47,56,57,84,87] Many protocols for selective angiography dictate that in acute knee dislocations with symmetric distal pulses and normal ABIs, patients should be admitted for at least 24 hours' duration for observation and serial physical examination. The algorithm used at the University of Washington and Harborview Medical Center is the most frequently cited in current literature (Fig. 22-4).[56,57,84]

In addition to formal angiography, new techniques such as computed tomographic angiography (CTA) and magnetic resonance angiography (MRA) are being developed. These techniques make use of readily available imaging techniques, often with a bolus of contrast to define the lower extremity arterial system. Potter and coworkers[64] demonstrated 100% correlation between conventional angiography and MRA in a small cohort of patients (six patients: four normal, one intimal tear, one decreased flow).

Duplex ultrasonography is a noninvasive and less expensive alternative to arteriography with comparable accuracy in detecting traumatic vascular injury; however, no study specific to knee dislocations has been performed.[7,22] Although not specific to vascular trauma, in general, this modality has limitations in assessing lower extremity vasculature in the morbidly obese.[70]

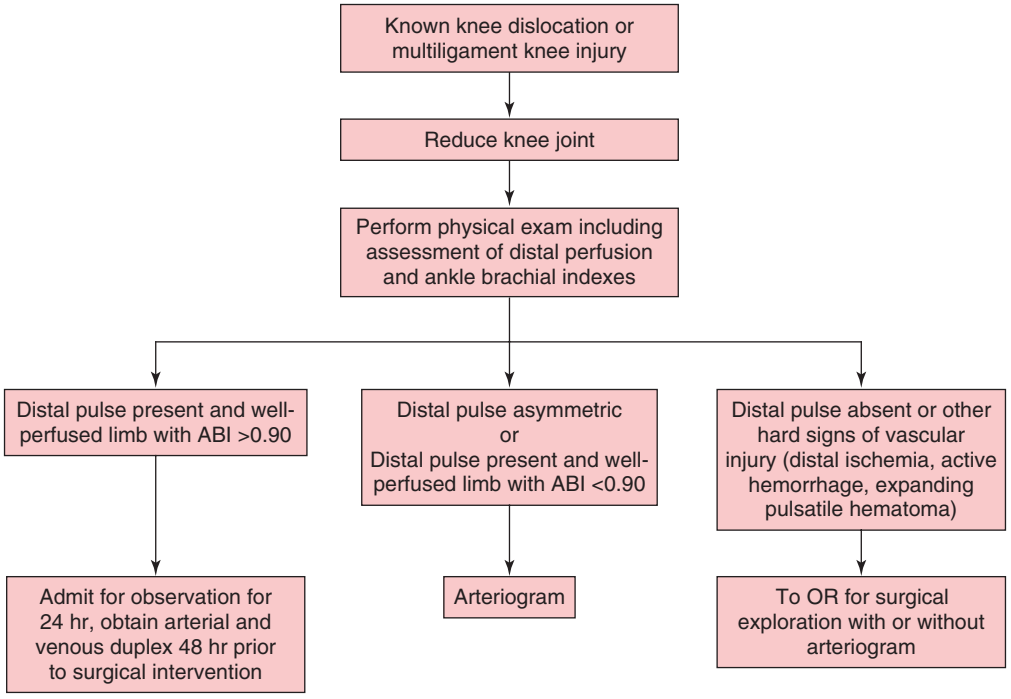


FIG 22-4 University of Washington and Harborview Medical Center algorithm for diagnosis of vascular injury following multiligament knee injuries. *ABI,* Ankle/brachial index; *OR,* operating room. (From Nicandri GT, Dunbar RP, Wahl CJ. Are evidence-based protocols which identify vascular injury associated with knee dislocation underutilized? *Knee Surg Sports Traumatol Arthrosc* 2010;18;1005-1012.)

NEUROLOGIC INJURIES

Neurologic damage occurs in 16% to 40% of knee dislocations.[2,82] This may range from a stretch injury (neurapraxia) to a complete transection (neurotmesis). The peroneal nerve is most commonly injured as it is stretched over the fibular neck during a posterolateral dislocation (Fig. 22-5).[23,68,86,88,94] A common presentation for peroneal nerve injuries is a patient with a drop foot and sensory deficit over the dorsum of the foot. Tibial nerve injury associated with a popliteal artery injury has also been reported.[94] Although difficult, a complete neurologic examination of both lower extremities should be performed both before and after any attempt at reducing a knee dislocation. Repeated examinations are recommended during the course of treatment because there is a potential for nerve compromise caused by soft tissue swelling and compartment syndrome, pressure, immobilization, and/or positioning.

In the posterior mid-thigh, the sciatic nerve divides into the common peroneal nerve and the tibial nerve (Fig. 22-6).[41] The common peroneal nerve courses obliquely through the popliteal fossa, then traverses along the fibular neck in an exposed subcutaneous fibroosseous tunnel.[75,86] This subcutaneous position adjacent to the fibula makes the nerve susceptible to direct contact during sports and to indirect injury during a forced varus stress as it is stretched over the fibular neck.[28] The tibial nerve lies lateral to the popliteal vessels within the popliteal fossa. As it courses distally, it crosses posterior to the vessels and then lies medially. It passes between the two heads of the gastrocnemius muscle and anterior to the arch of the soleus muscle to lie in the deep posterior compartment of the lower leg. Within the popliteal fossa, the tibial nerve gives off several branches. The medial sural cutaneous nerve joins the peroneal communicating branch of the common peroneal nerve to form the sural nerve. The posterior articular branch pierces the posterior capsule to innervate the contents of the knee. Finally, there is a motor branch to the popliteus muscle.[41]

A complete neurologic examination including motor and sensory evaluation of the peroneal and tibial nerve should be well documented before and after any intervention including reductions, surgical procedures, splinting, or casting. The peroneal nerve is divided into superficial and deep branches. The superficial peroneal nerve (lumbar nerve root 5 [L5] and sacral nerve roots 1 and 2 [S1, S2]) controls the peroneal muscles of the foot, which provide foot eversion. The superficial peroneal nerve provides sensation to lateral aspect of the leg and dorsum of the foot. The deep peroneal nerve (L4, L5, and S1) controls the tibialis anterior, extensor hallucis longus, and extensor digitorum longus muscles. This function can be tested manually by having the patient perform resisted ankle dorsiflexion and great and lesser toe

CRITICAL POINTS Neurologic Injuries

- Neurologic damage occurs in 16% to 40% of knee dislocations.
- The peroneal nerve is most commonly injured as it is stretched over the fibular head during a posterolateral dislocation.
- A complete neurologic examination, including motor and sensory evaluation of the peroneal and tibial nerve, should be well documented before and after any intervention including reductions, surgical procedures, splinting, or casting.
- A progressive deterioration in the neurologic examination may indicate compartment syndrome or ischemia.
- Most commonly, nerve injury from a knee dislocation is a stretch injury or lesion in continuity.
- These injuries are observed for 4 to 6 months to allow for spontaneous recovery and/or delineation of the zone of injury.

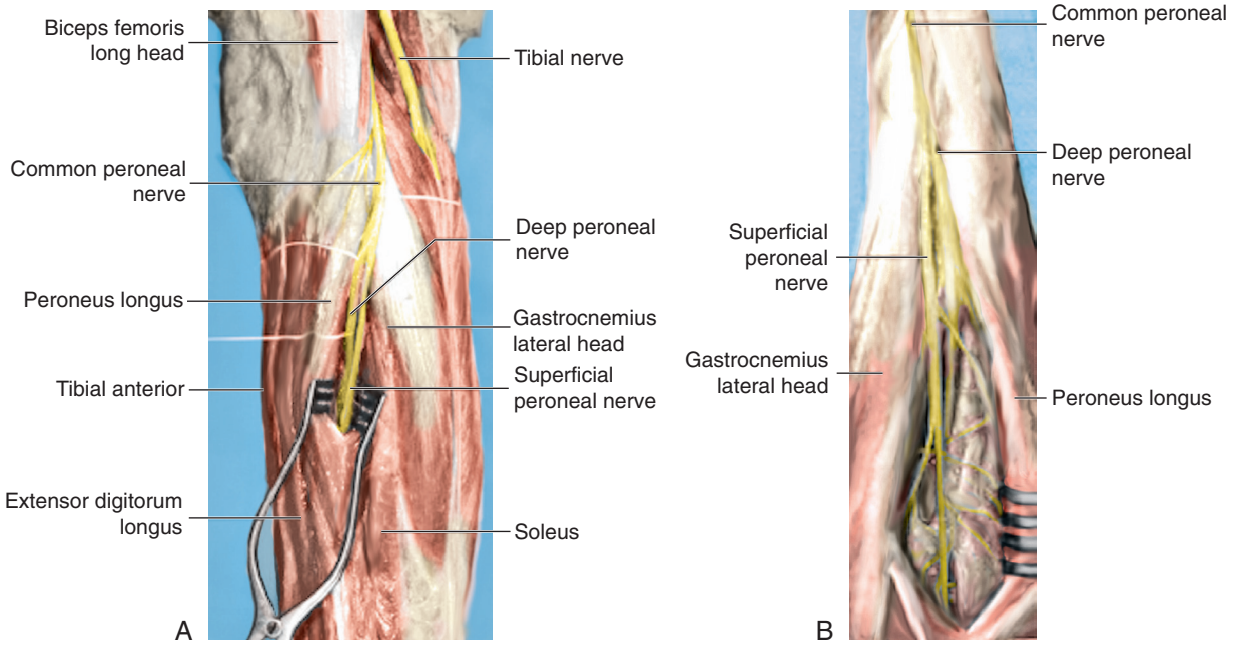


FIG 22-5 **A,** Posterolateral view of a left lower extremity cadaveric microdissection depicts the common peroneal nerve in the distal popliteal fossa and its branches, the superficial and deep peroneal nerves. **B,** Lateral view of a right lower extremity cadaveric microdissection shows the deep peroneal nerve muscular branches supplying the tibialis anterior, extensor digitorum longus, extensor hallucis longus, and peroneus tertius muscles. (From Kim DH, Murovic JA, Tiel RL, Kline DG. Management and outcomes in 318 operative common peroneal nerve lesions at the Louisiana State University Health Sciences Center. *Neurosurgery* 2004;54:1421-1428.)

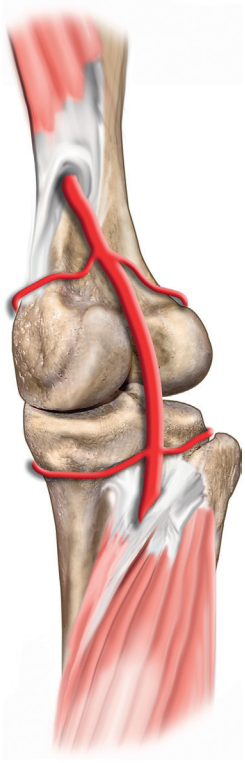


FIG 22-6 Schematic diagram of the popliteal artery.

extension, respectively. Sensory function of the deep peroneal nerve is located primarily within the first web space on the dorsum of the foot. The tibial nerve (L5, S1, and S2) innervates the muscles of the superficial and deep posterior compartments of the leg. The gastrocnemius and soleus muscles are tested by resisted plantar flexion of the foot. The flexor hallucis longus and flexor digitorum longus are tested by having the patient curl his or her great and lesser toes, respectively, and then performing resisted plantar flexion. The tibialis posterior is tested by resisted plantar flexion and inversion of the foot. Sensory distribution for the tibial nerve is located on the plantar aspect of the foot.[31]

Manual muscle testing is graded on a 5-point scale with 0 indicating no muscle activation; 1, muscle activation without joint movement; 2, motion observed when gravity eliminated; 3, motion against gravity; 4, resisted submaximal contraction; and 5, maximal resisted motion. As with the vascular examination, the patient should have frequent neurologic examinations that are well documented. A progressive deterioration in the neurologic examination may indicate compartment syndrome or ischemia.[67] Compartment pressure testing is indicated in this scenario.

Further neurologic studies may be indicated when a nerve deficit is noted on physical examination. These include electromyography, nerve conduction studies (NCS), ultrasonography, and MRI. MRI is more commonly used to identify ligament, meniscal, or articular cartilage injuries. Ultrasonography may be helpful but is definitely operator dependent. Electromyography and NCS cannot differentiate extraneural and intraneural causes of nerve impairment, nor can they distinguish between a damaged but continuous nerve and a completely dissected nerve. These studies are usually used in the subacute or chronic setting.

Ultrasonography of the peroneal nerve is performed with the patient in the prone position and the knee flexed 20 degrees with the ankle positioned in a cushion to allow access to the popliteal region. A 12.5-MHz and 15.7-MHz broadband linear array transducer and a silicone standoff pad are used. Gruber and associates in 2005[28] demonstrated that sonography by experienced technicians reliably demonstrated the state of the nerve and the surrounding soft tissues. Specifically, the level of the lesion and any scar tissue or hematoma that was surrounding the nerve were identified. It correlated precisely with intraoperative findings. It is important to identify a treatment program for peroneal nerve injury associated with dislocation.[21]

Nerve injuries from sharp laceration should be repaired acutely; those from blunt laceration should be delayed 3 to 4 weeks to delineate proximal and distal stump damage. Most commonly, nerve injury from a knee dislocation is a stretch injury or lesion in continuity. These injuries are observed for 4 to 6 months to allow for spontaneous recovery and/or delineation of the zone of injury.[40] Within this time interval, splinting and dedicated therapy with nerve stimulation and reeducation should be instituted. An ankle-foot orthosis (AFO) should be used to maintain the ankle in a neutral position and prevent contracture of the Achilles tendon. Initiating stretching exercises to correct the equinovarus foot positions may help prevent the development of contractures. Baseline electrodiagnostic studies should be performed at 6 weeks and again at 3 months if there has been no clinical evidence of tibialis anterior muscle function.[86]

With ongoing absence of clinical signs of recovery, nerve exploration may be indicated.[25,86] At the time of surgery, nerve action potentials across the lesion are assessed. If conduction is demonstrated, neurolysis can be performed with 80% to 88% recovery of grade 3 muscle strength (peroneal and anterior tibial muscle contract against gravity and some resistance).[39,40] End-to-end suturing or nerve grafting is recommended when there is no conduction across the deficit. Resection and suturing of short-segment deficits with partial fibulectomies may result in an 84% chance of grade 3 recovery.[40] Kim and colleagues[40] also found grade 3 functional return in 42% of grafts overall; 75% of those that were less than 6 cm in length had good outcome. The outcome depends strongly on the degree of neural damage and the surgical technique used.[28] Recently data were published from an academic Level I trauma center that has developed a registry for analyzing outcomes after multiligament knee reconstruction.[51] Patient follow-up averaged 6.2 years and patients were excluded if they had less than 2 years follow-up. Objective outcomes revealed that 69% of patients with peroneal nerve injury recovered antigravity or better tibial anterior strength. Three patients with complete nerve palsy (38%) and 15 patients with partial nerve palsy (83%) regained antigravity ankle dorsiflexion strength ($P = .06$). In comparison, one patient with complete nerve palsy (13%) and 13 patients with partial nerve palsy (72%) regained antigravity strength of the extensor hallucis longus ($P = .01$). Subjectively, no significant differences in Lysholm and International Knee Documentation Committee scores were detected between those who did or did not regain antigravity dorsiflexion or between those who had complete versus partial peroneal nerve palsy originally. These latter findings likely demonstrate a limitation in these knee outcome–measuring tools in measuring functional outcome in this patient population. Another recent 5-year retrospective review focused on factors influencing peroneal nerve injury and recovery. Gender (odds ratio, 5.47), body mass index (odds ratio, 1.14), and fibular head fracture (odds ratio, 4.77) were associated with peroneal nerve injury. The rate of full peroneal nerve recovery in this study was 31%; younger patient age was the only favorable factor for peroneal nerve recovery. The average age of patients who had spontaneous recovery of peroneal nerve function was 22.7 years.[42] When sufficient return of function does not occur, an anterior transfer of the posterior tibial tendon or other technique can maintain neutral ankle dorsiflexion and eliminate the need for the AFO.[18,30,34,63,81,89,90,92]

CRITICAL POINTS Ligamentous Injuries

- The most accurate examination for identification of anterior cruciate ligament integrity is the Lachman test.
- With the knee at 90 degrees, a posterior drawer or posterior force on the tibia is used to assess the posterior cruciate ligament.
- The medial and lateral collateral ligaments are evaluated by applying a valgus or varus stress, respectively, at both extension and 30 degrees of flexion.
- A posteromedial or posterolateral complex injury can be identified with additional joint space opening at 0 degrees of flexion.

CRITICAL POINTS Reduction and Immobilization

- Knees that are dislocated at the time of presentation should be reduced immediately.
- Reduction is accomplished by applying traction to the tibia while manipulating the proximal tibia in the appropriate direction.
- Reevaluation of joint congruence and neurovascular status must follow reduction.
- Adequate reduction and maintenance of tibiofemoral alignment must be documented in both the anteroposterior and the lateral planes.

LIGAMENTOUS INJURIES

Dislocation of the knee results in damage to the soft tissue stabilizers of the knee. Physical examination of the ligamentous stabilizers should be performed only after the life- and limb-threatening injuries have been addressed. It should also be delayed in the case of femoral or tibial fractures. Examination in this setting may further displace the fracture, and it may make the ligamentous examination less reliable. Pain may also hinder accurate examination.

A systematic approach to the evaluation of knee stability should be undertaken. The most accurate examination for identification of ACL integrity is the Lachman test.[16] This is performed by applying an anteriorly directed force on the tibia with the knee in 20 to 30 degrees of flexion. With the knee at 90 degrees, a posterior drawer or posterior force on the tibia is used to assess the PCL. Translation and endpoint are evaluated. Evaluation of posterior sag, or the position of the medial femoral condyle with respect to the tibial plateau, is also useful to identify PCL injuries.

The MCL and FCL are evaluated by applying a valgus or varus stress, respectively, at both 0 degree and 30 degrees of flexion. Increased medial or lateral joint space opening at 30 degrees typically indicates a collateral ligament injury. A posteromedial or posterolateral complex injury can be identified with additional joint space opening at 0 degree of flexion. The posterolateral corner can be assessed further with the dial test. Increased external rotation of the tibia, a greater than 10- to 15-degree side-to-side thigh-foot angle at 30 degrees of knee flexion, indicates a posterolateral corner injury. If there is additional external rotation of the dial test at 90 degrees of flexion, a PCL and lateral corner injury are present. Twaddle and coworkers[88] in 2003 presented 63 dislocatable knees in 60 patients. These authors reported bicruciate ligament injuries in 71% of patients. The ACL was injured in 84%, the PCL in 87%, the MCL in 44%, and the FCL in 62%.

REDUCTION AND IMMOBILIZATION

Often, spontaneous reduction has taken place before presentation. If the knee is dislocated at the time of presentation, reduction on the field by knowledgeable medical personnel is preferred. The neurovascular status of the limb must be assessed before reduction. The use of intravenous adjuvant medications is usually sufficient anesthesia. Reduction is accomplished by applying traction to the tibia while manipulating the proximal tibia in the appropriate direction.

The presence of a dimple sign, indication of a posterolateral dislocation, may be a contraindication to closed reduction. Imaging should be pursued if possible. Reevaluation of joint congruence and neurovascular status must follow reduction.[25] The limb should then be immediately immobilized in a long-leg splint or knee immobilizer. Once the patient is out of the emergency department, a hinged knee brace locked in extension is the preferred form of immobilization during the time period antecedent to surgical intervention. Adequate reduction and maintenance of tibiofemoral alignment must be documented in both the anteroposterior (AP) and the lateral planes. If reduction cannot be maintained in a splint, the knee may be transfixed temporarily with cross pins (through the notch) or an external fixator until sufficient capsular healing occurs. Other potential indications for use of an external fixator are the presence of fractures, vascular injury, and skin coverage issues.



FIG 22-7 Anteroposterior radiograph of an acute knee dislocation.

IMAGING

Radiographs of the knee should be obtained for all suspected knee dislocations (Fig. 22-7). Routine radiographs may be useful not only in assessing joint congruity and finding potential fractures, but also in determining a diagnosis. In a case series by Edwards et al.[17] in 2013, four obese females with a low-energy fall and no noticed deformity to the leg in the field or in the emergency department were found to have knee dislocations only with radiography (Fig. 22-8). Radiographs may be delayed until a clinically apparent knee dislocation has been adequately reduced. The basic knee series consists of an AP and a lateral



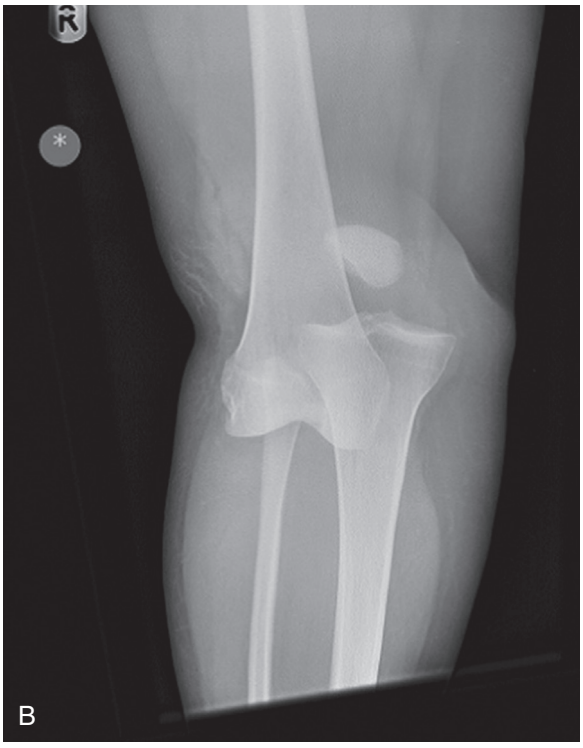


FIG 22-8 Lateral (**A**) and anteroposterior (**B**) radiographs of a 33-year-old woman, body mass index 35, who fell in her garden. (From Edwards GA, Sarasin SM, Davies AP. Dislocation of the knee: an epidemic in waiting? *J Emerg Med.* 2013;44[1]:68-71, 2013.)

CRITICAL POINTS Imaging

- Radiographs of the knee should be obtained for all suspected knee dislocations.
- Magnetic resonance imaging will further define soft tissue and cartilage injuries and aid in planning of definitive care.

plain radiograph. In cases in which fracture is noted or suspected, oblique views or stress views of the knee may be indicated. These views can determine the direction of dislocation as well as assess the adequacy of reduction and note any residual subluxation. In addition, the identification of fractures may direct treatment. Often, femoral and/or tibial fractures will require stabilization before the dislocation can be addressed.

A tibial eminence fracture and lateral capsular avulsion fractures from the tibia, also known as *Segond fractures*, indicate an ACL injury (Fig. 22-9).[8,15,76] The tibial eminence fractures may be complete, incorporating the entire ACL footprint, or incomplete, primarily affecting the anteromedial bundle.[27] The Segond fracture, best detected on the AP projection, is indicative of detachment of the middle third of the lateral capsular ligament and is associated with an ACL rotational instability (Fig. 22-10). The fracture originates from the lateral cortex of the proximal tibia, superior, and posterior to Gerdy's tubercle, approximately 2 to 10 mm distal to the articular surface.[24] Tears of the ACL are present in 75%[11] to 100%[24] of patients with Segond fractures.

PCL and posterolateral ligament injuries can also be identified on plain radiographs (Fig. 22-11). PCL injuries may present as posterior avulsion fractures of the proximal tibia. These fractures will usually involve the entire PCL and may be comminuted or split sagitally.[27] A cortical avulsion of the middle medial tibial plateau, a *reverse* Segond fracture, caused by a valgus and external rotation force, corresponds to an avulsion of the deep MCL. This is usually associated with a PCL injury and medial meniscal tear. This may be the only radiologic suggestion of a knee dislocation/multiligamentous injury.[18]

On the lateral side, the *arcuate sign* describes an avulsion fracture of the fibular head consisting of the FCL, popliteal fibular ligament, and fabellofibular ligaments. Huang and associates[33] found that, in addition to the injury to the posterolateral stabilizers, 13 of 13 patients with the arcuate sign had PCL disruptions (six tibial avulsions and seven midsubstance) and MCL injuries (five acutely abnormal and eight with chronic fibrous thickening). Also identified were medial and lateral meniscal tears (five medial and six lateral).

After a knee dislocation has been reduced, the patient stabilized, and plain radiographs confirm reduction, MRI can be obtained subacutely (Fig. 22-12). MRI will further define soft tissue and cartilage injuries and aid in planning definitive care. Whereas the physical examination is best for determining degrees of abnormal translation and rotation, MRI can help determine the location of the injury (e.g., midsubstance tear). This information can be useful in deciding the need for repair—augmentation versus reconstruction.

A precise description of the following pathology should be made by the interpreting radiologist[36,64,91]: location of any fractures, especially the presence of ligament avulsion fractures, including fragment dimensions; bone contusions and osteochondral injuries, the location of which may clarify direction of dislocation; ligament tears and nonosseous avulsions, including location of the tear (proximal, midsubstance or distal) and severity (partial versus complete); tendon injuries (quadriceps, patellar, biceps femoris, popliteus, and iliotibial band); meniscal tears, including location of displaced meniscal fragments; soft tissue damage, such as muscle tears and capsular injury; vascular assessment, including evaluation for perivascular hematoma or signs of vessel thrombosis, dissection, or the development of a pseudoaneurysm; and visual description of the tibial and common peroneal nerves, including alteration in signal, morphology, and location. Regardless of the level of detail provided by the interpreting radiologist in describing the injuries seen on MRI of the dislocated knee, the orthopedic surgeon should personally review all imaging modalities before taking a patient to the operating room for surgical intervention. Intraobserver and interobserver reliability in describing the lesions seen on MRI in the dislocated knee are low.[5]

EMERGENT SURGERY

Although the rationale for determining the type of treatment (surgical or nonsurgical) most appropriate for a patient with a dislocated knee

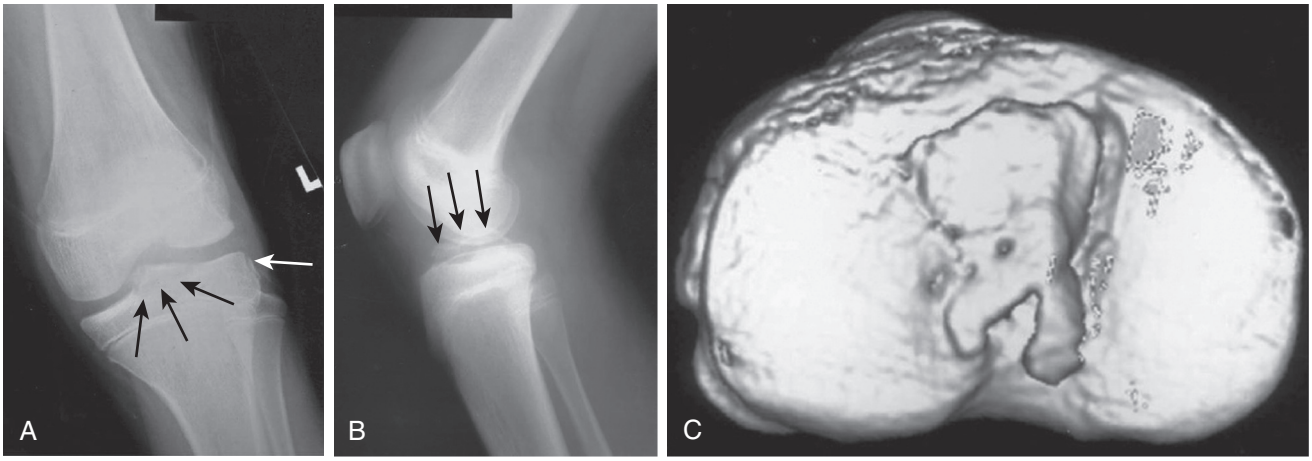


FIG 22-9 A 13-year-old boy with a twisting knee injury sustained while playing basketball. Frontal (**A**) and lateral (**B**) radiographs of the knee show a large avulsion fracture of the anterior cruciate ligament ([ACL]; *black arrows*). There is a Segond fracture of the proximal tibia (*white arrow*). C**,** A 3-dimensional computed tomographic image shows this fracture fragment to be a large, noncomminuted fragment extending beyond the insertion area of the ACL toward, but not involving, the posterior cruciate ligament insertion area. (From Griffith JF, Antonio GE, Tong CWC, Ming CK. Cruciate ligament avulsion fractures. *Arthroscopy.* 2004;20:803-812.)

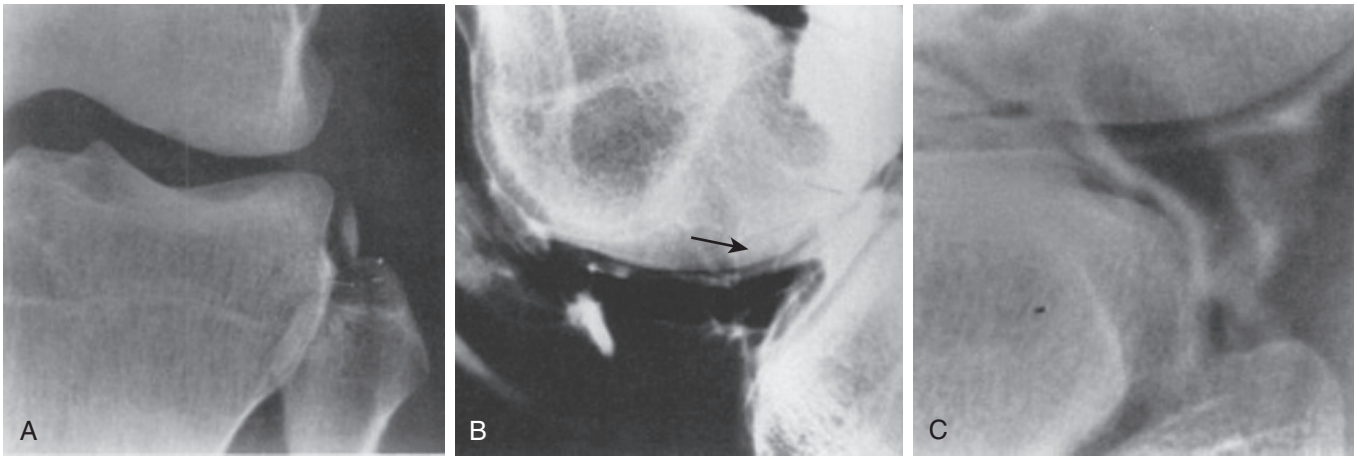


FIG 22-10 Segond fracture with characteristic arthrographic findings. Four days before presentation, this 26-year-old man fell while playing tennis. **A,** Anteroposterior view shows a 9-mm avulsion fracture arising from the lateral tibial cortex. Site of origin is 3 mm below the plateau. **B,** Overpenetrated cross-table lateral view during double-contrast arthrogram shows absence of normal anterior cruciate ligament (*arrow*). **C,** Arthrogram of the posterior horn of the lateral meniscus shows compression of the normal tendon sheath. (From Goldman AB, Pavlov H, Rubenstein D. The Segond fracture of the proximal tibia: a small avulsion that reflects major ligamentous damage. *Am J Roentgenol.* 1998;151:1163-1167.)

is beyond the scope of this chapter, the timing of surgical procedures is dependent on the postinjury physical examination and associated injuries.

Emergent surgery is indicated for vascular injury, compartment syndrome, open injury, or irreducible dislocations.[67] Vascular reconstruction, often performed with reverse saphenous vein grafts, should be performed within 6 hours to minimize ischemia to the muscles and increase the chances for limb survival. The orthopedic surgeon may need to stabilize the limb with an external fixator to allow access to the limb during reconstruction and for postoperative wound management. Fasciotomies are often required after revascularization to prevent compartment syndrome.

Acute compartment syndrome is a condition in which the pressure within a fascial compartment rises to a level that decreases tissue perfusion, leading to cellular anoxia, muscle ischemia, and death. Diagnosis is primarily clinical with supplementation by compartment pressure measurements. Clinical signs of compartment syndrome include pain out of proportion, pain aggravated by passive stretch, paresthesia, and late signs that include pulselessness, paralysis, and pallor. Compartment pressure measurements of 20 mm Hg below diastolic pressure or 30 mm Hg below the mean arterial blood pressure suggest muscle ischemia. Urgent restoration of perfusion and normalization of compartment pressures is accomplished by complete fasciotomy of all compartments.[60]

When open knee dislocations are encountered, wound management principles should be used. Irrigation and debridement of the open wound should be performed urgently. The patient should be started on appropriate antibiotics and tetanus immunization. Acute

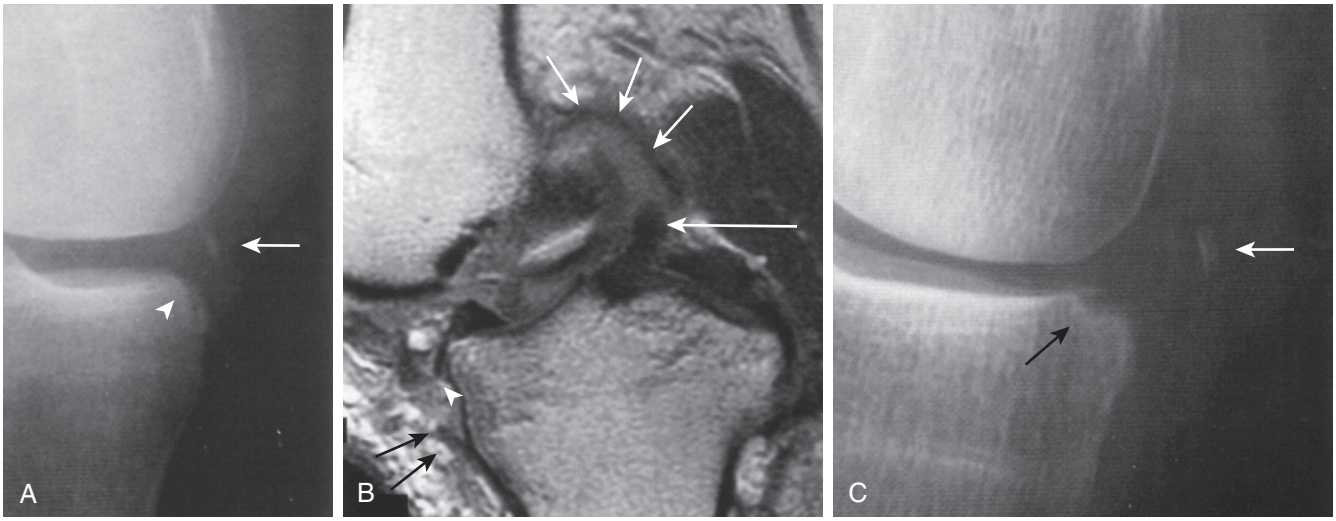


FIG 22-11 A 52-year-old woman involved in a high-energy motor vehicle collision. **A,** Anteroposterior (AP) intraoperative fluoroscopic spot film of the knee shows a small avulsion fragment (*arrow*) adjacent to the medial joint line and evidence of cortical disruption (*arrowhead*) of the medial tibia. **B,** Proton density–weighted fast spin-echo sagittal magnetic resonance image shows disruption of the posterior cruciate ligament (PCL). Note the coronal position of the tibia that results from ligamentous instability. The distal end of the PCL (*long white arrow*) is intact, but the entire proximal portion (*short white arrows*) is disrupted. Disruption (*black arrows*) of the superficial medial collateral ligament (*arrowhead*) is shown. The deep medial collateral ligament (*arrowhead*) is also torn. **C,** AP radiograph of the knee 6 months after trauma shows avulsion fragment (*white arrow*), now well corticated. The *black arrow* indicates the medial tibial bony defect. (From Escobedo EM, Mills WJ, Hunter JC. The "reverse Segond" fracture: association with a tear of the posterior cruciate ligament and medial meniscus. *Am J Roentgenol.* 2002;178:979-983.)

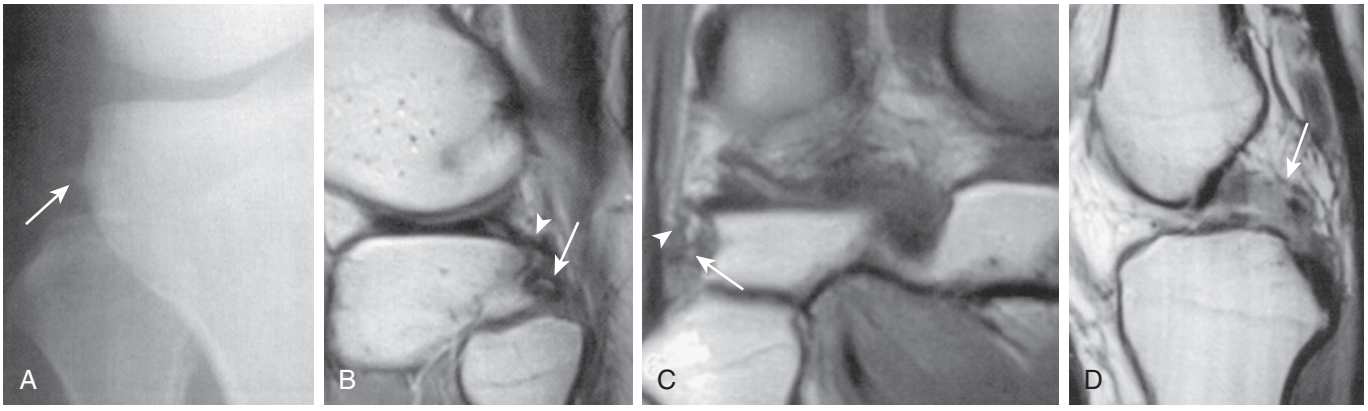


FIG 22-12 A 21-year-old man with chronic posterolateral instability of the right knee after a motor vehicle collision. **A,** Anteroposterior radiograph reveals avulsed bone fragment of the fibular styloid process (*arrow*). **B,** Sagittal spin-echo proton density–weighted magnetic resonance image (MRI) (TR/TE, 1800/20) reveals avulsed osseous fragment (*arrow*) adjacent to the popliteal tendon (*arrowhead*). **C,** Coronal spin-echo proton density–weighted MRI (1800/20) reveals disruption of the lateral collateral ligament (*arrowhead*) and avulsed osseous fragment (*arrow*) in the corresponding course of the popliteofibular ligament. **D,** Sagittal spin-echo proton density–weighted MRI (1800/20) obtained medial to image **B** reveals a tear of the posterior cruciate ligament (*arrow*). *TE*, Echo time; *TR*, repetition time. (From Huang G-S, Yu JS, Munshi M, et al. Avulsion fracture of the head of the fibula [the "arcuate sign"]: MR imaging findings predictive of injuries to the posterolateral ligaments and posterior cruciate ligament. *Am J Roentgenol.* 2003;180:381-387.)

CRITICAL POINTS Emergent Surgery

- Emergent surgery is indicated for vascular injury, compartment syndrome, open injury, or irreducible dislocations.
- Acute compartment syndrome is a condition in which the pressure within a fascial compartment rises to a level that decreases tissue perfusion, leading to cellular anoxia, muscle ischemia, and death.
- Urgent restoration of perfusion and normalization of compartment pressures is accomplished by complete fasciotomy of all compartments.

ligament reconstruction is contraindicated in the face of an open wound. Soft tissue issues may delay reconstruction for several months.[67]

Irreducible dislocations, most commonly posterolateral dislocations with a dimple sign, require surgical reduction to avoid neurovascular compromise. Although possible, ligament reconstruction should be delayed until adequate imaging of the knee and appropriate resources for reconstruction have been assembled.

DEFINITIVE MANAGEMENT

Except for knee dislocations occurring in the severely obese (body mass index ≥40),[4,95] there is firm evidence in the literature supporting definitive surgical intervention to manage these complicated injuries.[14,32,45,58,96] Controversies still exist with regard to timing, repair versus reconstruction of medial and lateral structures, graft types, surgical techniques, and postoperative rehabilitation. Most, if not all, surgeons would agree that soft tissue dissection, ligament, and capsular repairs are easier in the acute setting, less than 2 weeks after the injury. Unfortunately, this is when the knee is usually swollen and range of motion is poor with decreased or absent muscle control of the limb. All of these factors can increase the risk of a permanently stiff knee. Even in the environment of a high-volume knee trauma center,[9,83] loss of motion with a multiple ligament reconstruction is difficult to prevent. Therefore these decisions must take into account this risk of stiffness along with other patient factors, such as complicating injuries, medical comorbidities, participation in rehabilitation efforts, ability to maintain knee reduction, soft tissue coverage and skin condition, and patient expectations. External fixators are best removed within 10 to 14 days to allow protected knee motion, even when vascular surgery is required. This is a decision between the vascular surgeon and orthopedist regarding when knee motion would not risk disrupting the vascular repair.

With respect to surgical timing, many advocate for early intervention (within 2-3 weeks).[6,29,32] In a recent systematic review of early versus delayed surgery, significantly better outcomes were achieved with early intervention (within 3 weeks).[45] Arthroscopically assisted surgery should usually be delayed a minimum of 10 days after the injury to allow the joint capsule to heal and therefore minimize the risk of fluid extravasation and subsequent compartment syndrome.[73] Single versus staged operative intervention remains without consensus and depends on the severity of dislocation and potentially associated fracture patterns.[12,20,53] Reconstruction of cruciate injury is well accepted predominantly because of the large body of literature indicating superior results in single-ligament injury. With regard to the posterolateral corner, repair has shown a significantly higher failure rate in comparison with reconstruction, as well as a reduced rate of return to sporting activities.[45] Stannard and coworkers[83] compared acute repair (within 3 weeks) of the posterolateral corner with reconstruction. These investigators found significantly inferior results of repair (37% failure) compared with reconstruction (9% failure) in 56 patients with 57 posterolateral corner injuries at 2 years. Reconstruction is therefore recommended and a multitude of techniques are described.[29,32,43,53] Multiple grafts are often required and graft type is generally determined by autologous structures still present and surgeon preference. No single combination of graft types has demonstrated superiority, but a combination of autologous and allografts is used.[19,53,77,85]

CRITICAL POINTS Definitive Management

- For patients with high physical demands, optimizing the condition of the knee (muscle function, range of motion, and swelling) and relying on reconstruction rather than acute repair may yield a superior functional result.

Ultimately, knee dislocation is a serious injury and is often only one of many medical problems in the patient with multiple injuries. The initial and definitive management of the dislocated knee presents one of the most challenging and complex injuries the orthopedic surgeon is intimately involved in treating.

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23

Meniscus Tears: Diagnosis, Repair Techniques, and Clinical Outcomes

Frank R. Noyes, Sue D. Barber-Westin

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INTRODUCTION

The crucial roles of the menisci in the human knee are well understood and include load bearing, load transmission, shock absorption, knee joint stability, and lubrication and nutrition of articular cartilage.[120] Meniscectomy frequently leads to irreparable joint damage, including articular cartilage degeneration, flattening of articular surfaces, and subchondral bone sclerosis. Poor long-term clinical results have been reported by many investigators following partial and total meniscectomy.[8,49,75,118,125,139,170,181,183,184,189,199] For instance, Scheller and coworkers[189] followed 75 patients who underwent partial lateral meniscectomy 5 to 15 years postoperatively and noted that 78% had Fairbank's signs of radiographic deterioration. Rockborn and Messner[181] reported a 50% rate of radiographic osteoarthritis in 30 patients a mean of 13 years after meniscectomy. Roos and associates[184] found that 48% of 107 patients had advanced radiographic osteoarthritis compared with a control group 21 years after meniscectomy. These authors reported that the relative risk of developing advanced degenerative radiographic changes was 14.0. It is important to note that some problems exist in meniscectomy natural history studies, such as including both partial and total meniscectomy in the same cohort; not assessing the effects of patient body weight, activity level, and overall lower limb alignment on the functional result; failure to include weight-bearing posteroanterior (PA) radiographs in the assessment; and lack of a carefully defined control group for comparison.

At least half of patients who sustain injuries to the anterior cruciate ligament (ACL) also sustain meniscus tears,[61,112,117] which is markedly concerning because well over 1 million ACL injuries occur yearly worldwide.[152] We conducted a systematic review to determine the treatment of meniscus tears during ACL reconstruction based on studies published from 2001 to 2011.[153] There were 11,711 meniscus tears in

159 investigations, of which 65% were treated by meniscectomy, 26% were treated by repair, and 9% were left in situ. These results were distressing because the majority of patients in the studies were young athletes in whom resection of meniscal tissue may accelerate the development of osteoarthritis, regardless of the outcome of the ACL reconstruction. This study included investigations from 16 different countries, approximately one third of which were from the United States.

In comparing the incidence of meniscectomy and meniscus repair just within the United States between the years 2005 and 2011, Abrams and colleagues[1] reported that the incidence of meniscus repairs increased 11% in isolated cases and 48% when a concomitant ACL reconstruction was performed. Approximately half of these repairs were done in patients younger than 25 years, and 20% were done in individuals ages 25 to 34 years. These authors attributed the increase in the attempt to preserve meniscal tissue to improved surgeon education, arthroscopic techniques, meniscus-specific rehabilitation protocols, and an overall comfort level with the procedure.

Several studies have reported superior results of meniscus repair compared directly with meniscectomy.[90,166,199,228] In addition, our recent systematic review that encompassed 1326 meniscus repairs for tears in the central third region found an overall clinical healing rate of 83%.[20] The repairs in this review were performed with either newer flexible suture-based all-inside suture devices or the traditional inside-out technique. It is well known that complications and deteriorating results have occurred with rigid all-inside meniscus fixation devices such as meniscal arrows, screws, and darts.[107,110,116,134,194,210] More recently, flexible all-inside devices have become commercially available that contain anchors attached to suture that are passed into the periphery of the meniscus.[15,22,122] These devices include:

- Ultra Fast-Fix (Smith & Nephew, Andover, MA)
- RapidLoc (DePuy-Mitek, Raynham, MA)
- OmniSpan (DePuy-Mitek)
- Meniscal Cinch (Arthrex, Naples, FL)
- Sequent (ConMed Linvatec, Largo, FL)
- MaxFire (Biomet, Warsaw, IN)
- NovoStitch (Ceterix Orthopaedics, Menlo Park, CA)

The lack of long-term, prospective, randomized level I clinical studies precludes definitive recommendations for these devices[15,116]; however, the short-term clinical outcomes achieved in mostly single longitudinal meniscus repairs found in our systematic review were encouraging.[20] This chapter focuses on surgical techniques using newer all-inside suture devices and inside-out repair procedures for a variety of meniscus tears and published clinical outcomes. The postoperative rehabilitation program is described in detail in Chapter 25.

INDICATIONS

Candidates

Candidates for meniscal repair are active patients younger than 60 years, including skeletally immature children and adolescents.[105] Trauma during sports activities involving sudden twisting and turning is one of the most common etiologies of meniscus tears. Many meniscus tears that occur during ACL injuries extend into the middle third avascular region and are amendable to a meticulous inside-out suture repair. Magnetic resonance imaging (MRI) provides important information regarding the type of meniscus tear and potential for repair to preserve function.[48,66,77,93,149,209] In knees in which repair is deemed possible, it is important to restrict strenuous activities and athletics until surgery to avoid further damage to the joint and meniscus.

Degenerative meniscus tears are much less frequently repaired because the meniscus tissue is poor in quality[135] and often fragmented into multiple pieces. Occasionally, MRI will indicate that a repair may be possible, such as in cases of large horizontal tears. Frequently, the symptoms of tibiofemoral pain will diminish over 6 to 12 weeks in degenerative tears in older patients, allowing a conservative approach. In other knees, symptoms of locking episodes and joint swelling are more persistent or severe and require arthroscopic intervention.

CRITICAL POINTS Indications

- Meniscus tear with tibiofemoral joint line pain
- Active patient younger than 60 years
- Concurrent knee ligament reconstruction or osteotomy
- Meniscus tear reducible, good tissue integrity, normal position in the joint once repaired
- Meniscus tear classified by location, type of tear, integrity, damage to meniscus tissue, remaining meniscus bed
- Peripheral single longitudinal tears: R/R, one plane: repairable in all cases, high success rates
- Middle third region: R/W (vascular supply present) or W/W (no blood supply)
- Outer third and middle third regions longitudinal, radial, horizontal tears: R/W, one plane: often repairable
- Outer third and middle third regions complex double or triple longitudinal, flap tears: R/W, multiple planes: repair versus excision

Meniscus repair is frequently performed with concurrent operative procedures such as knee ligament reconstruction.[20,117] Patients with lower extremity varus or valgus malalignment and associated meniscus tears are especially considered for meniscus repair. The malalignment produces high medial or lateral tibiofemoral compartment loads, and a functional meniscus is required to prevent articular cartilage deterioration. Unfortunately, many meniscus tears in varus- or valgus-aligned limbs are degenerative in nature and not repairable.

Candidates for meniscus repair must be compliant and willing to follow the postoperative program of rehabilitation, including crutch support for 4 weeks. Those in whom complex tears are repaired must agree to avoid strenuous activities and deep knee flexion for 4 to 6 months; otherwise, the repair site may be disrupted and fail.

Meniscus Tear Classification

Meniscus tears are classified according to location, type of tear, and integrity and damage to meniscal tissue and the meniscus attachment sites.[7,190] This classification, along with meticulous arthroscopic inspection of the tear site, allows the surgeon to determine whether a tear is repairable. The meniscus body is divided into anterior, mid body, and posterior thirds. In addition, Anderson and associates[7] recommended a classification system of zone 1 (rim width <3 mm), zone 2 (rim width 3-4 mm), and zone 3 (rim width >5 mm). Tears located at the peripheral attachment sites (meniscofemoral and meniscotibial), or zone 1, are referred to as *outer third* or *red-red* (R/R) tears. Single longitudinal tears are usually located in this region (Fig. 23-1). These tears are classified as R/R because both portions have an internal blood supply and are repaired in all cases with high success rates expected.

Tears located in the middle third region (zone 2) are classified as red-white (R/W), and tears located in the inner third (zone 3) are termed white-white (W/W). R/W tears occur at the junction between the outer and middle third regions, approximately 4 mm from the meniscal attachment, with a vascular supply present predominately in the outer third of the tear. White-white tears are located in the region in which no blood supply exists to either portion of the tear. When a repair is performed for these tears, the sutures may provide access to the vascular supply. In addition, rasping of the meniscus-synovial

border provides a vascular supply to the repair site from synovial migration of cells on the surface of the meniscus.[216] It should also be noted that the vascular supply to the meniscus, particularly in younger patients, still requires study and may extend greater than 5 mm in depth into the central zone.

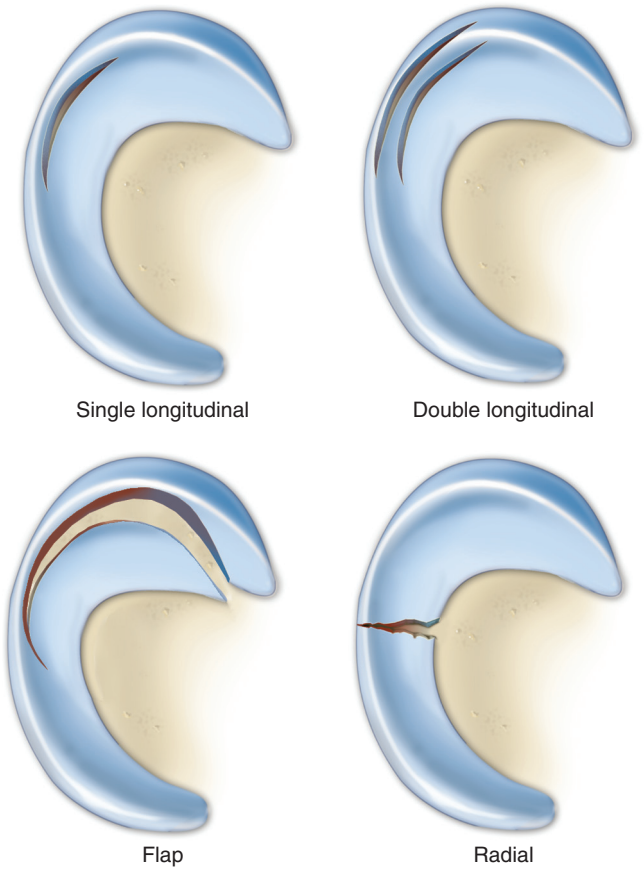


FIG 23-1 The common complex and avascular meniscus tear patterns. Note the single plane configuration of the single longitudinal and radial tears and the multiplane (complex) configuration of the double longitudinal and flap tears.

Repairs of complex tears and tears that extend into the middle third region are evaluated on an individual basis. Tear patterns in this region include single longitudinal, double longitudinal, triple longitudinal, horizontal, radial, and flap. The rationale for repair of these tears is that removal results in essentially a total meniscectomy because a substantial amount of meniscal tissue is resected (Fig. 23-2). This is especially concerning in younger patients in their second to fourth decades of life and all athletically active individuals. These tears are often repairable with reasonable success rates, as described later in this chapter.

Single meniscal tears occur in a single plane, regardless of location. These include longitudinal, radial, and horizontal tears. These tears are most commonly found in the posterior horn and are usually repairable. Complex tears occur in more than one plane or direction. These include tears in the vertical plane (double or triple longitudinal), in the vertical and horizontal planes, or in the vertical and radial planes (flap tears). Each component of the tear is identified and may or may not be repairable.

The decision for repair is based on the qualitative evaluation of the meniscus tissue's integrity and absence of traumatic or degenerative changes. The meniscus tissue should appear nearly normal, with no secondary tears or fragmentation that would affect its projected function. The meniscus rim should be trimmed of tear fragments. A horizontal tear into the meniscus rim is a negative variable because it is difficult with sutures to fully restore the tear site owing to inner gaps between the horizontal tear arms. This is one indication in which a fibrin clot may provide a benefit. A large flap tear may be reduced and approximated, and if the tissue has adequate integrity, repair is considered in active patients. A meniscus that has been displaced in the notch may shorten and contract within 3 to 4 weeks, preventing reduction, and accordingly, early arthroscopy and repair are indicated. More specific recommendations of repair indications and techniques are provided for specific tears later in this chapter. The role of incorporating a fibrin clot or platelet-rich plasma to aid the healing process remains poorly understood. Clinical studies are lacking at present; the surgeon's judgment is therefore required on a case-by-case basis.

CONTRAINDICATIONS

Meniscus tears located in the W/W region are not repairable and require debridement. Chronic degenerative tears usually have tear

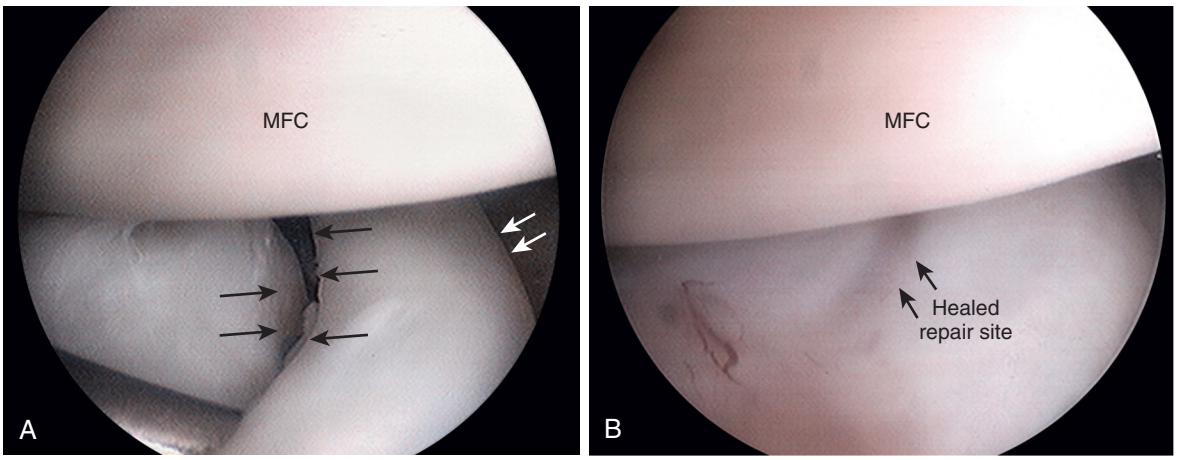


FIG 23-2 **A,** A double-longitudinal medial meniscus tear with a peripheral tear and another tear at the red-white junction. Removal of the red-white tear and repair of the peripheral tear would result in substantial loss of meniscus function; accordingly, a repair of both tears was performed. **B,** Complete healing of the tears on subsequent arthroscopy 1 year later. *MFC,* Medial femoral condyle.

CRITICAL POINTS Contraindications

- Meniscus tears located in inner third (W/W) region
- Chronic degenerative tears in which the tissue is of poor quality, not amendable to suture repair
- Longitudinal tears <10 mm in length
- Incomplete radial tears that do not extend into the outer third region
- Patient >60 years
- Patient unwilling to follow postoperative rehabilitation program

components in multiple planes and are classified as complex. The surgeon must carefully assess the tear pattern and determine the amount and integrity of meniscal tissue that is present. Many of these tears are not repairable (Fig. 23-3). Chronic degenerative tears in which poor tissue quality is encountered require debridement.[135] The tissue may be thickened or abnormally firm and altered in shape or length. Horizontal tears frequently involve displacement of the meniscus from the joint such that a repair of the horizontal flaps would not result in restoration of meniscus function.

Small longitudinal tears less than 10 mm in length are not repaired. In addition, incomplete radial tears that do not extend into the outer third region are either left alone or treated by minimal debridement of the unstable edges. Radial tears should not be debrided into functional meniscal tissue, which would disrupt circumferential hoop fibers and alter meniscus function. The goal in the repair of radial tears is to restore function in the outer and middle zones because the chance of a repair that extends into the inner zone retaining function is highly questionable.

Patient education is required before surgery because complex tears that extend into the avascular region may have a 20% to 40% failure rate and require a repeat arthroscopic meniscus debridement procedure. Patient education is important regarding the goals of the procedure and the failure rate. Patients involved in construction work or other demanding occupations may choose not to have a complex or avascular type of repair. A more difficult problem is the request to remove a repairable R/R tear owing to occupational or athletic pursuits. The senior author (F.R.N.) does not perform this procedure. The senior author categories meniscus tears into three different types. A R/R tear is repaired and, in select small medial tears (15-25 mm in length), an all-inside approach may be considered. However, if there is any associated meniscus tear site damage indicating the need for multiple sutures, an inside-out repair is performed. A R/W tear of either meniscus is repaired with an inside-out technique with accessory posteromedial or posterolateral approaches and multiple vertical sutures because this procedure offers a firmer internal fixation and chance of healing over two to four all-inside sutures. This procedure is performed in all active patients, except older patients (>50 years) who are sedentary. A complex tear that extends into both the R/W and W/W regions may have a success rate of approximately 50%, and the repair of these more difficult tears is usually performed in young patients in an attempt to preserve some meniscal function. In others, a partial meniscectomy is performed.

CLINICAL BIOMECHANICS

Meniscus Function

The menisci provide several vital mechanical functions in the knee joint. They act as a spacer between the femoral condyle and tibial plateau and, when there are no compressive weight-bearing loads across the joint, limit contact between the articular surfaces. The amount of joint narrowing due strictly to the physical absence of the menisci is in the range of 1 to 2 mm.

CRITICAL POINTS Clinical Biomechanics

Functions of the Menisci

- Spacer, prevents contact between articular surfaces
- Load-bearing:
  - 50% compressive load of knee joint transmitted through menisci at 0 degrees of extension
  - 85% compressive load of knee joint transmitted through menisci at 90 degrees of flexion
- Increase contact area, reduce contact stress
  - Partial meniscectomy (15%-34%) increases contact pressures by >350%
- Contributes to joint stability
- Shock absorption during walking
- May assist in overall lubrication of articular surfaces

Suture Repair Biomechanics

- Studies comparing biomechanic properties of vertical and horizontal sutures, and sutures to meniscus repair devices
  - Vertical sutures superior initial fixation strength and stiffness during load-to-failure testing compared with horizontal sutures and repair devices
  - Vertical sutures lower displacements under cyclical loading conditions compared with horizontal sutures and repair devices
- Future studies required to determine fixation strength and performance under cyclic loading of all-inside suture-based devices

Under static-loading conditions, the menisci assume a significant load-bearing function in the tibiofemoral articulation.[2,33,67,124,168] At least 50% of the compressive load of the knee joint is transmitted through the menisci in 0 degrees of extension, and approximately 85% of the load is transmitted at 90 degrees of flexion.[2,163] The presence of the menisci increases the contact area to 2.5 times the size compared with a meniscectomized joint.[24] The larger contact area provided by the menisci reduces the average contact stress (force/unit area) acting between the joint surfaces. Removal of as little as 15% to 34% of a meniscus increases contact pressures by more than 300%.[168,191] After total meniscectomy, the tibiofemoral contact area decreases by approximately 50%, and the contact forces increase twofold to threefold.[2,24,67,106,126,141,163,192,207,219]

Lee and colleagues[111] evaluated the effects of serial meniscectomies in the posterior segment of the medial meniscus. Compared with the intact state, the medial contact area decreased from 20% (after removal of 50% of the posterior segment of the medial meniscus) to 54% (total meniscectomy). Medial contact stress increased from 24% (50% meniscectomy) to 134% (total meniscectomy). Medial peak contact stress increased from 43% (50% meniscectomy) to 136% (total meniscectomy). The peripheral portion of the medial meniscus provides a greater contribution to increasing contact area and decreasing contact stresses compared with the central portion. Muriuki and associates[145] created 15- to 20-mm single longitudinal tears in the R/W portion of the posterior horn of the medial meniscus in cadaver knees and reported significant increases in maximum contact pressure and reductions in contact area that were similar to those associated with total meniscectomy.

The menisci remain in constant congruity to the tibial and femoral articular surfaces throughout knee flexion and extension[208,229] and contribute to stability of the knee joint.[144] Medial meniscectomy

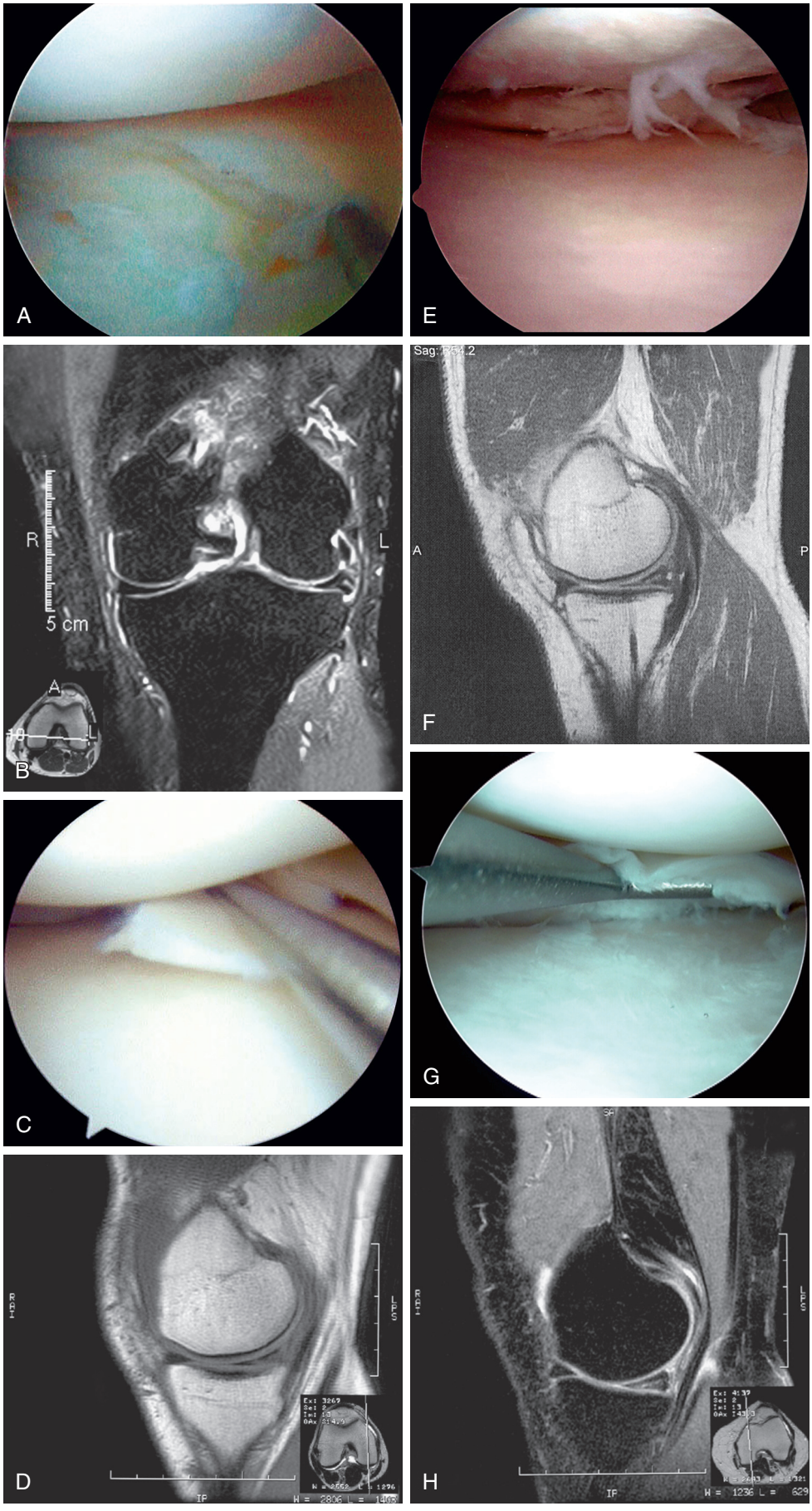


FIG 23-3 Examples of irreparable meniscus tears. **A** and **B,** A 40-year-old man with a complex middle third longitudinal tear of the lateral meniscus. **C** and **D,** A 39-year-old man with a complex flap tear to the posterior horn of the medial meniscus. **E** and **F,** A 43-year-old man with a degenerative tear extending to the under surface of the medial meniscus. **G** and **H,** A 55-year-old woman with a degenerative longitudinal tear to the medial meniscus. Magnetic resonance imaging does not provide sufficient detail of the tear and integrity of the meniscus tissue to determine if a repair of the complex tear is possible.

performed after sectioning of the ACL results in increased anterior tibial translation at 20 to 30 degrees of knee flexion during a Lachman test compared with that measured in knees with an intact ACL.[6,57,113,146,196] Thus the loss of the medial meniscus after an ACL rupture is problematic, especially in varus-angulated knees. Spang and associates[196] reported significant increases in ACL strain measured with a variable reluctance transducer in cadaver knees following medial meniscectomy at 60 and 90 degrees of knee flexion ($P < .05$). Increases in meniscal strain have also been reported following ACL transection in the laboratory.[86,165] In knees with posterior cruciate ligament (PCL) ruptures, the increase in posterior tibial translation allows a change in tibiofemoral contact in which the menisci posterior horns have a reduced weight-bearing function. This is sometimes referred to as a *PCL meniscectomy*. The effect is greater for the medial compartment in which the middle and anterior thirds of the medial meniscus have less weight-bearing function than the lateral meniscus.

The lateral meniscus provides concavity to the lateral tibiofemoral joint owing to the normal posterior convexity of the lateral tibial condyle, allowing the stabilizing effect of joint weight-bearing forces to reduce lateral compartment anterior and posterior translations.[121] Lateral meniscectomy performed after sectioning of the ACL results in increased anterior tibial translation at 30 degrees of knee flexion during a pivot shift test compared with that measured in knees with an intact ACL.[146] Recent studies indicate that the lateral meniscus may be a more important restraint than the medial meniscus to anterior tibial translation during the combined loads applied during the pivot shift test.[146] Partial lateral meniscectomy has been estimated to increase contact pressures by 50% during the stance phase of gait.[141] Total lateral meniscectomy results in a 45% to 50% decrease in total contact area and a 235% to 335% increase in peak local contact pressure.[163]

Loss of the medial meniscus results in a smaller, more medial displacement of the center of pressure. Load is subsequently transmitted through the articular cartilage and subchondral bone to the underlying cancellous bone through this more central route, thus stress-shielding the proximal aspects of the medial tibial cortex. The deleterious effects of meniscectomy on tibiofemoral compartment articular cartilage have been demonstrated in multiple experimental studies.[24,101,168,203,227] For these reasons, it is paramount to preserve meniscal function, if possible, in knees with varus osseous malalignment.

In addition, the menisci provide specific load-bearing functions to the knee joint during walking[141,201,224] and are theorized to assist in overall lubrication of the articular surfaces.[144,220] Even partial meniscectomy affects knee joint kinetics by reducing range of knee motion and increasing knee adduction moments during stance.[119,201]

Meniscus Suture Repair Biomechanics

Historically, biomechanical investigations have compared properties of suture techniques with those of rigid all-inside meniscus fixation devices.* Problems with devices such as meniscal arrows, screws, and darts have been well-documented experimentally and clinically.[107,116,131,134,137,194,210] In addition, several studies concluded vertical sutures were superior to both horizontal sutures and meniscus arrows in mean load-to-failure and maximum tensile strength values.†

More recently, suture repair techniques, suture materials, and all-inside devices have been tested experimentally to determine initial fixation strength and performance under cyclic loading with varying results (Table 23-1). The majority of studies published to date have been performed in porcine knee models rather than human models. Ultra-high-molecular-weight polyethylene-based (UHMWPE) sutures used in all-inside techniques are now available with newer all-inside repair devices, such as NovoStitch (Ceterix), Hi-Fi (Conmed Linvatec), and FiberWire (Arthrex).[15,62,177] Further studies are required to determine the biomechanical properties of these sutures and devices as used for meniscus repair. The lack of both experimental and clinical data precludes definitive recommendations for any one of the currently available all-inside devices over the others. In addition, the reported load-to-failure rates for most of these devices that use one or two sutures is low, justifying consideration for inside-out repairs with multiple sutures to be described. In addition, the low load-to-failure rates and creep properties identify the need for slower postoperative rehabilitation in regard to resumption of full weight bearing, especially for complex meniscus repairs and root repairs. At present, there is little scientific justification regarding when it is safe to resume full weight bearing or return to sports after these types of repairs, although it is appreciated that peripheral longitudinal tears at the R/R junction demonstrate adequate healing within the first 4 to 6 weeks after surgery. The postoperative rehabilitation recommendations are provided in Chapter 25, with empirical rules build in to protect the meniscus repair.

Meniscus Repair Healing

There are few published experimental studies on the strength of a healing meniscus suture repair (without cell-based therapy or growth factors) subjected to tensile loads or assessed for residual defects and complications.[89,137,138,148,180,182] In 1995, Miller and associates[138] reported acceptable healing rates of single longitudinal meniscus tears repaired in the periphery in a goat model. More recently, Miller and colleagues[137] found unacceptably high rates of chondral damage 6 months after implantation of Meniscal Fastners (Mitek, Westwood, MA), BioStingers (Linvatec), and Clearfix Screws (Mitek) in this same animal model. The authors cautioned against the use of these rigid all-inside devices in humans. In 2009, Hospodar and coworkers[89] reported superior healing of meniscus repairs done with an inside-out suture technique compared with the all-inside FasT-Fix device in goats. The FasT-Fix group had longer residual full-thickness defects ($P = .01$) and longer residual partial-thickness defects ($P < .001$) 6 months postoperatively.

CLINICAL EVALUATION

A thorough history includes assessment of the injury mechanism, initial and residual symptoms, and functional limitations. Common injury mechanisms are a sudden twist, change in direction (cut), or deep knee flexion. Meniscus tears are frequently encountered in knees with ACL ruptures. A comprehensive knee examination is performed that includes assessment of knee motion, patellofemoral indexes, tibiofemoral pain and crepitus, muscle strength, ligament subluxation tests, and gait abnormalities.

The presence of tibiofemoral joint line pain on joint palpation is a primary indicator of a meniscus tear. Other clinical signs include pain on forced flexion, obvious meniscal displacement during joint compression and flexion and extension, lack of full extension, and a positive McMurray test result.[127,140] All ligament stability tests are performed and compared with the opposite knee joint. MRI may be obtained with a proton density weighted, high-resolution, fast spin-echo sequence[172,173] to determine the status of the articular cartilage and menisci. This evaluation is useful in knees with suspected degenerative tears[221] and

*References 4, 13, 17, 18, 30, 32, 55, 65, 137, 178, 195, 223, 230, 231.
†References 13, 14, 17, 23, 25, 30, 32, 35, 55, 59, 65, 171, 178, 195, 197, 223, 230.

TABLE 23-1 Results of Cyclic Loading Studies of Meniscus Repair Suture Techniques and All-Inside Devices

Study	Type of Sutures or Devices	Models	Cycles	Results
Beamer et al[22] (2015)	Radial tears: one all-inside Ceterix NovoStitch suture or one 2-0 Force Fiber inside-out suture	Porcine	100, 200, 500	Load to failure (N): 95 inside-out, 111 all-inside ($P = .03$). Stiffness (N/mm): 11.19 inside-out, 14.53 all-inside ($P = .02$). Displacement (mm): 2.36 inside-out, 1.52 all-inside ($P < .001$). Vertical all-inside technique superior to horizontal inside-out technique.
Ramappa et al[177] (2014)	Bucket-handle tears: two running mattress sutures Sequent, two vertical mattress sutures Ultra FasT-Fix, 2 vertical sutures No. 0 Hi-Fi inside-out	Porcine	100, 300, 500	Load to failure (N): 138 ± 23 Sequent, 140 ± 30 Ultra FasT-Fix, 188 ± 42 Hi-Fi suture ($P < .001$). No differences in stiffness among three groups. Sequent lowest displacement after cycling ($P < .001$) but questionable clinical relevance.
Feucht et al[64] (2014)	Posterior medial root tears*: transtibial pull-out repair with two vertical sutures TP, or suture anchor repair with two SA	Porcine	100, 500, 1000	Load to failure (N): 180 ± 45 TP, 241 ± 45 SA, 862 ± 135 native posterior medial meniscus root. SA lower displacement all conditions ($P < .001$), higher stiffness ($P < .05$). Both techniques higher displacement, lower maximum load to failure, and stiffness compared with intact menisci ($P < .05$). SA technique beneficial; slow rehabilitation recommended.
Feucht et al[62] (2013)	Posterior medial root tears: TSS 5 mm apart, one HMS, MAA, two modified LS	Porcine	100, 500, 1000	Load to failure (N): 235 ± 39 TSS, 250 ± 57 TLS, 280 ± 65 HMS, 335 ± 59 MMA. MMA highest max load to failure ($P < .01$), less displacement after cycling ($P < .05$), higher stiffness ($P < .05$).
Feucht et al[63] (2013)	Posterior medial root tears: one suture No. 2 PDS, Ethibond, FiberWire, FiberTape	Porcine	100, 500, 1000	Load to failure (N): 133 ± 35 PDS, 146 ± 21 Ethibond, 169 ± 43 FiberWire, 196 ± 62 FiberTape. None of the suture materials had superior properties over the others.
Rosslenbroich et al[186] (2013)	Posterior lateral root tears: transtibial approach one suture or two sutures, 3 mm apart tied over button	Porcine	1000	Load to failure (N): 150 ± 24 SS, 301 ± 41 two sutures. Two-suture technique lower displacement, higher stiffness, higher ultimate failure load ($P < .05$).
Matsubara et al[123] (2012)	Radial tears: DHS, CS	Cadavers	500	Load to failure (N): 68 ± 13 DHS, 79 ± 19 CS. CS higher ultimate failure loads, greater stiffness, lower displacement ($P < .05$).
Herbort et al[83] (2010)	Radial tears: DHS, SS wider distance from meniscal rim	Porcine	1000	DHS higher maximum load (108 ± 12 N), highest stiffness, lower displacement ($P < .05$) compared with SS configurations.
Chang et al[44] (2009)	Single longitudinal tears: single vertical repair No. 2 FiberWire, No. 2 Ethibone, FasT-Fix, RapidLoc, Meniscal-Dart, BioStinger	Porcine	300	Load to failure (N): 16 Dart, 34 BioStinger, 41 RapidLoc, 68 FasT-Fix, 114 No. 2 Ethibone, 175 No. 2 FiberWire. Failure strength and stiffness highest in No. 2 FiberWire ($P < 0.05$). Failure load higher and displacement lower in suture groups compared with devices ($P < .01$).

Continued

TABLE 23-1 Results of Cyclic Loading Studies of Meniscus Repair Suture Techniques and All-Inside Devices—cont'd

Study	Type of Sutures or Devices	Models	Cycles	Results
Mehta & Terry[131] (2009)	Single longitudinal tear 25 mm: one HMS Meniscal Cinch, Ultra FasT-Fix, MaxFire	Cadavers	100, 500	Load to failure (N): 64 MaxFire, 86 Ultra FasT-Fix, 85 meniscal Cinch. Ultra FasT-Fix and Meniscal Cinch had more desirable biomechanical profiles (lower failure rate, greater stiffness, $P < .05$). MaxFire larger gap formation and lower load to failure ($P < .05$).
Nyland et al[156] (2008)	Single longitudinal tear 20 mm: two vertically or horizontally placed FasT-Fix, two horizontally placed RapidLoc devices	Cadavers, implants placed 5 mm apart	500	Vertical FasT-Fix less displacement, greater stiffness ($P < .001$).
Kocabey et al[103] (2006)	Single longitudinal tear 20 mm: two vertical, horizontal, oblique sutures	Bovine, sutures placed 5 mm apart	100	Load to failure (N): 89 ± 8 horizontal suture, 146 ± 32 vertical suture, 172 ± 26 oblique suture. Oblique and vertical sutures greater stiffness ($P < .05$), load to failure ($P = .001$) than horizontal. No difference in displacement.
Kocabey et al[102] (2006)	Single longitudinal tear 20 mm: two vertically or horizontally placed FasT-Fix, two horizontally placed RapidLoc devices	Cadavers	500	Load to failure (N): 87 ± 13 RapidLoc, 90 ± 14 horizontal FasT-Fix, 125 ± 39 Vertical FasT-Fix. Vertical FasT-Fix less displacement ($P < .01$), greater load to failure ($P < .05$), greater stiffness ($P < .001$).
Chang et al[43] (2005)	Single longitudinal tear 20 mm: two Vertical mattress sutures, two Meniscal Viper Repair sutures, two vertical FasT-Fix sutures	Porcine	500	Load to failure (N): 111 ± 30 Meniscal Viper, 133 ± 10 vertical mattress sutures, 146 ± 9 Vertical FasT-Fix. Vertical mattress suture less displacement, higher stiffness during cyclic testing ($P < .001$), suggesting potential for better healing.

BioStinger, No. 0 Hi-Fi suture, and Sequent manufactured by Linvatec; Ethibond and PDS manufactured by Ethicon; Ethibone, Meniscal Cinch, FiberTape, FiberWire, Meniscal Dart, and Meniscal Viper Repair System manufactured by Arthrex; Fast-Fix manufactured by Smith & Nephew; MaxFire manufactured by Biomet; No. 2 RapidLoc manufactured by Mitek; and Ultra FasT-Fix manufactured by Smith & Nephew.
*Root tear: avulsion of the tibial insertion of the meniscus or a radial tear close to the meniscal insertion.
CS, cross suture; *DHS*, double horizontal suture; *HMS*, horizontal mattress suture; *LS*, loop stich; *MAA*, Modified Mason-Allen suture; *P*, tied over plate; *SA*, vertical sutures; *SS*, single suture; *TSS*, two separate sutures.

CRITICAL POINTS Clinical Evaluation

Physical Examination
- Tibiofemoral joint line pain, compression pain
- McMurray test
- Knee flexion and extension
- Joint effusion
- Patellofemoral (medial and lateral subluxation, Q-angle, crepitus, compression pain)
- Muscle strength

Magnetic Resonance Imaging
- Proton-density-weighted, high-resolution, fast-spin-echo sequence

Ligament Subluxation Tests
- Pivot shift, Lachman
- KT-2000 (MEDmetric) 20 degrees of knee flexion, 134 N force
- Posterior drawer, 90 degrees of knee flexion
- External tibial rotation 30 degrees, 90 degrees of knee flexion
- Tibiofemoral rotation dial 30 degrees, 90 degrees of knee flexion
- External rotation recurvatum
- Lateral tibiofemoral joint opening 5 degrees, 20 degrees of knee flexion
- Reverse pivot shift
- Medial tibiofemoral joint opening 5 degrees, 20 degrees of knee flexion

Radiographs
- Anteroposterior
- Lateral, 30 degrees of knee flexion
- Posteroanterior, weight bearing, 45 degrees of knee flexion
- Patellofemoral axial

Assessment of Symptoms and Functional Limitations With Activity: Cincinnati Knee Rating System
- Sports Activity and Function Form
- Occupational Rating Form
- Symptom Rating Form

chronic ACL ruptures and to determine whether a meniscus cyst is present. A recent investigation that examined the ability of MRI to predict reparability of longitudinal full-thickness meniscus lesions reported high sensitivity and specificity rates (overall, 94% and 81%, respectively).[149]

LaPrade and Konowalchuk[109] described a figure-four test that attempts to replicate symptoms in patients with tears of the lateral meniscus popliteomeniscal attachments. The patient is placed supine, the knee flexed to approximately 90 degrees, the foot placed over the contralateral knee, and the hip externally rotated. A varus loading at the knee joint increases tensile loading in the damaged posterolateral soft tissue meniscal attachments. The primary symptom from popliteomeniscal tears is lateral compartment pain with activities, especially turning and twisting with sports. MRI findings are frequently negative. These authors described an open approach to repair the popliteomeniscal attachments. However, peripheral tears are amendable to an inside-out repair technique, as described.

The clinical examination may reveal tenderness on palpation at the posterolateral aspect of the joint at the anatomic site of the popliteomeniscal attachments. The McMurray test is performed in maximum flexion, progressing from maximum external rotation to internal rotation and then back to external rotation. This test may produce a lateral palpable snapping sensation, representing an anterior subluxation of the posterior horn of the lateral meniscus with maximum internal rotation. The snapping is produced with external rotation as the meniscus returns to a normal position. Of interest, patients with physiologic joint laxity and increases in tibial rotation limits can commonly produce this lateral snapping sign in both knees under examination, which is not painful. Patients with tears of the popliteomeniscal attachments may have a positive snapping sign in only the symptomatic knee, which produces posterolateral joint pain.

Radiographs taken during the initial examination include lateral at 30 degrees of knee flexion, weight-bearing PA at 45 degrees of knee flexion, and patellofemoral axial. Axial lower limb alignment is measured using full standing hip-knee-ankle weight-bearing radiographs[56] in knees that demonstrate varus or valgus alignment. Knees that have deficiency of the posterolateral structures may require lateral stress radiographs. Posterior stress radiographs may be obtained in patients with PCL ruptures.

Patients complete questionnaires and are interviewed to rate symptoms, functional limitations, sports and occupational activity levels, and patient perception of the overall knee condition according to the Cincinnati Knee Rating System (CKRS).[21]

PREOPERATIVE PLANNING

Concomitant injuries should be evaluated and may include cruciate or collateral ligament rupture, extensor mechanism injury or malalignment, chondral fracture, osseous malalignment, or an overuse syndrome. The patient is informed that the rehabilitation program may require modification according to the procedures performed. Knees with ACL or PCL deficiency require concomitant ligament reconstruction with the meniscus repair to achieve knee stability and protect the repair site. Knees with varus osseous malalignment that require osteotomy may also have chronic medial meniscus tears that are occasionally repaired.

CRITICAL POINTS Preoperative Planning

- Knees with cruciate deficiency: plan reconstruction with meniscus repair
- Other concomitant injuries may include collateral ligament ruptures, extensor mechanism injuries, chondral fractures
- Associated chronic conditions may include extensor mechanism malalignment, overuse syndrome, varus osseous malalignment. Consider meniscus repair whenever possible in these knees.

INTRAOPERATIVE EVALUATION

All knee ligament subluxation tests should be performed after the induction of anesthesia in both the injured and the contralateral limbs. The amount of increased anterior tibial translation, posterior tibial translation, lateral and medial joint opening, and internal-external tibial rotation should be documented.

A thorough arthroscopic examination is conducted, documenting articular cartilage surface abnormalities.[155] A probe inserted from the medial infrapatellar portal is used to tension the meniscus to determine the integrity of the peripheral rim and the anterior and posterior attachments. The probe is placed underneath the meniscus to visualize the entire undersurface (see Fig. 23-2). Flap tears that otherwise may not be evident may be discovered during this examination.

A 30- or 70-degree arthroscope is used in the anteromedial portal to examine the posteromedial meniscal region. The anteromedial portal is purposely placed immediately adjacent to the medial border of the patellar tendon. The arthroscope sheath with a blunt obturator is passed along the lateral aspect of the medial femoral condyle distal to the PCL attachment into the posteromedial compartment. The meniscal-synovial junction, the peripheral edge of the meniscus, the opening of a synovial cyst, and the posterior articular surface of the medial femoral condyle are inspected. A nerve hook is passed from the anteromedial portal and brought over the top of the meniscus into the posteromedial compartment. The peripheral attachment of the posterior horn of the medial meniscus frequently cannot be completely visualized unless this view is obtained.[34]

The posterolateral compartment of the knee may be inspected by passing the arthroscope adjacent to the medial aspect of the lateral

CRITICAL POINTS Intraoperative Evaluation

- Repeat all knee ligament subluxation tests under anesthesia, both injured and contralateral limbs.
- Rate all articular cartilage surfaces for abnormalities:
  - Normal
  - Grade 1, softening
  - Grade 2A, fissuring and fragmentation less than 50% depth of the articular surface
  - Grade 2B, fissuring and fragmentation more than 50% depth of the articular surface
  - Grade 3, subchondral bone exposed
- 30- or 70-degree arthroscope used in the anteromedial portal to examine the posteromedial meniscal region
- Inspect meniscal-synovial junction, peripheral edge of the meniscus, opening of a synovial cyst, and posterior articular surface of the medial femoral condyle.
- Perform displacement tests of the posterior horn at 60 to 70 degrees of flexion to detect subtle interstitial tearing of the meniscotibial posterior horn attachments.

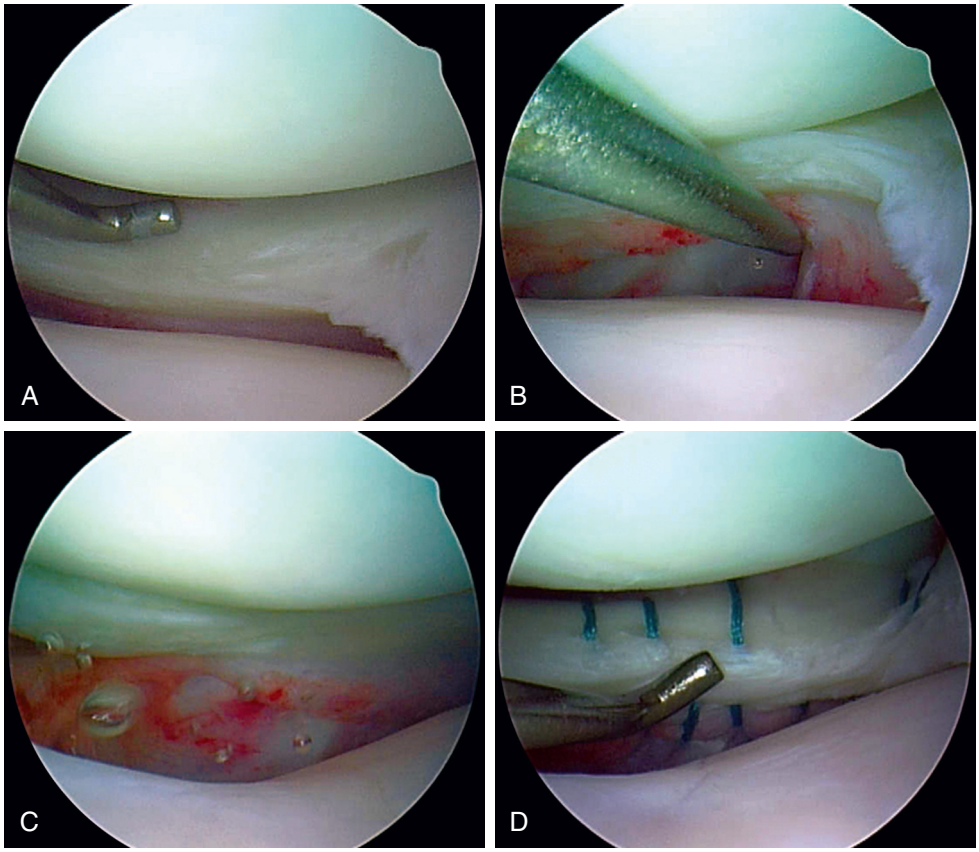


FIG 23-4 An athlete who had a prior negative arthroscopic examination and magnetic resonance imaging and continued posterolateral joint pain shows a demonstrable posterior horn popliteomeniscal attachment tear that required suture repair. **A,** A normal-appearing lateral meniscus. **B,** Enlarged popliteal hiatus showing laxity of the meniscotibial attachments. **C,** Meniscotibial attachments, and thin, disrupted tissues with cephalad displacement of the meniscus body. **D,** Multiple vertical divergent superior and inferior inside-out sutures.

femoral condyle at the notch, just distal to the ACL femoral attachment.

The meniscus tear pattern is classified as previously described. When a longitudinal tear in the middle third region is found, a thorough examination of the peripheral margin of the meniscus is required to determine whether a double longitudinal tear exists in the remaining meniscus rim.

The arthroscopic examination in patients with lateral and posterolateral joint pain may not reveal obvious tears of the posterosuperior meniscus attachments. There may be observable tears in the inferior meniscus tissues about the popliteal hiatus and meniscotibial attachments (Fig. 23-4). There is frequently enlargement of the popliteal hiatus and subtle interstitial tearing of the meniscotibial posterior horn attachments that allow the posterior horn to be abnormally elevated and displaced anteriorly into the lateral compartment. These displacement tests of the posterior horn are performed at 60 to 70 degrees of flexion using a figure-four position because the increased joint gap allows a nerve hook to easily displace the posterior horn and demonstrate the abnormal slackness of the attachments. We have frequently encountered athletes who have had a prior negative arthroscopic examination and MRI results who have demonstrable posterior horn popliteomeniscal attachment tears that require suture repair.

OPERATIVE TECHNIQUE

Patient Preparation

The patient is instructed to use a Hibiclens antimicrobial soap scrub of the operative limb ("toes to groin") the evening before and morning of surgery. Lower extremity hair is removed by clippers, not shaved. Antibiotic infusion is begun 1 hour prior to surgery. A nonsteroidal antiinflammatory drug (NSAID) is given to the patient with a sip of water upon arising the morning of surgery (and continued until the fifth postoperative day unless there are specific contraindications to the medicine). The use of an NSAID and a postoperative firm double-cotton, double-Ace compression dressing for 72 hours (cotton, Ace, cotton, Ace layered dressing) has proven very effective in diminishing soft tissue swelling and is used in all knee surgery cases. The patient's urinary output and total fluids are carefully monitored during the procedure and in the recovery room. The knee skin area is initialed by both the patient and surgeon before entering the operating room, with a nurse observing the procedure. The identification process is repeated with all operative personnel with a "time-out" before surgery to verify the knee undergoing surgery, procedure, allergies, antibiotic infusion, and special precautions that apply. All personnel provide verbal agreement.

The patient is placed in the supine position on the operating table so that the affected leg is elevated (Fig. 23-5). The foot of the

CRITICAL POINTS Operative Technique

Patient Preparation
- Tourniquet and leg holder used, but tourniquet inflated only for initial exposure
- Meniscus tear analyzed according to location, type, size
- Meniscus repair site and synovial junction prepared
- Rasp stimulates bleeding at meniscus-synovial border
- Meniscus tear reduced anatomically
- Inside-out meniscus repair technique requires accessory posteromedial or posterolateral incision

Exposure for Medial Meniscus Repair
- Knee flexed 60 degrees, 3-cm vertical skin incision made just posterior to superficial medial collateral ligament
- Infrapatellar bundles of saphenous nerve identified to avoid injury
- Interval medial gastrocnemius tendon and posterior capsule bluntly dissected
- Henning retractor or spoon inserted to allow safe suture placement and needle retrieval

Exposure for Lateral Meniscus Repair
- Knee flexed to 60 degrees, 3-cm skin incision centered just behind fibular collateral ligament
- Interval between biceps tendon insertion and iliotibial band identified, incised
- Remain posterior to fibular collateral ligament and other posterolateral structures
- Henning retractor pushes neurovascular bundle medially, protects common peroneal nerve
- Position anterior to the gastrocnemius muscle and tendon and directly posterior to the posterior capsule and posterior meniscus bed

Patient Positioning and Equipment
- Assistant sits in chair on medial or lateral side of the knee with headlight to see sutures.
- Scrub nurse stands opposite surgeon to pass sutures through single cannula, one at a time.
- Assistant holds lower leg with knee at 20 to 30 degrees of flexion, applies force to open tibiofemoral compartment.

Medial Meniscus Suture Repair Techniques
- Knee flexed 30 degrees, abduction load applied
- 30-degree arthroscope positioned through medial portal to visualize meniscus
- Cannula positioned through lateral portal
- Assistant passes 10-inch flexible needle through cannula
- First assistant catches double-armed needles, suture tied with five knots
- Vertical divergent sutures alternated; first, on superior surface to reduce meniscus and second, on inferior surface to close the tear
- For medial meniscus tears that extend around the posterior horn, place needle cannula in lateral portal to angle sutures away from neurovascular structures

Lateral Meniscus Suture Repair Techniques
- First assistant sits on lateral side of the knee, adduction stress applied.
- Sutures inserted through superior and inferior meniscal surfaces in an interrupted vertical fashion.
- Multiple 2-0 braided polyester nonabsorbable sutures used on 10-inch straight cutting needle.

Single and Double Longitudinal Tears
- Double-stacked suture technique, two layers of sutures placed at 3- to 4-mm intervals along length of tear.
- First pass of double-armed suture placed in meniscal synovial junction (periphery) of intact portion of meniscus
- Second pass of double-armed suture placed through torn portion of meniscus in vertical plane to bridge tear
- Sutures brought out through accessory incision, tied directly over posterior meniscal attachment and capsule
- Tension in each suture is confirmed arthroscopically after knot is tied.
- Double longitudinal meniscus tears require an additional set of sutures.

Radial Tears
- Horizontal sutures placed at 2- to 4-mm intervals along tear site
- Inner sutures placed first and securely tied followed by sutures in the periphery
- Three to four sutures on superior surface, one or two sutures on inferior surface

Lateral Radial Tear Associated With Cyst
- Excise cyst through limited open lateral exposure.
- Repair peripheral meniscus rim, open technique.
- Repair radial tear, any associated horizontal tears using arthroscopic techniques.

Horizontal Tears
- Rasp through superior and inferior synovial attachments and within tear.
- Use vertical divergent sutures to close tear site.

Meniscus Attachment Root Tears
- Repair with NovoStitch (Ceterix) or Scorpion (Arthrex) instruments to pass two mattress or looped sutures.
- Leg holder required.
- 4- to 5-mm tibial tunnel placed directly at attachment site.
- Sutures tied over tibial post.

Flap Tears
- Tension sutures inserted through flap and into intact meniscal rim to anchor, reduce flap into anatomic bed
- Remaining tear repaired in same fashion as longitudinal tear

Repair of Lateral Popliteomeniscal Fascicles and Attachments
- At arthroscopy, nerve hook is placed at superior and inferior popliteal hiatus to displace lateral meniscus anteriorly and superiorly.
- Knee joint placed in 30 to 60 degrees of flexion, figure-four varus load applied to allow distraction of lateral tibiofemoral joint and maximum meniscus displacement.
- Meticulous inside-out repair technique with multiple sutures.

Techniques to Stimulate Healing of Meniscus Repairs
- Incorporation of fibrin clot at repair site theoretically beneficial, provides scaffold to support reparative cells, provides chemotactic and mitogenic stimuli.
- Fibrin clot inserted between meniscus tear edges prevents meticulous suturing superiorly and inferiorly.
- Synovial abrasion stimulates vessels and mesenchymal cells to form a proliferate vascular pannus that migrates into repair site.
- Specific chemotactic and mitogenic agents may someday play an important role in stimulating the repair process.



FIG 23-5 Operating room setup for meniscus repair. A figure-four position for a lateral meniscal repair is shown with the assistant seated with a headlight to grasp the inside-out sutures.

surgical bed is adjusted to allow 90 degrees of knee flexion. A tourniquet and leg holder are used, but the tourniquet is inflated only for the initial exposure. The leg holder is placed at the middle of the thigh, which allows an assistant to open the tibiofemoral compartment under maximum tension for visualization and meniscus surgery. The extremity is draped free to allow easy positioning during surgery. Standard medial and lateral patellar arthroscopic portals, placed directly adjacent to the patellar tendon, are used for the diagnostic arthroscopy. A common mistake is to place the arthroscopic portals too far medially or laterally over the femoral condyles, where instrument passage damages the femoral articular cartilage. The safe area for instrument passage is with the portal just medial and lateral to the patellar tendon with passage into the femoral notch region.

Diagnostic arthroscopy is performed and the meniscus tear analyzed according to its location, type, and size. The meniscus tissue and synovial junction are rasped to stimulate bleeding at the meniscus-synovial border.[216] Loose, unstable meniscus fragments are removed. In bucket-handle tears, the meniscus rim is prepared before the displaced meniscus is reduced because there are often fragments or partial horizontal clefts in the rim preventing close apposition of the meniscus body to the meniscus rim. Once the synovial fringe and meniscal edges are roughened, the meniscus tear is reduced anatomically. The goal is to restore the meniscus to its original size and shape to promote healing and restore its normal hoop stresses and biomechanical properties.

The inside-out meniscus repair technique requires an accessory posteromedial or posterolateral incision. This exposure allows protection of the neurovascular structures during suture retrieval and knot tying. In our opinion, an outside-in repair does not allow for the meticulous placement of vertical divergent sutures required for complex and avascular repairs, although it may be adequate for anterior horn tears.

Exposure for Medial Meniscus Repair

With the surgeon seated using a headlight and the sterile prepped foot in the surgeon's lap, the knee is flexed to 60 degrees, and a 3-cm vertical skin incision is made just posterior to the superficial medial collateral ligament (SMCL; Fig. 23-6). The tourniquet is inflated for the surgical exposure. The incision is centered just below the joint line (one third above, two thirds below) to allow retrieval of sutures. Avoid placing the incision too posterior in order to protect the saphenous vein and nerve. The subcutaneous dissection proceeds from the superior aspect of the wound down to the fascia. Care must be taken in the inferior aspect of the wound to avoid damage to the saphenous vein and nerve. Two retractors are used to provide visualization of the next layer of structures, the crural fascia and sartorius.

The anterior sartorial fascia is incised, avoiding the sartorius muscle. The pes muscle group is retracted posteriorly. The infrapatellar branches of the saphenous nerve may be present at this location and are protected to avoid injury. The retractors are repositioned to expose the posterior capsule and the semimembranosus sheath and tendon attachments. The key step is to incise the sheath overlying the semimembranous tendon. This opens a window to visualize the medial gastrocnemius tendon. Often, a small synovial Baker cyst is encountered in this interval, which is easily excised. The interval between the medial gastrocnemius tendon and the posterior capsule is bluntly dissected. This plane is developed superior to the semimembranosus tendon. This may be difficult because the semimembranosus tendon may be partially adhered to the posterior capsule. In some knees, the oblique popliteal ligament attachment to the semimembranosus tendon is partially incised to allow the tendon to be posteriorly displaced for exposure and suture retrieval.

Blunt dissection with an index finger allows development of a plane between the medial gastrocnemius tendon and the posterior capsule. A Henning retractor or spoon is inserted, allowing safe suture placement and needle retrieval (Fig. 23-7). The anesthesiologist is asked to provide muscle relaxation so that the gastrocnemius and semimembranosus muscles can be retracted. If the exposure is inadequate at this point, an alternative approach is to further dissect the semimembranosus tendon, which is elevated proximally to gain exposure just distal to the tendon. This is a less ideal approach because it is necessary to avoid placing sutures through the semimembranosus tendon just above its tibial attachment site.

Exposure for Lateral Meniscus Repair

The tourniquet is inflated, and the surgeon is seated and wearing a headlight, with the sterile prepped foot in the surgeon's lap. The knee is flexed to 60 degrees, and a 3-cm skin incision is made just behind the fibular collateral ligament (FCL; Fig. 23-8). The incision is centered just below the joint line (one third above, two thirds below) to allow retrieval of sutures. The interval between the biceps tendon insertion and the iliotibial band is identified and incised, staying superior to the biceps short head muscle fibers. The fascia overlying the posterolateral structures and FCL is gently dissected and peeled from superior to the fibular head. This is performed by applying tension with forceps to the incised fascia and using a thin-blade scissor to peel and strip the fascial tissues to the head of the fibula, protecting the FCL. The retractors are positioned between the biceps tendon and iliotibial band. The deep layer consists of the posterior capsule and the lateral gastrocnemius tendon. The gastrocnemius tendon has a normal proximal attachment to the posterior capsule, making it necessary to gently dissect the tendon with scissors off the posterior capsule at the joint line. The peroneal nerve inferior to the biceps tendon is palpated and protected but is not dissected.

The surgeon must be careful to remain posterior to the FCL and other posterolateral structures. The key step is to initially enter the space anterior to the lateral gastrocnemius tendon just above the fibular head. This avoids penetrating and opening the posterior capsule. The space between the posterolateral capsule and the lateral

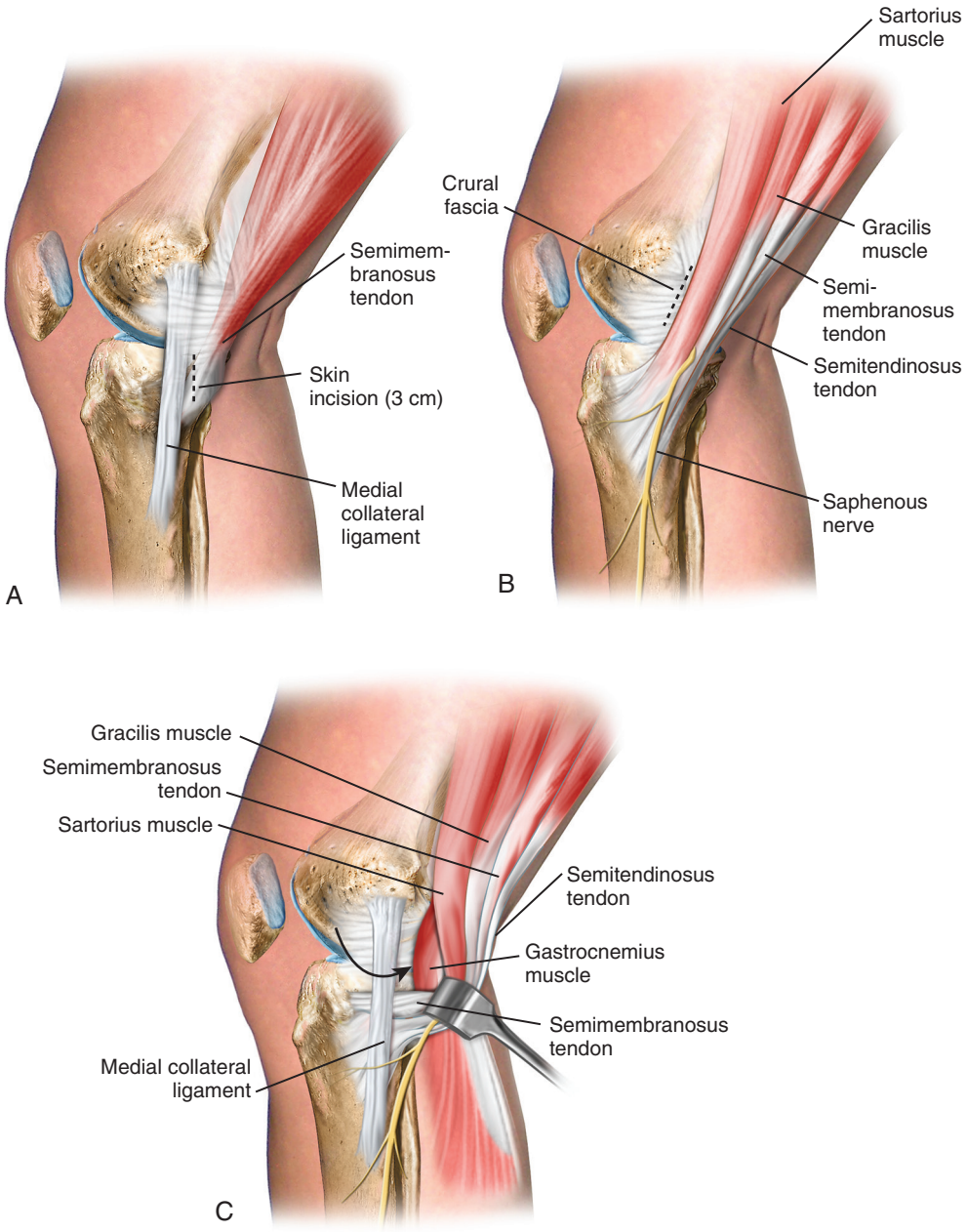


FIG 23-6 The accessory posteromedial approach is shown for a medial meniscus repair. **A,** Site of the posteromedial skin incision. **B,** The incision is shown through the anterior portion of the sartorius fascia. **C,** The interval is opened between the posteromedial capsule and the gastrocnemius tendon, just proximal to the semimembranosus tendon (*arrow*). The fascia over the semimembranosus tendon is excised to its tibial attachment to facilitate retrieval of the posterior meniscus sutures.

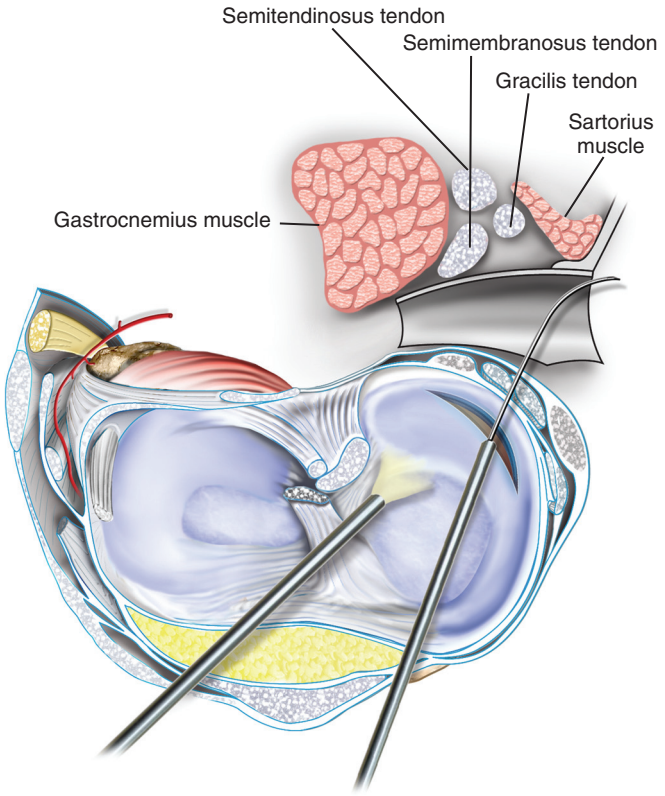


FIG 23-7 Cross-section shows popliteal retractor between the capsule and the medial gastrocnemius. The suture cannula is placed through the lateral or medial portal with care taken to angle the needle away from the neurovascular structures.

gastrocnemius tendon is further developed bluntly with the index finger. A Henning retractor is used to push the neurovascular bundle medially (Fig. 23-9). The inferior lateral geniculate artery may be visualized in the inferior aspect of the exposure and may be damaged and require electrocoagulation (which is avoided if possible to maintain the vascular supply to the lateral meniscus). The retractor must always be positioned anterior to the gastrocnemius muscle and tendon and directly posterior to the posterior capsule and posterior meniscus bed. The retractor blocks the suture needles from passing too posterior and potentially injuring the common peroneal nerve. During the meniscus suture steps, the surgeon should frequently check the position of the retractor to always ensure that it is anterior to the gastrocnemius muscle. If the retractor is mistakenly placed posterior to the gastrocnemius muscle, the peroneal nerve may be injured.

Patient Positioning and Equipment for Inside-Out Suture Repair

An assistant sits in a chair on the medial or lateral side of the knee with a headlight to visualize the posterior meniscus and capsule penetration of the inside-out-directed suture needles. The assistant has a needle holder to catch the suture needles and suture scissors. An inverted clamp is attached to the drapes to act as an instrument holder for this equipment. A scrub nurse stands opposite the surgeon to pass sutures through the single cannula, one at a time, after the surgeon has positioned the cannula. An assistant holds the lower leg with the knee at 20 to 30 degrees of flexion and applies the force required to open the tibiofemoral compartment. The articular cartilage is carefully protected at all times to avoid damage.

Instruments required in addition to routine arthroscopic equipment are a ball-tipped rasp for synovial rasping, a Henning or similar popliteal retractor for protection of the posterior neurovascular structures, a single-barrel straight and curved cannula for suture passage, and 10-inch double-armed meniscal sutures. Nonabsorbable sutures are used for interbody tears.

Suture Repair Techniques

For medial meniscus repairs, the knee is flexed 30 degrees, and an abduction load is applied. A 30-degree arthroscope is positioned through the medial portal to visualize the meniscus. The cannula is positioned through the lateral portal and pointed to the exact location of suture placement. This allows the suture needle to angle away from the midline neurovascular structures. Occasionally, the tibial spines block access for the suture cannula, and the surgeon must place the suture cannula in the medial portal. The suture cannula with a large radius curve is selected to angle the needle away from the neurovascular structures posteriorly. The second assistant passes a 10-inch flexible needle through the cannula. The first assistant, seated on the medial side of the knee, catches the needle with the needle holder as it exits through the exposed meniscus bed. The next suture is passed in the same manner. The first assistant catches the double-armed needles and pulls the suture through. Both needles are cut, and the suture is tied with five knots. The surgeon closely observes the reduction of the meniscus body and closure of the tear site with passage and tying of the vertical divergent sutures. The next sutures are placed in a similar fashion. Vertical divergent sutures are alternated; the sutures are placed first on the superior surface to reduce the meniscus, and second, on the inferior surface to close the inferior tear.

The neurovascular structures are protected throughout the procedure with the appropriate posteromedial exposure and a Henning retractor. For tears of the medial meniscus that extend entirely to the posterior horn, the surgeon must always place the needle cannula in the lateral portal to angle the sutures away from the neurovascular structures.

For lateral meniscus repairs, the first assistant is seated on the lateral side of the knee, and an adduction stress is applied to the flexed knee. Otherwise, the positioning and technique are the same as described for the medial meniscus repair.

Multiple 2-0 braided nonabsorbable sutures are used on a 10-inch straight cutting needle to repair all meniscus tears. The sutures are inserted through the superior and inferior meniscal surfaces in an interrupted vertical fashion to close the meniscus tear both superiorly and inferiorly. The vertical placement is used owing to its higher failure strength compared with horizontally placed sutures.[179] In addition, the vertical suture orientation mimics the function of the radial collagen fibers within the meniscus, which can improve its load-carrying capacity.[37]

In addition, a single-barrel straight or curved arthroscopic cannula is used that allows for accurate placement of the sutures along the edge in tissue that will hold the stitches. A double-barrel cannula is not advocated because the distance between the barrels is insufficient, and needle control is compromised. The location of sutures depends on the tear pattern to be described.

Single and Double Longitudinal Tears

Only select double longitudinal tears are repaired; those with a peripheral meniscal-capsular disruption and those in which the second tear is at or close to the red-white junction. A tear entirely within the central meniscus third is only of 6 to 7 mm in width and is not repaired. A longitudinal tear of the anterior horn of the medial or lateral meniscus

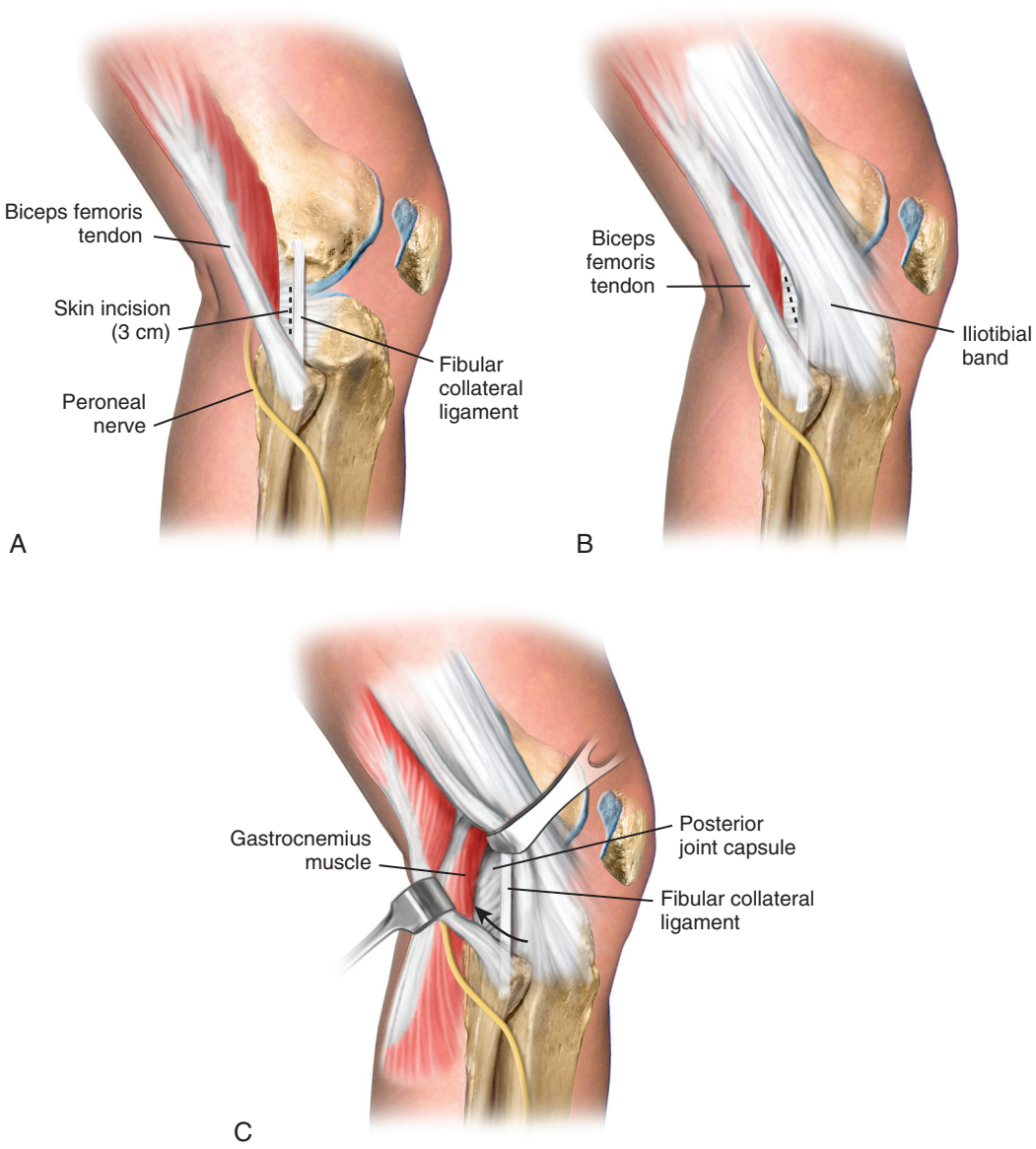


FIG 23-8 A, Site of the posterolateral incision for a lateral meniscus repair. **B,** Incision site in the interval between the posterior edge of the iliotibial band and the anterior edge of the biceps tendon. **C,** The interval between the lateral gastrocnemius and posterolateral capsule is opened bluntly, just proximal to the fibular head, avoiding entering the joint capsule.

that is at the periphery or extends into the red-white junction that fulfills the repair criteria is occasionally encountered. The senior author performs a mini-open direct 2- to 3-cm incision for an open repair. An outside-in placement of sutures for a simple tear is a second option.

A double-stacked suture technique is used for single and double longitudinal meniscus tears. This technique consists of two layers of sutures (Figs. 23-10 and 23-11) placed at 3- to 4-mm intervals along the length of the tear. The first layer of sutures is placed superiorly to anchor the meniscus to its bed and prevent superior migration of the meniscus during the repair. The cannula is used to hold and reduce the torn meniscus on the tibia.

The first pass of the double-armed suture is placed in the meniscal-synovial junction (periphery) of the intact portion of the meniscus. The second pass of the double-armed suture is placed through the torn portion of the meniscus in a vertical plane so that it bridges the tear (Fig. 23-12). The inferior sutures are placed next in a vertical plane, crossing the tear in the same manner as the superior sutures. The sutures are brought out through the accessory incision and tied directly over the posterior meniscal attachment and capsule. The sutures are tied as they are passed to determine the apposition of the tear surfaces. The tension in each suture is confirmed arthroscopically after the knot is tied. This double-stacked technique provides stable fixation of the meniscal tear on both sides and entirely closes the meniscus gap at the repair site (Fig. 23-13).

Double-longitudinal meniscus tears require an additional set of sutures. The peripheral tear is repaired in the same manner as a single longitudinal tear with superior and inferior sutures. The longitudinal tear located in the middle body is repaired with two or three additional superior and inferior sutures. Care is taken to avoid excessive suture

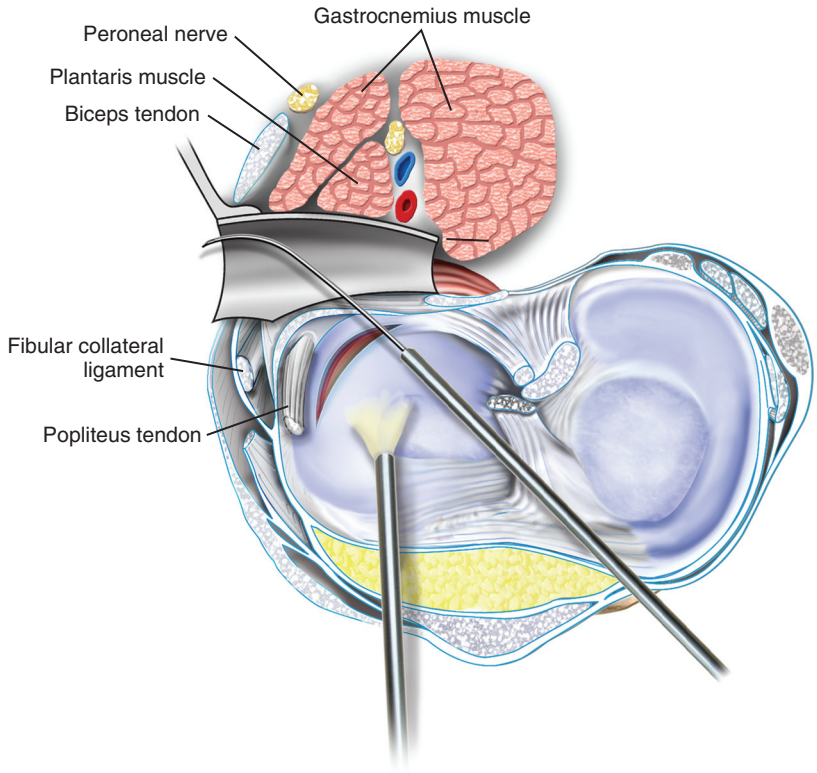


FIG 23-9 Cross-section shows popliteal retractor between the lateral gastrocnemius and the posterior capsule. A curved suture cannula is also used to angle the needles away from the neurovascular structures.

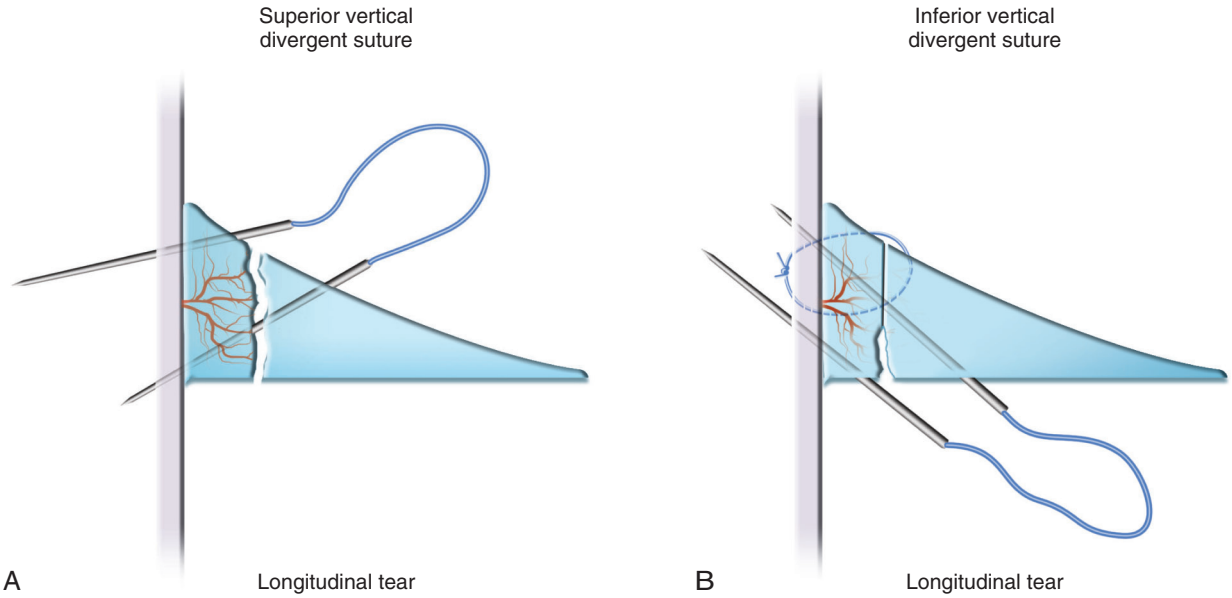


FIG 23-10 Double-stacked vertical suture pattern used in the repair of longitudinal meniscus tears. **A,** The superior sutures are placed first to close the superior gap and to reduce the meniscus to its bed. **B,** The inferior suture is then placed through the tear to close the inferior gap.

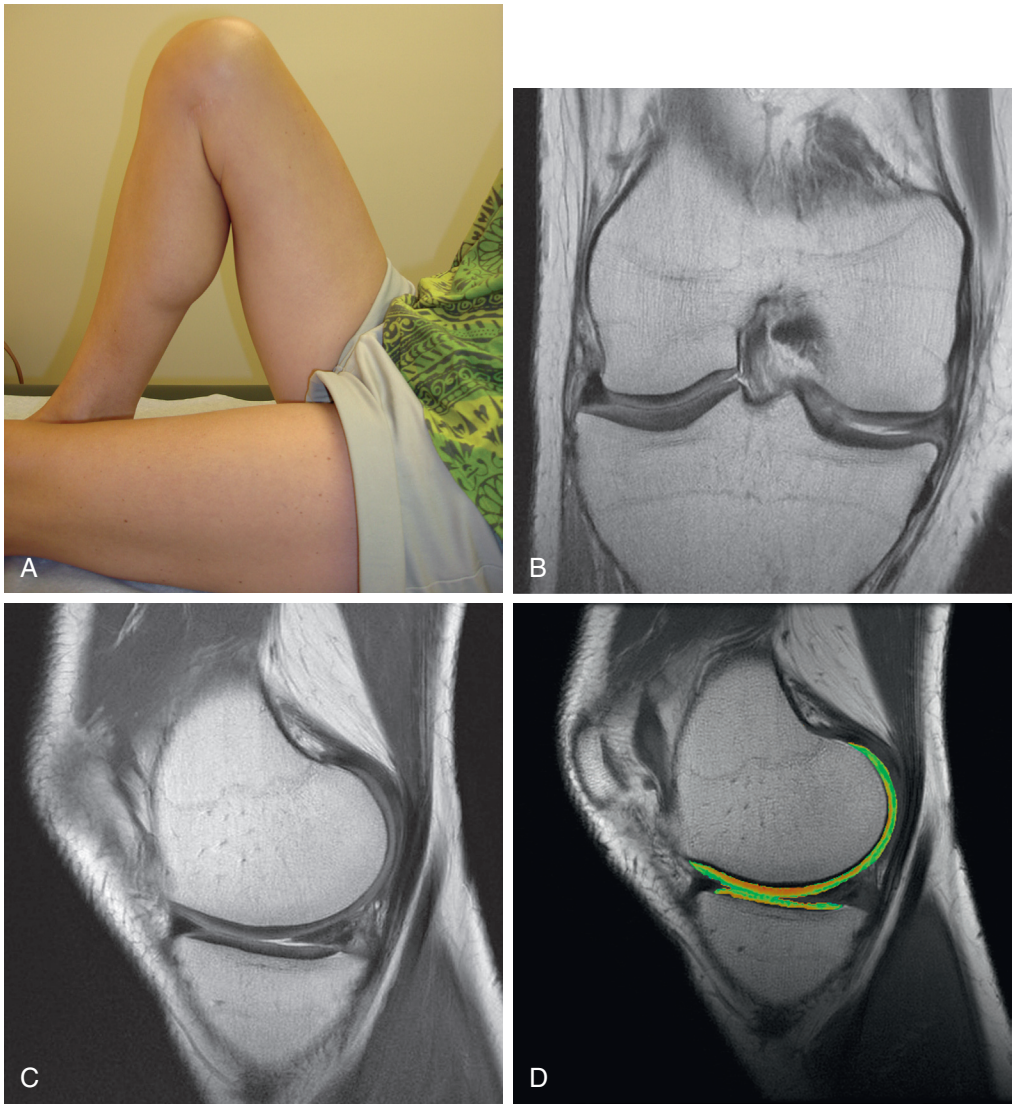


FIG 23-11 A 35-year-old woman 20 years after a repair of an avascular 15-mm longitudinal medial meniscus tear involving the posterior horn. An inside-out technique with multiple vertical sutures was performed. The tear extended from the red-white to white-white region, with a 4-6 mm meniscus rim. **A,** The patient is entirely asymptomatic and participates in recreational activities. **B** and **C,** A 3-Telsa magnetic resonance image shows an intact medial meniscus and normal appearing articular cartilage. **D,** T2-weighted cartilage mapping shows no definite abnormality.

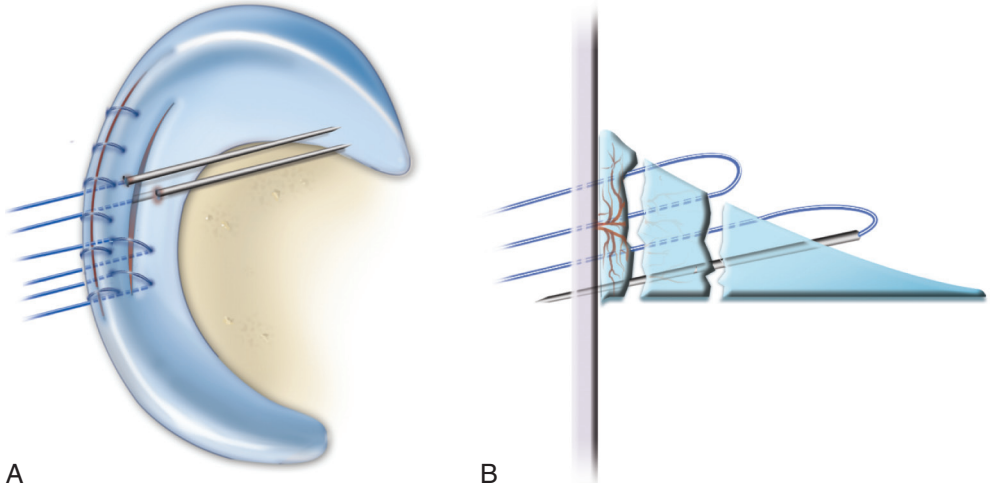


FIG 23-12 Double-stacked repair technique for double longitudinal tears. The peripheral tear is repaired first with superior and inferior vertical divergent sutures (**A**), followed by repair of the inner tear in the same fashion (**B**).

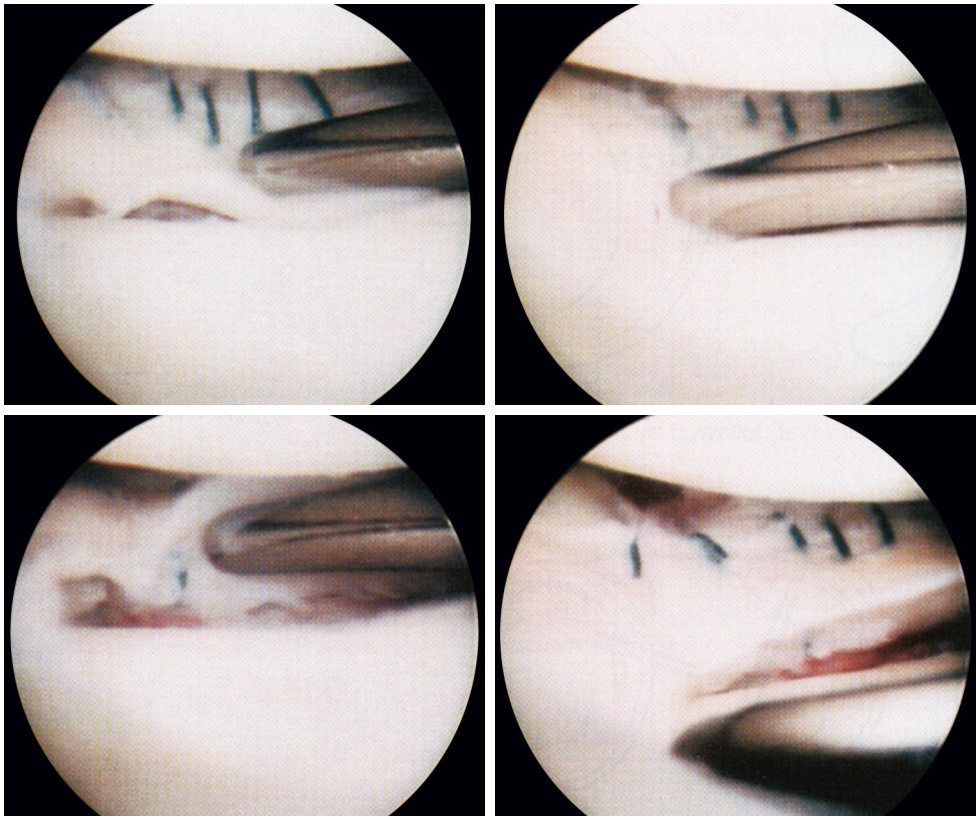


FIG 23-13 A longitudinal meniscal tear site demonstrating some fragmentation inferiorly. This tear required multiple superior and inferior vertical divergent sutures to achieve an anatomic reduction. (From Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscal tears extending into the avascular zone in patients younger than twenty years of age. *Am J Sports Med.* 2002;30:589-600.)

placement between tears in order to maintain meniscus integrity and function.

Radial Tears

Horizontal sutures are placed at 2- to 4-mm intervals along the tear to repair radial meniscus tears. The inner sutures are placed first and securely tied, followed by sutures located in the periphery (Fig. 23-14). Three to four sutures are used on the superior surface, and one or two sutures are used on the inferior surface. The initial sutures are placed first through the body using the needle to displace the meniscus toward the tear site, followed by needle passage through the meniscus bed. This allows the tear site gap to be closed. Only radial tears that extend to the outer third of the meniscus body are repaired because those that are confined to the inner and middle zones have a poor blood supply and will not heal. A radial tear that extends to the meniscus rim compromises the hoop stress and is equivalent to a total loss of meniscus function. Occasionally, the edges of the radial tear are degenerative with poor suture-holding capability and repair is not possible. Traumatic radial tears have a better chance of healing. The goal is to retain partial meniscus function, if possible, because it is rare to have successful healing of a tear in the inner third of the meniscus. As shown in Table 23-1, horizontal sutures carry low load-to-failure values, and therefore a period of non–weight bearing for 4 weeks is required to prevent disruption of the repair site. The patient is advised that this type of repair has a guarded prognosis in terms of providing function. The repair may heal, but the meniscus tear edges separate in the healing process with the interval replaced with poorly organized fibrous tissue with an elongated meniscus structure that displaces from the joint.

There is a common clinical presentation of a radial tear of the posterior horn of the medial meniscus in older patients. This type of tear represents a degenerative tear without trauma, and there is usually associated osteoarthrosis to the medial compartment. The radial tears are usually widely separated and are not repairable because of the poor quality of the tissues.[6,29,161]

Lateral Radial Tears Associated With a Cyst

Because partial meniscectomy and cyst excision may remove a substantial portion of the meniscus body and disrupt its peripheral rim, a cyst should be excised through a limited open lateral exposure (Fig. 23-15). This is followed by repair of the peripheral rim of the meniscus using an open technique. The radial tear and any associated horizontal tears may then be repaired using the arthroscopic techniques described previously. It is not recommended to evacuate the cyst through the intra-articular radial tear site because this damages meniscus tissues and prevents repair. A lateral meniscus cyst is commonly associated with combined radial and horizontal tears that are not repairable; however, this is difficult to determine preoperatively. The mistake is to excise the meniscus in a patient age 50 years or younger in whom a repair is possible to preserve some meniscus function in which progression to lateral compartment arthritis occurs in a short time, particularly in a valgus-aligned lower extremity.

Horizontal Tears

The majority of horizontal tears are degenerative with poor tissue quality and are not reparable. These irreparable tears have thickened tissues, fatty deposition, and partial flap tears. Occasionally, a large

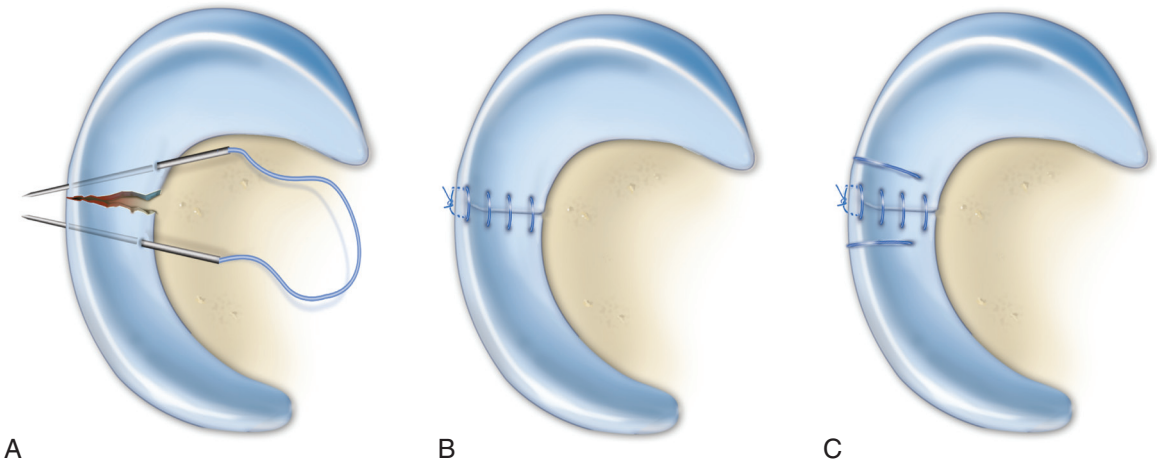


FIG 23-14 Repair technique for radial meniscal tears. The inner sutures (**A**) are placed first, followed by the peripheral sutures (**B**). The first suture needle is placed midway through the meniscus body and then used to apply a circumferential tension to reduce the tear gap, then advanced through the posterior meniscus bed. The second suture needle is placed in a similar manner. This reduces the radial gap, allowing subsequent sutures to be placed. Usually, 3 to 4 sutures are placed superiorly and two sutures, inferiorly. **C,** Occasionally, superior vertical divergent sutures are placed along the tear site to help stabilize the repair.

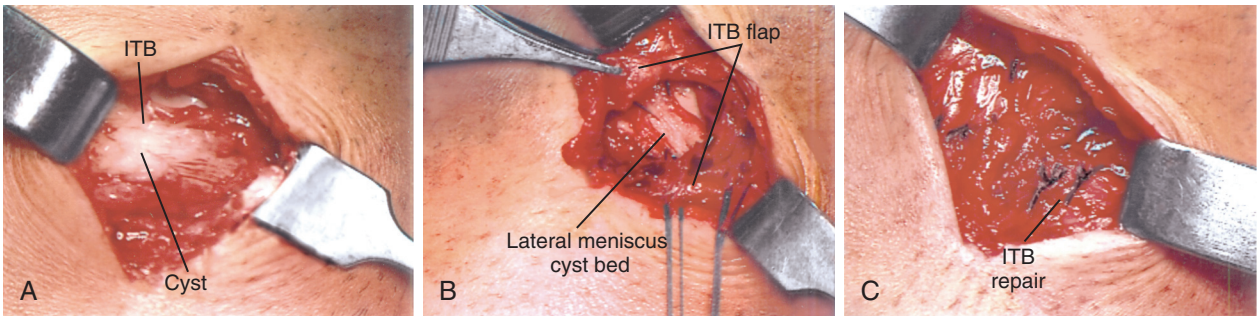


FIG 23-15 Demonstration of repair of lateral meniscus horizontal tear with a meniscal cyst. **A,** A 3-cm lateral joint incision placed directly over the cyst shows iliotibial band and obvious protruding cyst. **B,** Iliotibial band is split in a line of fibers over the cyst and retracted, the cyst is removed, and repair is performed of the remaining meniscus to attachments. **C,** Closure iliotibial band over the meniscus. Vertical sutures placed through the peripheral meniscus and iliotibial band help stabilize the repair. The arthroscopic inside-out repair of the meniscus body tear is then performed.

horizontal flap tear is encountered in patients younger than 50 years in which the tear extends throughout the body, creating superior and inferior segments, but the meniscal tissue is of good quality, has not displaced outside the tibiofemoral compartment, and can be repaired. The meniscus is rasped through the superior and inferior synovial attachments and within the horizontal tear. Minor meniscus fragments are removed. Vertical divergent sutures are used to close the tear site. A fibrin clot may be added to the repair site and placed within the horizontal tear. However, whether this technique increases the repair success rate has not been scientifically proven.

Meniscus Attachment Root Tears

Recently, there has been increased attention on the importance of identifying meniscus tears at their attachment site and repairing these root tears to restore medial or lateral meniscus function.[98,108,186,197,222] Without a suture repair, there is a complete loss of meniscus function because it displaces under weight-bearing loads. It is important to note that tears located 8 to 10 mm from the meniscus root attachment are frequently degenerative in nature and may not be amenable to repair. This section focuses on the successful repair of a meniscus directly at its attachment site. In a cadaveric study, LaPrade and associates[108] showed the importance of an anatomic repair to restore function of medial or lateral meniscus root tears. Johannsen and coworkers[98] described the quantitative arthroscopically pertinent anatomy of the posterior meniscal root attachments (Fig. 23-16).

During surgery, a thigh holder is required to allow sufficient joint opening for passing a suture device, particularly for medial meniscus root tears. A 4- to 5-mm tibial tunnel using an ACL tibial guide is placed directly at the attachment site. Different suture lasso instruments may be selected, and increased tensile strength may be gained by using multiple single sutures, a Mason-Allen suture, mattress sutures, or looped sutures. There is still considerable disagreement among studies regarding which suture fixation type is best used for root tears.

As shown in Table 23-1, all the suture configurations have relatively low maximum failure loads. Anz and associates[9] performed a biomechanical comparison of four different suture configurations for posterior meniscus root tears. All repairs used No. 2 braided polyester and

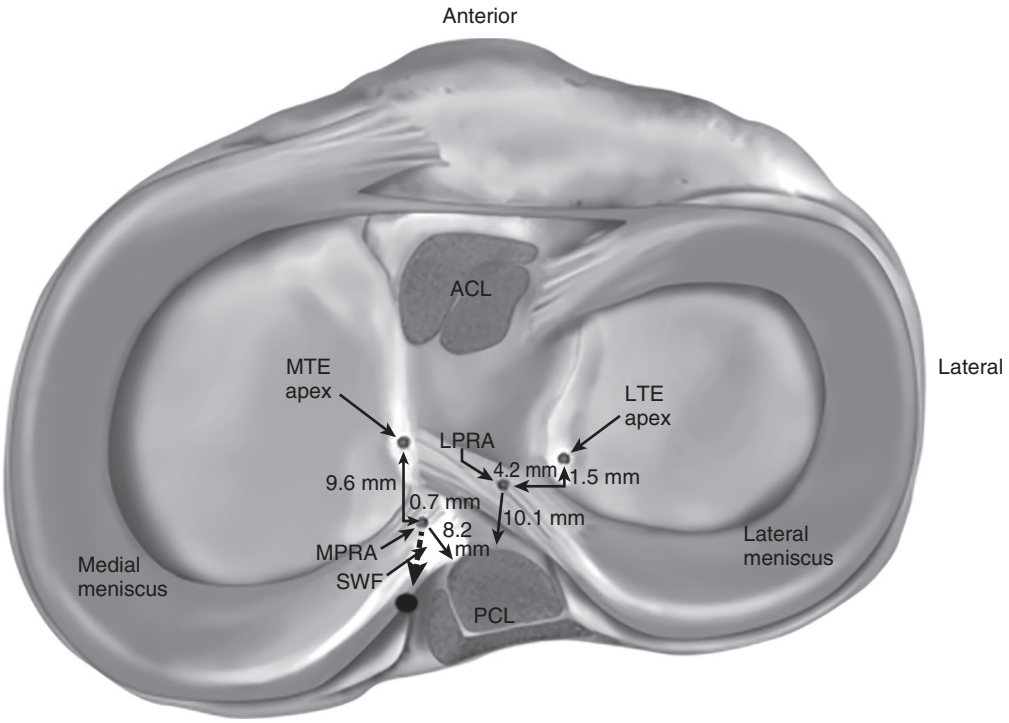


FIG 23-16 The medial and lateral meniscal posterior root attachments and relevant arthroscopically pertinent anatomy (right knee, superior view). *ACL,* Anterior cruciate ligament; *LPRA,* lateral meniscus posterior root attachment; *LTE,* lateral tibial eminence; *MPRA,* medial meniscus posterior root attachment; *MTE,* medial tibial eminence; *PCL,* posterior cruciate ligament; *SWF,* shiny white fibers of posterior horn of medial meniscus. (From Johannsen AM, Civitarese DM, Padalecki JR, et al. Qualitative and quantitative anatomic analysis of the posterior root attachments of the medial and lateral menisci. *Am J Sports Med.* 2012;40: 2342-2347.)

ultrahigh molecular weight polyethylene sutures. The configuration of two double-locking loop sutures had the highest failure load (368 ± 76 N), followed by a single double-locking loop suture (186 ± 43 N), one inverted mattress suture (126 ± 44 N), and two simple sutures (137 ± 49 N). These results provide the surgeon with objective data on the highest strength repair configuration possible. Native meniscal root strength was assessed in 43 cadaver specimens by Kopf and colleagues,[104] who reported a mean failure load of 678 ± 200 N for the posteromedial root and 648 ± 140 N for the posterolateral root.

A cadaveric investigation by Feucht and associates[63] showed the tendency of some suture repairs to elongate under cyclic loading. These findings indicates that, with any suture repair, the surgeon should proceed with conditioning (as is done with an ACL graft), loading the sutures (10 lb, empirical) with knee flexion-extension to diminish the potential for creep elongation of the construct.

Starke and coworkers[197] performed a cadaveric study on the tensile forces that occurred after a repair of a medial meniscus root tear. The highest mean tension of 60 ± 20 N occurred with internal tibial rotation and a 500-N compressive load at 90 degrees of knee flexion. The authors cautioned that, on weight bearing, there may be considerable tensile forces that occur within the medial meniscus root repair. This study is frequently quoted as providing a safe level for the suture fixation strength at the time of surgery. However, it should be noted that the loading conditions were only 500 N, which is less than one body weight as applied to a patient population and considerably less than the three to five times body weight loads incurred under certain activities of daily living.

The senior author prefers the use of the Novostitch (Ceterix) to place two looped or mattress type sutures (shown later in Illustrative Case 9). The sutures are tied over a tibial post. Weight bearing is restricted as described in Chapter 25.

Flap Tears

Two sets of sutures are required to repair flap tears (Fig. 23-17). Tension sutures are inserted first through the flap and then into the intact meniscal rim to anchor and reduce the flap into its anatomic bed. This restores the longitudinally running fibers of the meniscus and is performed in a manner similar to that for a radial tear repair. With the meniscus reduced, the remaining tear is repaired in the same fashion as a longitudinal tear, with superior and inferior vertical divergent sutures. The radial portion of the flap tear may only partially heal; however, the more peripheral longitudinal tear may heal, retaining partial meniscus function. Flap tears that represent 75% of the meniscus with the tear at the periphery or R/W junction are amendable for repair. Smaller flap tears 10 to 12 mm in length that occupy the R/W and W/W zone are not repaired.

Repair of the Lateral Meniscus Popliteomeniscal Fascicles and Attachments

During arthroscopy, a nerve hook is placed at the superior and then inferior popliteal hiatus to displace the lateral meniscus anteriorly and superiorly. The knee joint is placed in 60 to 90 degrees of flexion with a figure-four varus load applied to allow lateral tibiofemoral joint opening and maximum meniscus displacement (which is otherwise obstructed by the lateral femoral condyle). The posterior horn may be subluxated anteriorly 8 mm or more (usually not enough for locking into the joint) and superior "lift-off" of 10 to 12 mm is usually present, indicating laxity of the meniscotibial attachments. There is usually a

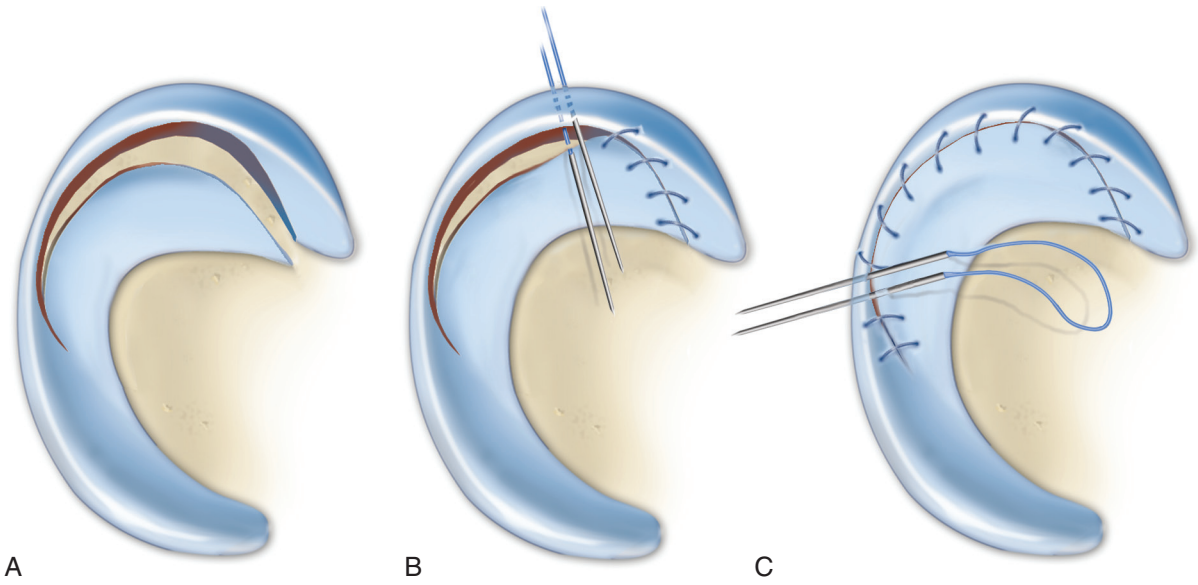


FIG 23-17 Repair technique for flap tears. **A,** The tear is identified and reduced. **B,** Horizontal tension sutures are placed to anchor the radial component of the tear. **C,** The longitudinal component is sutured using the double-stacked suture technique.

tear of the meniscotibial attachments in which the normal posterior-inferior popliteal hiatus is enlarged with attenuation or tearing of the meniscus attachments. The normal width of the popliteal hiatus is 10 to 15 mm. A larger width, particularly extending medially, allows for anterior subluxation of the posterior horn of the lateral meniscus to occur, even though the posterior-superior attachments are intact.[167,202]

The repair of the popliteomeniscal fascicles requires a meticulous inside-out technique with multiple sutures to obtain stability of the lateral meniscus and alleviate clinical symptoms. All-inside meniscus fixators or use of only a few sutures is not suitable to provide a stable construct and repair. The arthroscope is placed in the lateral portal and the suture cannula in the medial portal. The superior and inferior sites are rasped to encourage healing. The inside-out meniscus repair technique requires placement of multiple vertical divergent sutures, placed superiorly at the anteroinferior and posterosuperior fascicle attachments (either side of the popliteus tendon) to reduce the lateral meniscus posterior horn to a normal tibial position and restore the meniscus attachments.

The more difficult repair involves inferior vertical divergent sutures at the inferior popliteal hiatus and meniscotibial meniscus attachments. The tissues may be thin, and four to six sutures must be placed through the inferior capsule at the level of the tibial attachment and then in a vertical manner through the inferior outer third of the meniscus posterior horn. It is important that the previously placed superior vertical sutures retain the meniscus reduction so that placement of the inferior sutures does not displace the meniscus in an abnormal cephalad direction.

Techniques to Stimulate Healing of Meniscus Repairs

The initial vascular response of the meniscus to injury and tearing is characterized by the formation of a fibrin clot that is rich in inflammatory cells. This clot acts as a scaffold through which cells from the synovial membrane adjacent to the meniscus migrate.[10,11] The meniscal fibrochondrocytes may add to the intrinsic healing process.

Several experimental studies have investigated techniques to stimulate meniscus healing, including trephination or vascular ingrowth,[11,69,233,235] abrasion of the meniscal-synovial region,[41,81,147,159,180] grafting of the synovial pedicle,[70] incorporation of a fibrin clot,[147,180] and use of growth factors and cell-based therapy.[26,78,84,85,96,99,169,200,213,214] Although trephination, or creation of vascular access channels, has been demonstrated experimentally to promote healing,[11,180,234,236] the creation of these channels disrupts the normal peripheral structure and architecture of the meniscus.[115]

The incorporation of a fibrin clot[12,82,176,217] at the repair site of radial and avascular meniscus repairs is theoretically beneficial because it provides a scaffold to support the reparative cells and provide chemotactic and mitogenic stimuli.[225] The absence of a well-defined fibrin clot in the initial healing period along with a limited vascular supply may be the most important factors limiting meniscus healing in tears located in the middle third region. The problem is that a fibrin clot inserted between the tear edges of the meniscus prevents meticulous suturing of the tear both superiorly and inferiorly. A fibrin clot may be beneficial in horizontal tears in which the clot may be placed between the superior and inferior tear sites. The clot is prepared with a glass stirring rod. The clot is passed into the knee joint through a cannula, guided by a loop of suture placed around the clot from previously passed meniscus suture needles.

Ritchie and coworkers[180] found that abrasion of the parameniscal synovium was more effective than the incorporation of a fibrin clot in central meniscus repairs. Synovial abrasion stimulates vessels and mesenchymal cells to form a proliferate vascular pannus that migrates into the repair site.[53,80,190]

Several studies have demonstrated that an ACL reconstruction performed concomitantly with meniscal repair increases the success rate because the reconstruction protects the meniscus repair site owing to the restored knee stability and provides the beneficial healing effects of the postoperative hemarthrosis, including the release of growth factors.[40,51,54,97,142,206] In the majority of meniscus repairs done without concomitant ACL reconstruction, the meniscal-synovial junction is abraded (rasped), and a micropick is used in the intercondylar notch region to produce bleeding, which promotes adherence of platelets and fibrin at the repair site.[158] The meticulous suture placement described in this chapter stabilizes the tear and prevents gap formation at the repair site, allowing the subsequent repair process to progress.

The remodeling events and extent of reformation of a normal collagen architecture following meniscus repair remain unknown. Whether repaired meniscal tears in the middle third region have normal load-sharing capabilities and mechanical and material properties to prevent joint arthrosis remains unanswered. In the future, specific chemotactic and mitogenic agents may play an important role in stimulating the repair process of tears that extend into the avascular portions of the meniscus. Investigations of cytokines, growth factors, platelet rich plasma, and cell-based therapies have all been experimental to date, with no published clinical trials to document the potential effectiveness.[79,94,115,128-130,204,213-215,225]

OUR CLINICAL STUDIES

Arthroscopic Evaluation of 79 Meniscus Repairs in the R/R and R/W Zones

We conducted an investigation in 66 patients who underwent meniscus repair and ACL reconstruction, then follow-up arthroscopy 6 to 25 months postoperatively.[38] There were 79 meniscus repairs: 51 for tears located in the R/R zone and 28 for complex tears that extended into the R/W zone. The postoperative rehabilitation program included immediate knee motion and strengthening exercises the first postoperative day. Early partial weight bearing was initiated between the first and third postoperative weeks and was progressed to full by the eighth to tenth week. Follow-up arthroscopy was done for symptoms related to either tibial hardware or tibiofemoral joint pain.

The arthroscopic videotapes and operative records were reviewed by a surgeon who had not been involved in the care of the patients. The rate of meniscus healing was classified as completely healed (no visible surface defect), partially healed (at least 50% healed with meniscus stability and continuity restored), or failed (no visible healing). The three healing categories were analyzed separately, and then the categories of healed and partially healed were combined into one category (retained meniscus) and compared with the failure rates.

Repairs of R/R tears were classified as completely healed in 94%, partially healed in 4%, and failed in 2% (Table 23-2). Repairs of R/W tears were classified as completely healed in 54%, partially healed in 32%, and failed in 14%. The other factors analyzed in this study had no significant effect on the healing rates.

The program of immediate knee motion and early weight bearing was not deleterious to the healing meniscus repairs. This was one of the first investigations to demonstrate that repair of meniscus tears located in either the R/R or R/W zones have a satisfactory rate of healing when clinical grounds warrant the procedure. The increase in healing of meniscus tears when concurrent ACL surgery is performed is well appreciated. In knees that undergo meniscus repairs without ACL surgery, the femoral notch region is trephinated to induce joint bleeding and potentially aid in the deposition of blood products at the healing site for the initial fibrin clot formation.

CRITICAL POINTS Our Clinical Studies: Arthroscopic Evaluation of 79 Meniscus Repairs in the R/R and R/W Zones

- $n = 79$ meniscus repairs: 51 tears in R/R, 28 in R/W zones
- All had anterior cruciate ligament reconstruction with meniscus repair.
- Follow-up arthroscopy 6 to 25 months after repair
- Healing rates:
  - R/R: 94% healed, 4% partially healed, 2% failed
  - R/W: 54% healed, 32% partially healed, 14% failed
- No effect on meniscus repair healing rates: length of meniscus tear, tibiofemoral compartment of repair, patient age, length of time from injury to repair, length of follow-up, arthroscopic versus open procedure
- Use of immediate knee motion and early weight bearing not deleterious to healing meniscus repair

Outcome of 198 Meniscus Repairs in the R/W Zone

The clinical outcome of 198 meniscus tears in 177 patients that extended into the R/W, or who had a rim width of 4 mm or greater, was determined in a prospective study.[187] A total of 180 repairs (91%) were evaluated with a clinical examination a mean of 3.5 years (range, 2-9.7 years) postoperatively, and 91 repairs (46%) were evaluated with a follow-up arthroscopic examination a mean of 1.5 years (range, 2 months to 6.7 years) after the initial repair.

Seventy-six of the meniscus repairs were performed for acute or subacute tears and 122 for chronic tears. ACL ruptures also occurred in 128 patients. Of these, 126 (71%) underwent ACL reconstruction either with the meniscus repair (96 patients) or a mean of 22 weeks following the repair (30 patients). The ACL reconstructions were done with allografts in 72 knees and with bone-patellar tendon-bone (B-PT-B) autografts in 54 knees. After surgery, patients began immediate knee motion from 0 to 90 degrees. Flexion was advanced to 125 degrees by the third postoperative week. Crutches were used for the first 4 weeks for longitudinal tears and for the first 6 weeks for horizontal, radial, or

TABLE 23-2 Effect of Six Factors on Healing Rate of Meniscal Repairs

Factor	Complete Healing (*n*)	Partial Healing (*n*)	Failed (*n*)
Rim Width			
Outer third (0-3 mm, $n = 51$)	48*	2	1
Central third (4-6 mm, $n = 14$)	6	5	3
Double longitudinal ($n = 10$)	6	4	0
Flap ($n = 4$)	3	0	1
Length of Meniscus Tear			
≤2.5 cm ($n = 43$)	34	7	2
>2.5 cm ($n = 36$)	29	4	3
Type of Meniscus			
Medial ($n = 51$)	40	6	5
Lateral ($n = 28$)	23	5	0
Age of Patient			
<25 years ($n = 51$)	44	5	2
≥25 years ($n = 28$)	19	6	3
Interval to Repair			
Initial, ≤8 weeks ($n = 37$)	33	3	1
Delayed, >8 weeks ($n = 42$)	30	8	4
Length of Follow-Up			
<12 months ($n = 55$)	35	5	1
≥12 months ($n = 24$)	28	6	4
Open Versus Scope			
Open ($n = 33$)	32	1	0
Scope ($n = 30$)	24	4	2

*$P < .01$.

CRITICAL POINTS Our Clinical Studies: Outcome of 198 Meniscus Repairs in the R/W Zone

- $n = 198$ meniscus repairs in 177 patients
- 71% had anterior cruciate ligament reconstruction either with or after the meniscus repair.
- 91% evaluated clinically 2 to 9.7 years postoperatively
- 46% evaluated follow-up arthroscopy 2 months to 6.7 years postoperatively
- Advanced rehabilitation program allowed 0 to 90 degrees of knee motion immediately postoperatively
- Deep knee flexion, full sports delayed for 6 months to protect repair site
- Overall reoperation rate for tibiofemoral symptoms: 20%
- 80% asymptomatic for tibiofemoral symptoms, not interpreted as rate of healing
- Significant differences in healing rates in menisci evaluated with follow-up arthroscopy:
  - Higher rate retention lateral meniscus compared with medial meniscus
  - Higher rate healing repairs assessed ≤12 months compared with repairs assessed >12 months with follow-up arthroscopy
  - Higher rate healing in knees without tibiofemoral joint symptoms compared with those with joint line pain
- Results support repair of meniscus tears that extend into the middle avascular region, especially in patients between 20 and 40 years of age.

complex multiplanar tears. Squatting or deep knee flexion greater than 125 degrees was not permitted for 4 to 6 months postoperatively. Return to full sports was restricted for 6 months.

At follow-up arthroscopy, the meniscus repairs were classified as healed if full-thickness apposition of the original tear occurred with no more than 10% of the original tear remaining. Repairs were considered partially healed if at least 50% of the original tear was healed and was stable when probed and the meniscus body was in its normal position in the tibiofemoral joint. Repairs were considered failed if more than 50% of the original tear was present or if unstable fragments required additional sutures. On clinical examination, a McMurray test was used with joint line palpation and compression to detect tibiofemoral joint symptoms.

The overall reoperation rate for tibiofemoral symptoms was 20% (39 meniscus tears). All patients who had tibiofemoral pain underwent follow-up arthroscopy. The reoperation rates according to the type of tear are shown in Table 23-3. The limited number of meniscal tears in the individual classification categories precludes specific conclusions on the outcome for each tear pattern. Of the 39 menisci examined, 2 were classified as healed, 13 as partially healed, and 24 as failed.

A total of 91 meniscus repairs were evaluated by follow-up arthroscopy: the 39 described earlier and 52 others that underwent surgery for reasons other than tibiofemoral joint symptoms. Of these 91, 23 (25%) were classified as healed, 35 (38%) as partially healed, and 33 (36%) as failed.

The effects of six factors on healing rates of meniscal repairs were evaluated (Table 23-4). Statistically significant differences were found in the rates of healing for three factors: tibiofemoral compartment of the meniscus repair (higher healing rate in lateral meniscus repairs than in medial meniscus repairs), time from repair to follow-up arthroscopy (higher healing rate in patients evaluated at ≤12 months compared with those evaluated >12 months postoperatively), and the presence of tibiofemoral symptoms (higher healing rate in asymptomatic patients compared to symptomatic patients).

The significantly higher rate of retention of lateral meniscus repairs found in this study agrees with those of other reports.[142,185,190] The reasons for the higher failure rate of medial meniscus repairs are unknown at present. The results of this investigation support the repair

TABLE 23-3 Reoperation Rates for Meniscal Repairs Attributed to Tibiofemoral Joint Symptoms

Type of Meniscus Tear	Total Meniscus Tears in Study	Number Requiring Repeat Arthroscopy
Single longitudinal	92	11 (12%)
Double longitudinal	40	11 (28%)
Complex multiplanar	26	7 (27%)
Radial	15	4 (27%)
Horizontal	14	4 (29%)
Flap	9	2 (22%)
Triple longitudinal	2	0
Total	198	39 (20%)

TABLE 23-4 Effect of Various Factors on Healing Rates of Meniscal Repairs With Follow-up Arthroscopy

Factor	Healed (*n*)	Partially Healed (*n*)	Failed (*n*)
Tibiofemoral Compartment of Meniscal Repair*			
Medial ($n = 47$)	8	15	24
Lateral ($n = 44$)	15	20	9
Time from Meniscus Repair to Follow-up Arthroscopy†			
≤12 months ($n = 61$)	18	27	16
>12 months ($n = 30$)	5	8	17
Timing of ACL Reconstruction			
With meniscal repair ($n = 39$)	12	18	9
After meniscal repair ($n = 27$)	9	11	7
Presence of Tibiofemoral Compartment Symptoms‡			
Symptomatic ($n = 39$)	2	13	24
Asymptomatic ($n = 52$)	21	22	9
Time from Original Knee Injury to Meniscal Repair§			
≥10 weeks ($n = 33$)	13	10	10
>10 weeks ($n = 58$)	10	25	23
Patient Age			
<25 years ($n = 44$)	13	17	14
≥25 years ($n = 47$)	10	18	19

*Lateral success rate is significantly higher than medial; $P = .008$.
†Follow-up arthroscopy <12 mo postoperative success rate is significantly higher than >12 mo; $P = .02$.
‡Tibiofemoral symptoms have a higher failure rate than no symptoms; $P = .0001$.
§<10 weeks from injury higher success rate; $P = .06$.
ACL, Anterior cruciate ligament.

of meniscus tears that extend into the middle third region, especially in patients in their 20s and 30s and in highly competitive athletes. The study's reoperation rate should not be interpreted as the rate of meniscal healing. The long-term function and chondroprotective effects of the repaired menisci need to be determined, and this group of patients is under prospective long-term evaluation.

Outcome of 30 Meniscus Repairs in the R/W Zone in Patients 40 Years of Age and Older

The clinical outcome of 30 meniscus tears that extended into the R/W zone in patients 40 years of age and older was prospectively determined.[150] ACL reconstruction was performed concurrently with the meniscus repair in 72%. Ten meniscus repairs were done for acute knee injuries (≤10 weeks from injury), and 20 were done for chronic injuries. Twenty-eight repairs were evaluated with a clinical evaluation a mean of 2.8 years (range, 2-5.9 years) postoperatively, and six repairs were evaluated with arthroscopy a mean of 2 years (range, 1.3-3 years) after the repair.

At follow-up, 26 meniscus repairs (87%) were asymptomatic for tibiofemoral joint symptoms and had not required further surgery. There was no significant effect of the tibiofemoral compartment of the meniscus repair, chronicity of injury, concomitant ACL reconstruction, or condition of the articular cartilage on the presence of tibiofemoral pain or meniscus resection (Table 23-5).

A subjective evaluation using the CKRS was completed at follow-up on 25 knees; 3 knees whose meniscal repairs failed and required removal at follow-up arthroscopy and 1 other knee that had follow-up arthroscopy but not a clinical evaluation 2 years postoperatively were not included. Of these 25 knees, 17 had chronic meniscal tears and eight had acute tears before the index repair procedure. Nineteen had a concomitant ACL reconstruction.

The 17 knees with chronic symptoms had statistically significant improvements in the mean scores for pain, swelling, and giving-way ($P < .01$); squatting ($P < .05$); and running, jumping, and cutting ($P < .0001$). Before the meniscal repair, 12 had given up sports, and five were participating with symptoms and functional limitations. At follow-up, 12 had returned to sports without problems, 1 was participating with symptoms, and 4 had not returned to sports owing to the knee condition. In the patient rating of the overall knee condition, 11 rated their knees as normal or very good, 3 as good, 2 as fair, and 1 as poor.

Seven of the eight patients with an acute injury were involved in athletics prior to their injuries. The one patient who was not involved in athletics returned to normal activities of daily living without symptoms. Six patients returned to athletics without problems. Only one patient reported difficulty with squatting, and one patient had problems with running, jumping, and cutting. All eight patients rated their overall knee condition as normal or very good. There were no infections, knee motion problems, saphenous neuritis, or other major complications.

With many patients remaining active in middle age, the ability to retain the meniscus after an injury is an important goal. This study demonstrated that repair of complex tears in older adults is feasible and that the majority are asymptomatic for tibiofemoral joint symptoms an average of 3 years postoperatively. In athletically active patients, the indications of meniscus repair are based on current and future activity levels and the authors recommend preservation of meniscal tissue wherever possible regardless of age. It should be noted that the majority of meniscus tears in patients older than 40 years are degenerative and not repairable. This group of select patients had tears that were classified as amendable to repair by the criteria already provided.

Outcome of 71 Meniscus Repairs in the R/W Zone in Patients 20 Years of Age or Younger

A prospective study was conducted on 71 consecutive meniscus repairs done in 58 patients younger than 20 years to determine the clinical outcome.[151] A total of 67 meniscal repairs were examined clinically a mean of 4.2 years (range, 2-16.3 years) postoperatively, and 36 were evaluated during follow-up arthroscopy a mean of 1.4 years (range, 3 months to 5 years) postoperatively.

CRITICAL POINTS Our Clinical Studies: Outcome of Meniscus Repairs in the R/W Zone in Patients ≥40 Years

- $n = 30$ meniscus repairs in 29 patients
- 72% had ACL reconstruction with the meniscus repair.
- 93% evaluated clinically 2 to 5.9 years postoperatively
- 20% evaluated follow-up arthroscopy 1.3 to 3 years postoperatively
- 87% asymptomatic for both tibiofemoral symptoms and had not required further surgery
- No significant effect on presence of tibiofemoral pain or meniscus resection of tibiofemoral compartment of meniscus repair, chronicity of injury, concomitant ACL reconstruction, condition of articular cartilage
- Knees with chronic injuries had significant improvements in symptoms, functional limitations with sports and daily activities.
- Patient rating overall knee condition: 76% normal/very good, 12% good, 12% fair/poor
- 76% returned to sports or regular activities with no problems, 4% returned to sports but had symptoms, and 20% did not return to sports.
- Indications for meniscus repair should be based on patient's current and future desired activity level, not on age.

TABLE 23-5 Effect of Four Factors on Presence of Tibiofemoral Symptoms or Arthroscopic Second-Look Failure of Meniscal Repair

Factor	Asymptomatic	Tibiofemoral Symptoms or Arthroscopic Failure	*P* Value
Tibiofemoral Compartment of Meniscal Repair			
Medial ($n = 19$)	17 (89%)	2 (11%)	0.55
Lateral ($n = 11$)	9 (82%)	2 (8%)	
Time From Injury to Meniscal Repair			
≤10 weeks ($n = 10$)	9 (90%)	1 (10%)	0.7
>10 weeks ($n = 20$)	17 (85%)	3 (15%)	
Concomitant ACL Reconstruction			
Yes ($n = 22$)	20 (91%)	2 (9%)	0.26
No, ACL intact ($n = 8$)	6 (75%)	2 (25%)	
Articular Cartilage			
Normal ($n = 16$)	13 (81%)	3 (19%)	0.35
Abnormal ($n = 14$)*	13 (93%)	1 (7%)	

ACL, Anterior cruciate ligament.
*Abnormal defined as fissuring and fragmentation of more than half of the involved surface, or subchondral bone exposed.

CRITICAL POINTS Our Clinical Studies: Outcome of 71 Meniscus Repairs in R/W Zone in Patients <20 Years

- $n = 71$ meniscus repairs in 58 patients
- 61% had anterior cruciate ligament reconstruction either with or after the meniscus repair.
- 94% evaluated clinically 2 to 16.3 years postoperatively
- 51% evaluated follow-up arthroscopy 3 months to 5 years postoperatively
- 75% had no tibiofemoral symptoms or failed meniscus repair according to arthroscopic classification.
- Reoperation rates attributed to tibiofemoral joint symptoms: 8% single longitudinal tears, 33% double longitudinal tears, 14% complex multiplanar tears
- No effect on tibiofemoral joint symptoms or arthroscopic classification of failure: tibiofemoral compartment of meniscal repair (medial vs. lateral), chronicity of injury, concomitant ACL reconstruction
- Presence of tibiofemoral pain: sensitivity rate of 57%, specificity rate of 93% in identifying repairs classified as failed at follow-up arthroscopy
- Knees with concomitant meniscus repair and ACL reconstruction:
  - No problems with daily activities
  - 73% return to sports without problems
  - 87% rated overall knee condition as normal or very good
  - No complications, arthrofibrosis
- Presence of tibiofemoral pain not always indicative of a failed meniscus repair; consider MRI before arthroscopy to determine source of pain.
- Results allow recommendation repair meniscus tears that extend into middle third region when conditions indicate that a stable repair can be obtained.
- This recommendation is particularly appropriate in young active individuals in whom removal of a meniscus tear that extends into the middle avascular region would result in major loss of meniscus function and risk for future joint arthrosis.

TABLE 23-6 Diagnostic Test Rates of Tibiofemoral Joint Pain on Clinical Examination in Identifying Failed Meniscal Repairs

Diagnostic Test	Result (%)
Prevalence	58
Sensitivity	57
Specificity	93
False-positive	7
False-negative	43
Positive predictive value	92
Negative predictive value	61

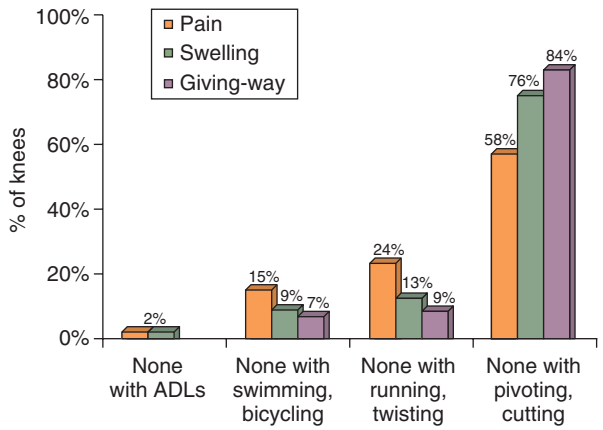


FIG 23-18 Analysis of symptoms at follow-up (mean, 47 mo after the operation) for 45 knees that had anterior cruciate ligament reconstruction and meniscus repair procedures. *ADL*, Activities of daily living. (From Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscal tears extending into the avascular zone in patients younger than twenty years of age. *Am J Sports Med.* 2002;30:589-600.)

There were 36 males and 25 females whose mean age at the time of the meniscus repair was 16 years (range, 9-19 years). Skeletal maturity, according to closed or nearly closed physes on radiographs of the distal femur and proximal tibia, had been reached in 54 knees (88%). Forty meniscal repairs were done for an acute knee injury (1-12 weeks after the injury), and 31 meniscal repairs were done for a chronic knee injury. Forty-three meniscal repairs (61%) were performed concurrently with an ACL reconstruction. Fourteen meniscal repairs (20%) were done in 11 knees a mean of 34 weeks (median, 4 weeks; range, 4-176 weeks) prior to an ACL reconstruction. Skeletal maturity had been completed in all knees that had ACL reconstructions.

At follow-up, 53 of 71 meniscal repairs (75%) had no tibiofemoral symptoms and had not been classified as failed on follow-up arthroscopy.

Fourteen meniscal repairs (20%) developed tibiofemoral joint symptoms; all but one of these had follow-up arthroscopy a mean of 19 months (range, 3-49 months) postoperatively. One repair had healed, and four had partially healed. Eight repairs had failed: two required removal at the prior repair site, three required near-total meniscectomy, and two had a repeat repair. In one knee that required a near-total lateral meniscectomy, a meniscus allograft was implanted.

Twenty-three other meniscal repairs had follow-up arthroscopy for reasons other than tibiofemoral symptoms a mean of 17 months postoperatively (range, 7-60 months). Twelve of these meniscal repairs had healed. Seven repairs had partially healed; partial meniscectomy was required in five, and meniscal tears were deemed stable and left intact in 2. Four of these 23 meniscal repairs (in three knees) failed. A lateral and medial meniscus allograft were implanted 40 months and 42 months, respectively, after the index repair procedure in one knee. A repeat meniscus repair was done in one knee, and a partial meniscectomy at the prior repair site was required in another knee.

There was no statistically significant effect of the tibiofemoral compartment of the meniscal repair, chronicity of injury, or concomitant ACL reconstruction on the presence of tibiofemoral joint symptoms or arthroscopic classification of failure. The presence of tibiofemoral pain on the physical examination was found to have a sensitivity rate of 57% and a specificity rate of 93% (Table 23-6) in identifying meniscus repairs classified as failed or that required partial resection at follow-up arthroscopy. The positive predictive value was 92% and the negative predictive value was 61%.

Of the 45 knees that had a concomitant meniscal repair and ACL reconstruction, 26 (58%) had no pain, 34 (76%) had no swelling, and 38 (84%) had no giving-way with sports activities involving jumping cutting, and pivoting at follow-up (Fig. 23-18). None of these knees

TABLE 23-7 Sports Activities of Patients Before the Meniscal Repair and at Follow-up*

Type of Sport	Preoperative	Follow-up
Jumping, hard pivoting, cutting	28	18
Running, twisting, turning	3	10
Swimming, bicycling	3	8
None	11	9
Change in Sports Activities		
Increased level, no symptoms		10
Same level, no symptoms		13
Decreased level, no symptoms		10
Playing with symptoms		3
No sports, knee-related reasons		2
No sports, non–knee-related reasons		7

*In 45 knees with an anterior cruciate ligament reconstruction and a meniscal repair.

CRITICAL POINTS Our Clinical Studies: Long-Term Outcome of 29 Meniscus Repairs in the R/W Zone in Patients ≤20 Years of Age

- $n = 29$ meniscus repairs followed 10.1 to 21.9 years postoperatively
- Success rate determined from MRI, 45 degrees weight-bearing posteroanterior radiographs, two knee rating systems
- Overall success rate: 62% (18 of 29)
- Failures: six partial meniscectomy, two loss joint space on radiographs, three MRI criteria
- No association return to strenuous sports, concurrent ACL reconstruction, chronicity of injury and failure of repair
- No significant difference between 4 years and 17 years evaluations for pain, swelling, patient rating
- Chondroprotective effect demonstrated in patients with healed meniscus repairs

had functional limitations with walking, stair climbing, or squatting. Forty (89%) had no or only slight problems with running, jumping, and twisting.

Before the meniscus repair, 34 patients were participating in various types of athletic activities, and 11 had given up sports owing to knee problems (Table 23-7). At follow-up, 33 (73%) had returned to athletics without symptoms or limitations, and three (7%) were participating in sports with symptoms against advice. Two (4%) had not returned to sports owing to the knee condition, and 7 (16%) had given up sports activities owing to factors unrelated to the knee condition. At follow-up, 39 (87%) rated the overall knee condition as normal or very good, 2 (4%) as good, 3 (7%) as fair, and 1 (2%) as poor.

There were no instances of infection, accessory posteromedial or posterolateral incision pain, saphenous neuritis, or arthrofibrosis.

The results of this study allow recommendation of repair of simple or complex meniscal tears that extend into the R/W zone when the conditions are met that a stable repair of a potentially functional meniscus can be obtained. This recommendation is particularly appropriate in young active individuals in whom removal of a meniscus tear that extends into the middle third region would result in major loss of meniscus function and risk for future joint arthrosis.

Long-Term Outcome of 29 Meniscus Repairs in the R/W Zone in Patients 20 Years of Age or Younger

From the group of 71 meniscus repairs just described, a homogenous cohort of 29 repairs for single longitudinal R/W tears was selected for a long-term analysis of outcome and chondroprotective effects of the operation.[154] The patients were followed a mean of 16.8 years (range, 10.1-21.9 years) postoperatively. The success rate was determined with a critical rating system that required normal or nearly parameters from two validated knee rating systems, MRI, 45-degree weight-bearing PA radiographs, a comprehensive knee examination, and a KT-2000 knee arthrometer test. A 3T MRI scanner with cartilage-sensitive pulse sequences was used, and T2 mapping was performed by an independent radiologist. The CKRS and the International Knee Documentations Committee Rating System (IKDC) were completed.

The overall success rate was 62% (18 of 29 repairs). The failures included six (21%) that required partial meniscectomy, 2 (that were asymptomatic) that had a loss of joint space on radiographs, and 3 (that were asymptomatic and had normal radiographs) that failed according to MRI criteria.

There was no significant association between return to strenuous sports, concurrent ACL reconstruction, or chronicity of the injury and failure of the meniscus repair. There was a higher rate of failure in medial meniscal repairs compared with lateral repairs ($P = .05$). There were no instances of infection, incision pain, saphenous neuritis, or arthrofibrosis.

There was no significant difference between the initial (4-year) and long-term (17-year) follow-up evaluations for the mean scores of pain, swelling, jumping, the patient rating of the overall knee condition, or the overall rating score. All but four patients were participating in mostly low-impact sports activities at follow-up without problems; the four not participating had given up athletics for reasons other than their knee condition. The results of the KT-2000 test were rated as normal or nearly normal in all 18 patients who underwent concurrent ACL reconstruction.

This study was the first long-term investigation that used weight-bearing PA radiographs and MRI in addition to the clinical examination to determine the healing rates of R/W single longitudinal repairs. A chondroprotective effect was demonstrated in patients with healed meniscus repairs, which is especially important considering the patient age at the time of surgery (9.4-20 years) and concurrent ACL injuries. Healing adjuncts in the future are most likely required to increase the success rate.

RESULTS OF MENISCUS REPAIRS FROM OTHER CLINICAL STUDIES

A summary of the clinical outcome of R/W meniscal repairs from a variety of investigations is shown in Table 23-8. Recent studies assessing clinical healing rates for tears located in other regions of the meniscus, or those that combined regions together in the investigation's analysis, are shown in Table 23-9.

Complications such as chondral damage, cyst formation, chronic effusions, joint irritation, synovitis, and device breakage and migration into the extra-articular soft tissues and deteriorating results have been reported following the use of rigid, all-inside fixation devices.[5,39,91,92,100,107,110,133,134,160,194,210] Investigations of newer flexible

TABLE 23-8 Minimum 2-Year Clinical Outcome of Red-White Suture-Based Meniscus Repairs

Study	No. Repairs	Tear Type	Follow-up (yr)	Surgical Details	Evaluation Methods	Clinical Heal Rate	Factors Associated With Failures
Haklar et al[74] (2008)	5	Radial lateral	2.5	I-O	Physical exam, MRI	100%	NA
Steenbrugge et al[198] (2005)	8	Not provided	9	I-O, all ACL deficient or ACL intact	Physical exam, follow-up arthroscopy if needed	100%	NA
Haklar et al[73] (2013)	112	Longitudinal medial	4	I-O, ACL reconstruction in 89	Physical exam, MRI	88%	Isolated repair, tear length >20 mm, full thickness tear, smoking
Vanderhave et al[218] (2011)	33	Simple, bucket handle, complex	2.2	I-O, ACL reconstruction	Physical exam, follow-up arthroscopy in all	94%	NA
Ra et al[176] (2013)	12	Radial	2.5	I-O, ACL reconstruction in 2	Physical exam, MRI, follow-up arthroscopy if needed	92%	NA
Ahn et al[3] (2010)	58	Single longitudinal, double longitudinal, bucket handle, complex	3	I-O, all ACL reconstruction	Physical exam, follow-up. arthroscopy in all	91%	Location tear (combined R/R, R/W)
O'Shea & Shelbourne[157] (2003)	11	Locked bucket handle	4.3	I-O, ACL reconstruction staged 77 days postoperatively	Physical exam, follow-up arthroscopy in all	91%	NA
Papachristou et al[164] (2003)	10	Longitudinal	3	I-O	Physical exam, follow-up arthroscopy if needed	70%	NA
Biedert[27] (2000)	17	Horizontal intrasubstance	2.1	I-O	Physical exam, MRI, x-rays	90% access channel, 43% fibrin clot	NA
Choi et al[47] (2009)	14	Longitudinal posterior horn	3	A-I (5) or I-O (9); ACL reconstruction in all	Physical exam, MRI	100%	NA
Quinby et al[175] (2006)	47	Vertical, bucket handle, complex posterior horn	2.8	A-I with RapidLoc, ACL reconstruction in all	Physical exam, follow-up arthroscopy if needed	91%	Bucket handle tears, complex tears, tears >2 cm long
Barber et al[16] (2006)	21	Longitudinal	2.5	A-I with RapidLoc, ACL reconstruction	Physical exam, follow-up arthroscopy if needed	90%	NA
Billante et al[28] (2008)	28	Vertical, bucket handle, complex	2.5	A-I with RapidLoc, ACL reconstruction in all	Physical exam, follow-up arthroscopy if needed	89%	NA
Barber et al[19] (2008)	26	Longitudinal	2.5	A-I with FasT-Fix, ACL reconstruction	Physical exam, follow-up arthroscopy if needed	85%	NA

Continued

TABLE 23-8 Minimum 2-Year Clinical Outcome of Red-White Suture-Based Meniscus Repairs—cont'd

Study	No. Repairs	Tear Type	Follow-up (yr)	Surgical Details	Evaluation Methods	Clinical Heal Rate	Factors Associated With Failures
Kraus et al[105] (2012)	21	Longitudinal, bucket handle, radial, complex, horizontal	2.3	A-I device NA; ACL reconstruction in 11	Physical exam, follow-up arthroscopy if needed	81%	NA
DeHaan et al[52] (2009)	5	Vertical	3	A-I with FasT-Fix, ACL reconstruction in all	Physical exam, follow-up arthroscopy if needed	80%	NA
Miao et al[136] (2011)	31	Longitudinal, bucket handle	2.1	A-I device NA; ACL reconstruction in all	Physical exam, follow-up arthroscopy in all	87%	Bucket handle tears
Kalliakmanis et al[100] (2008)	106	Vertical, bucket handle, horizontal, complex	2	A-I with RapidLoc, T-Fix, FasT-Fix; ACL reconstruction in all	Physical exam, follow-up arthroscopy if needed	85% all; 89% FasT-Fix, 85% T-Fix, 80% RapidLoc	None

ACL, Anterior cruciate ligament; *A-I*, all-inside; *I-O*, inside-out; *MRI*, magnetic resonance imaging; *NA*, not available; *R/R*, red-red; *R/W*, red-white.

TABLE 23-9 Minimum 2-Year Clinical Outcome of Red-Red or Combined Red-Red/Red-White Meniscus

Study	No. Repairs	Tear Type	Follow-up (yr)	Surgical Details	Evaluation Methods	Clinical Heal Rate	Factors Associated With Failures
Westerman et al[226] (2014)	233	R/R-R/W, longitudinal, bucket-handle	6	A-I: 208 I-O: 19 O-I: 6 ACL reconstruction in all	Questionnaires, telephone interviews	A-I: 85% I-O: 95% O-I: 83%	None
Bogunovic et al[31] (2014)	75	R/R-R/W, longitudinal, bucket-handle	7	A-I: FasT-Fix ACL reconstruction in 49	Questionnaires, telephone interviews	86%	None
Hagino et al[72] (2014)	57	Lateral longitudinal, bucket handle	1-4	A-I: Viper	Physical exam, follow-up arthroscopy in 32	86%	NA
Choi et al[45] (2014)	60	R/R-R/W, longitudinal, oblique	3.9	A-I FasT-Fix: 25 Sutures: 35 ACL reconstruction in all	Physical exam, MRI	*R/R:* Sutures: 91% FasT-Fix: 92% *R/W:* Sutures: 91% FasT-Fix: 96%	NA
Furumatsu et al[68] (2013)	20	Longitudinal medial, R/R	2	A-I: FasT-Fix, Ultra FasT-Fix ACL reconstruction in all	Physical exam, follow-up arthroscopy in all	95%	NA
Pujol et al[174] (2013)	31	Vertical, R/R-R/W	9.7	A-I: Fast-Fix ACL reconstruction	Physical exam, x-ray	87%	NA

TABLE 23-9 Minimum 2-Year Clinical Outcome of Red-Red or Combined Red-Red/Red-White Meniscus—cont'd

Study	No. Repairs	Tear Type	Follow-up (yr)	Surgical Details	Evaluation Methods	Clinical Heal Rate	Factors Associated With Failures
Tucciarone et al[211] (2013)	40	Longitudinal R/R-R/W	2	A-I: Fast-Fix ACL reconstruction in 20	Physical exam, MRI, x-ray	92%	NA
Melton et al[132] (2011)	24	Bucket handle, R/R	10	I-O; ACL reconstruction in all	Physical exam	Survival analysis "best case" 89% at 10 yr	NA
Tengrootenhuysen et al[205] (2011)	54	Menisco-synovial junction, R/R	5.8	I-O; ACL reconstruction	Physical exam	80%	Older age, repair done > 6 wk after injury, no concurrent ACL reconstruction
Choi et al[46] (2010)	14	Radial lateral R/R-R/W	3	A-I	Physical exam, MRI 6 months	93%	NA
Stein et al[199] (2010)	16	Longitudinal, bucket handle R/R-R/W	8.8	I-O	Physical exam, x-ray	85%	NA
Choi et al[47] (2009)	34	Longitudinal posterior horn medial meniscus, R/R	3	I-O; ACL reconstruction in all	Physical exam, MRI at 6 mo	100%	NA
Logan et al[114] (2009)	45	Bucket handle, radial, complex	8.5	I-O; ACL reconstruction in 38	Physical exam	73%	Medial repairs.
Feng et al[60] (2008)	67	Bucket handle, R/R-R/W	2.2	I-O: 24 A-I: 3 Combined: 40 ACL reconstruction in 62	Physical exam, follow-up arthroscopy	A-I: 92% I-O: 83% Combined: 100% R/R: 89% R/W: 91%	Failed ACL reconstruction
Bryant et al[36] (2007)	49	Menisco-synovial junction R/R to R/W	2.3	I-O; ACL reconstruction in 31	Physical exam	78%	NA
Haas et al[71] (2005)	42	Longitudinal, R/R-R/W	2	A-I: FasT-Fix ACL reconstruction in 22	Physical exam	88%	NA

ACL, Anterior cruciate ligament; *A-I*, all-inside; *I-O,* inside-out; *MRI*, magnetic resonance imaging; *NA*, not available or none; *O-I,* outside-in; *R/R*, red-red; *R/W*, red-white; *W/W*, white-white.

all-inside suture systems (Fig. 23-19) reported acceptable short-term clinical healing rates, as shown in Tables 23-8 and 23-9. However, longer term follow-up is required of these devices to ensure that the rate of failure does not increase with time. In addition, most surgeons use only two to three sutures with the all-inside systems. Concern exists regarding the fixation strength of these devices compared with the multiple vertical divergent suturing procedure described in this chapter.

The question of whether meniscal repair is effective in preventing joint deterioration remains unanswered according to published clinical data. The problem of commonly associated ACL tears or other injuries found in these knees precludes scientifically justifiable answers. However, based on the well-documented irreparable joint damage and poor results of long-term clinical studies after partial and total meniscectomy, preservation of meniscal tissue is paramount for long-term joint function. It is our opinion that the gold standard for meniscus repair procedures remains a meticulous inside-out repair with multiple vertical divergent sutures and an accessory posteromedial or posterolateral approach to tie the sutures directly posterior to the meniscus attachment. This procedure requires added time and assistants. The newer all-inside devices are more time efficient, but longer term clinical studies are required. We consider meniscus repair as important, if not more important, as an ACL reconstruction in regard to long-term knee function. The procedures and surgical approaches are not difficult, and the anatomical approach is straightforward. There should be an exceedingly low risk of intraoperative complications such as nerve damage and arthrofibrosis if the operative procedure and rehabilitation program discussed in this and other chapters are followed.

We disagree with the approach of leaving a meniscus tear greater than 10 mm in length untreated at the time of ACL surgery. To use a

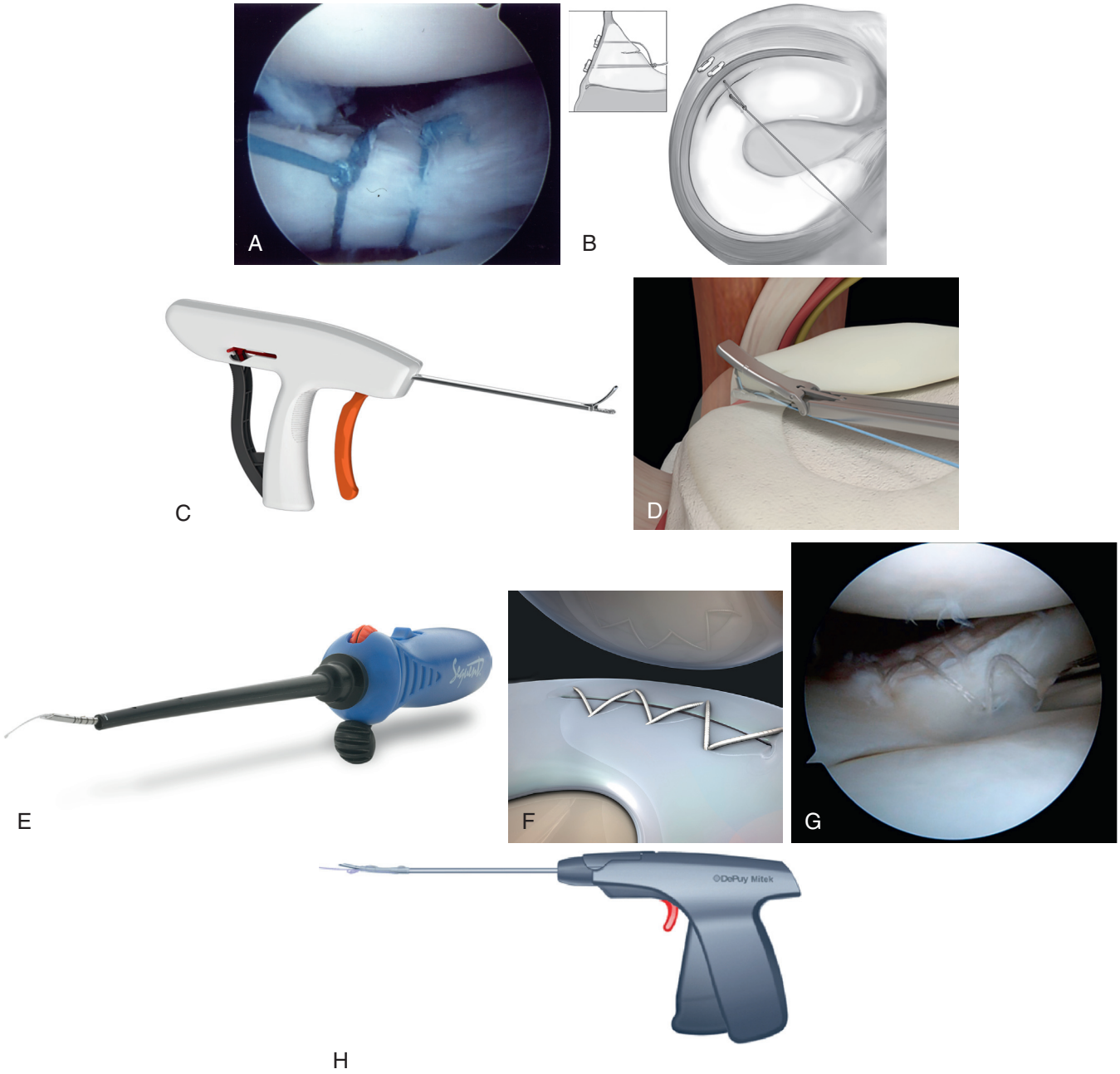


FIG 23-19 Examples of meniscus repairs using newer generation all-inside suture-based devices that allow tensioning. See text for published results of these procedures. Careful selection of the type of meniscus tear for these techniques is required because usually only two to four sutures are used and the fixation strength is inferior to that of multiple vertical divergent sutures. With proper selection of tears and avoidance of complex tears, there appears to be a role for these procedures in simple longitudinal tears in the red-red and red-white zones. **A** and **B,** Ultra Fast-Fix. **C** and **D,** NovoStitch. **E** to **G,** Sequent; **H,** Omnispan. (**B,** Courtesy Accufex, Smith & Nephew, Andover, MA. **C** and **D,** Courtesy Ceterix Orthopaedics, Menlo Park, CA. **E** to **G,** Courtesy ConMed Linvatec, Largo, FL. **H,** Courtesy DePuy Synthes Mitek Sports Medicine, Raynham, MA.)

conservative approach and hope for healing may risk further tearing and subsequent loss of meniscus function. Unfortunately, once a meniscectomy has been performed in a younger patient, few options exist and even meniscus transplants do not provide a dependable long-term successful solution. In patients requiring meniscus transplants, we have frequently observed that the original treatment of the meniscus tear was ineffective; either a large tear was left untreated, a repair was done with too few sutures or with fixators that provided only limited stability, or a tear that extended into the middle third region was removed that may have been repaired.

In the future, tissue engineering may provide increased success rates of meniscus repair, especially for tears that extend into the avascular region.[42,50,87,88,120,143,188,212] Cell-based therapy using meniscal fibrochondrocytes, articular chondrocytes, or mesenchymal stem cells seeded onto scaffolds offers promise, as does the introduction of growth factors into repair sites.[58,76,95,162,213-215,232]

ILLUSTRATIVE CASES

Case 1. A 30-year-old female U.S. military instructor presented with complaints of pain to the lateral aspect of her right knee of 3 years' duration. The symptoms began after the patient had completed a 7-mile marathon and gradually progressed to pain with daily activities. MRI was negative for a lateral meniscus abnormality. Physical examination revealed tenderness to the lateral tibiofemoral joint, but all other tests and radiographs were normal. All meniscus tests were negative, including standing single-leg rotation, McMurray flexion-rotation, and varus axial loading.

Arthroscopy was performed that initially demonstrated a normal lateral meniscus (Fig. 23-20, *A*). However, further evaluation revealed a large tear of the meniscotibial attachments (Fig. 23-20, *B*) with an abnormal lift-off and anterior subluxation of the posterior horn from the tibia (Fig. 23-20, *C*). Maximal varus loading and lateral joint opening were required to separate the tibiofemoral joint, which produced the subluxation of the posterior horn. Multiple vertical divergent sutures were placed superiorly and inferiorly with an outside-in technique, avoiding the popliteal tendon (Fig. 23-20, *D* and *E*). The initial sutures were placed superiorly to reduce the meniscus onto the tibia. The patient recovered and returned to athletic activities 6 months postoperatively without pain. The cosmetic appearance of the 2-cm posterolateral approach is shown (Fig. 23-20, *F*).

Case 2. A 16-year-old male athlete presented with a chronic medial meniscus tear that had been treated conservatively. Physical examination demonstrated medial tibiofemoral joint pain, but all other tests and radiographs were normal. At arthroscopy, an unusual complex horizontal meniscal tear was found that extended throughout the entire meniscal body from the periphery to the inner meniscal margin (Fig. 23-21, *A*). Removal of either the superior or inferior tear

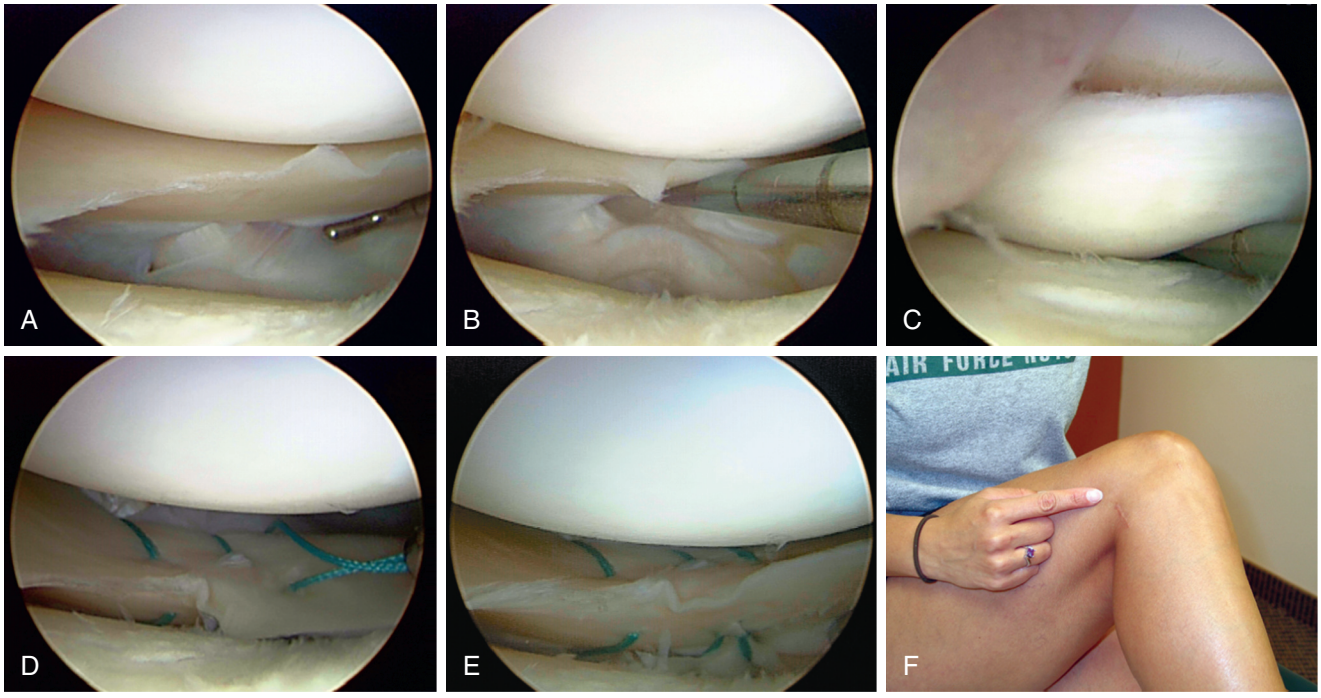


FIG 23-20 Case 1.

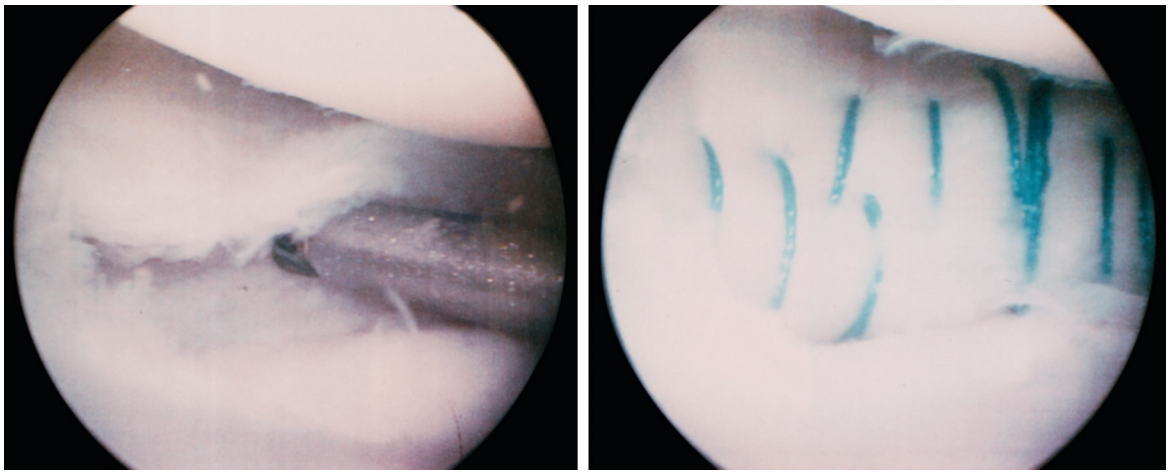


FIG 23-21 Case 2.

component would have substantially compromised the remaining meniscal tissue and function. The body of the meniscus, between the superior and inferior tear edges, was rasped. Multiple vertical divergent sutures were placed to close the gap between the superior and inferior tear edges (Fig. 23-21, *B*).

At the most recent follow-up evaluation, 4 years postoperative, the patient had no symptoms and had returned to recreational athletics without problems.

Case 3. An 18-year-old Division I collegiate hockey player presented 10 months after sustaining a right knee injury in which the lateral aspect of his leg was struck with a helmet. He complained of pain with squatting, twisting, and turning activities. Examination demonstrated lateral joint line tenderness in deep flexion but no other abnormalities. MRI was negative for a lateral meniscus tear. The patient continued to have pain over the ensuing 5 months and elected to undergo arthroscopy for a potential hypermobile meniscus abnormality. The lateral meniscus hiatus was noted to be increased in size (Fig. 23-22, *A*), and although the meniscus was firmly attached to the capsule, there was increased translation in the central portion of the lateral tibiofemoral compartment. In addition, the anterior rim at the meniscocapsular junction demonstrated fraying (Fig. 23-22, *B*). An inside-out lateral meniscus repair was performed with eight sutures under arthroscopic control, which successfully resolved the meniscus hypermobility (Fig. 23-22, *C*).

The patient did well and returned to collegiate hockey without problems. Three years later, he sustained a twisting injury to the same knee and sustained a complete ACL tear and a radial lateral meniscus tear. An ACL autogenous B-PT-B reconstruction was performed. The lateral compartment demonstrated the healed prior meniscus repair in the posterior horn (Fig. 23-22, *D*). A new radial tear, found at the junction of the anterior and middle thirds, extending to the capsular margin was repaired with six horizontal mattress sutures (Fig. 23-22, *E*). The patient recovered without complications.

Case 4. A 33-year-old man presented 1 week after a left knee injury sustained while playing basketball. Physical examination revealed 7 mm of increased anterior tibial translation and severe medial joint line tenderness. The patient had a mild effusion and 90 degrees of knee flexion. He was referred to physical therapy for 4 weeks of rehabilitation to regain normal knee motion and muscle function. A B-PT-B ACL autograft, repair of a complex multiplanar lateral meniscus central third tear, and repair of a 15-mm single longitudinal medial meniscus central third tear were performed (Fig. 23-23, *A*). The patient had a chronic PCL rupture on the right knee of 12 years' duration, which had been treated conservatively.

At the latest follow-up evaluation, 15 years postoperatively, the patient had no complaints with his right knee. He had participated in basketball without symptoms and rated the overall condition of his knee as normal. Physical examination demonstrated a grade 1 pivot shift, a full range of knee motion, and no crepitus, swelling, or joint line pain. All meniscus tests were negative. Standing PA radiographs demonstrated only 1 mm of decrease in the lateral tibiofemoral compartment joint space compared with the opposite knee and no decrease in the medial tibiofemoral compartment joint space (Fig. 23-23, *B*).

Case 5. A 31-year-old man presented 2 months after a twisting injury to the right knee sustained during a soccer game that had been treated elsewhere with diagnostic arthroscopy. Physical examination revealed 10 mm of increased anterior tibial translation, moderate medial tibiofemoral joint line pain, and a mild effusion. The patient underwent a B-PT-B autogenous ACL reconstruction and a repair of a 20-mm peripheral medial meniscus tear (Fig. 23-24, *A*). Noteworthy fissuring and fragmentation were noted on the medial femoral condyle (Fig. 23-24, *B*). The patient recovered and was released to full sports activities 9 months later.

At the most recent follow-up evaluation, 16 years postoperative, the patient stated he had participated in competitive soccer without symptoms or functional limitations until a reinjury that had occurred 3

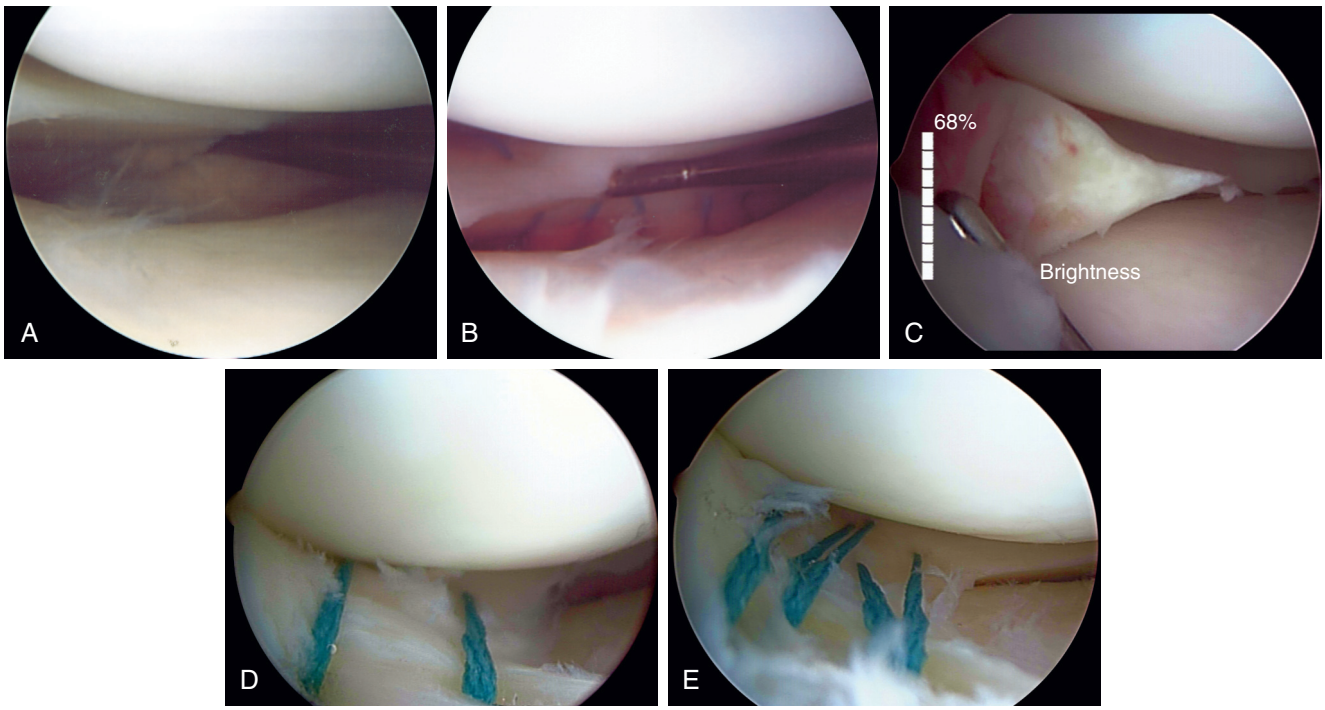


FIG 23-22 Case 3.

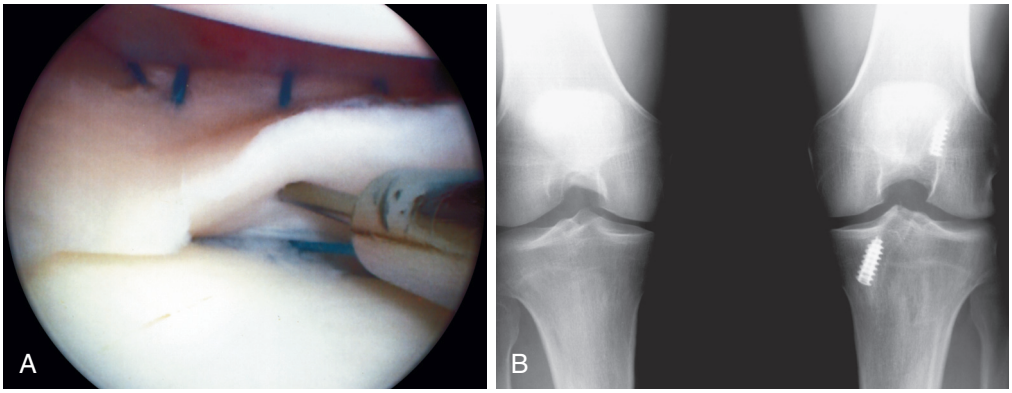


FIG 23-23 Case 4.

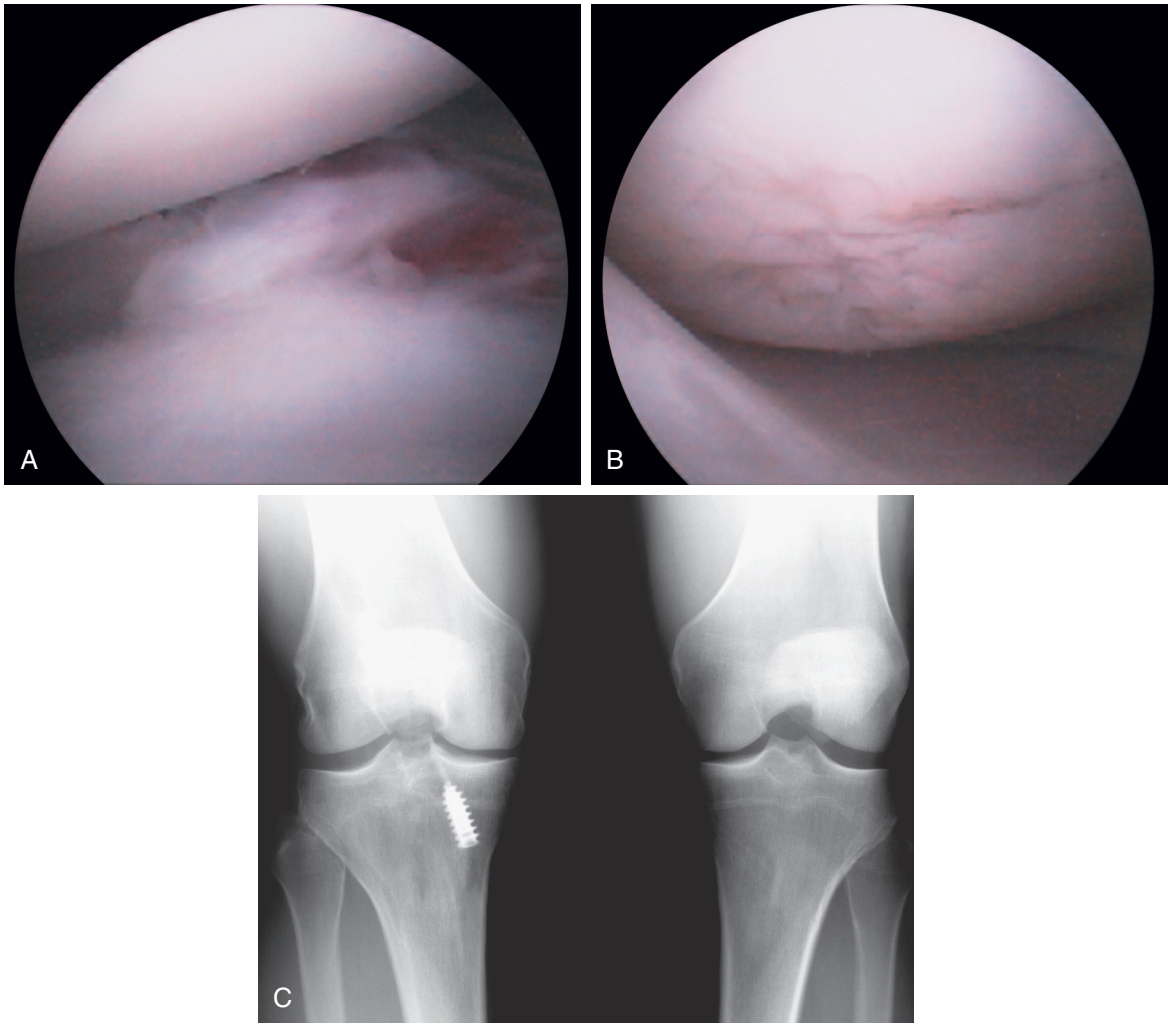


FIG 23-24 Case 5.

months prior to his examination. He underwent a partial medial meniscectomy elsewhere. Physical examination revealed 2 mm of increased anteroposterior tibial displacement on KT-2000 testing, no crepitus, a normal range of motion, and no joint line pain. The patient rated the overall condition of his knee as very good. Radiographs demonstrated preservation of the medial tibiofemoral compartment (Fig. 23-24, *C*). However, the patient was warned that continued high-impact activities might accelerate medial compartment joint arthrosis with the loss of the medial meniscus and preexisting damage noted on the medial femoral condyle.

Case 6. An 18-year-old man sustained a right knee injury playing basketball and presented 2 weeks later with a mild effusion, 12 mm of increased anterior tibial translation, medial joint line pain, and a nearly normal range of knee motion. He underwent a B-PT-B autogenous ACL reconstruction and bilateral meniscus repairs for double longitudinal posterior horn tears (Fig. 23-25, *A*). There was noteworthy fissuring and fragmentation of the medial femoral condyle (Fig. 23-25, *B*). He recovered well and returned to basketball for several years. The patient sustained a left knee injury 5 years later and underwent an ACL reconstruction and total medial meniscectomy elsewhere.

At the most recent follow-up evaluation, 14 years postoperative, the patient rated his right knee as nearly normal without symptoms. Physical examination of the right knee demonstrated negative Lachman and pivot shift, no meniscus pathology, a full range of knee motion, and no joint effusion. The left knee was symptomatic for medial tibiofemoral compartment symptoms and had drifted into varus malalignment. Radiographs demonstrated preservation of the medial and lateral tibiofemoral compartment joint spaces in the right knee (Fig. 23-25, *C*) but loss of medial joint space in the left knee (Fig. 23-25, *D*). An opening wedge high tibial osteotomy was subsequently performed on the left knee.

Case 7. A 24-year-old man presented 3 days after a right knee injury sustained playing volleyball. Physical examination demonstrated a moderate effusion, range of motion from 10 to 70 degrees, poor quadriceps contraction, moderate medial joint line pain, and 5 mm of increased anterior tibial translation. He underwent 4 weeks of physical therapy to regain knee motion and quadriceps strength. A B-PT-B autogenous ACL reconstruction and a repair of a 30-mm double longitudinal medial meniscus tear were done. Noteworthy fissuring and fragmentation were noted on the medial and lateral femoral condyles.

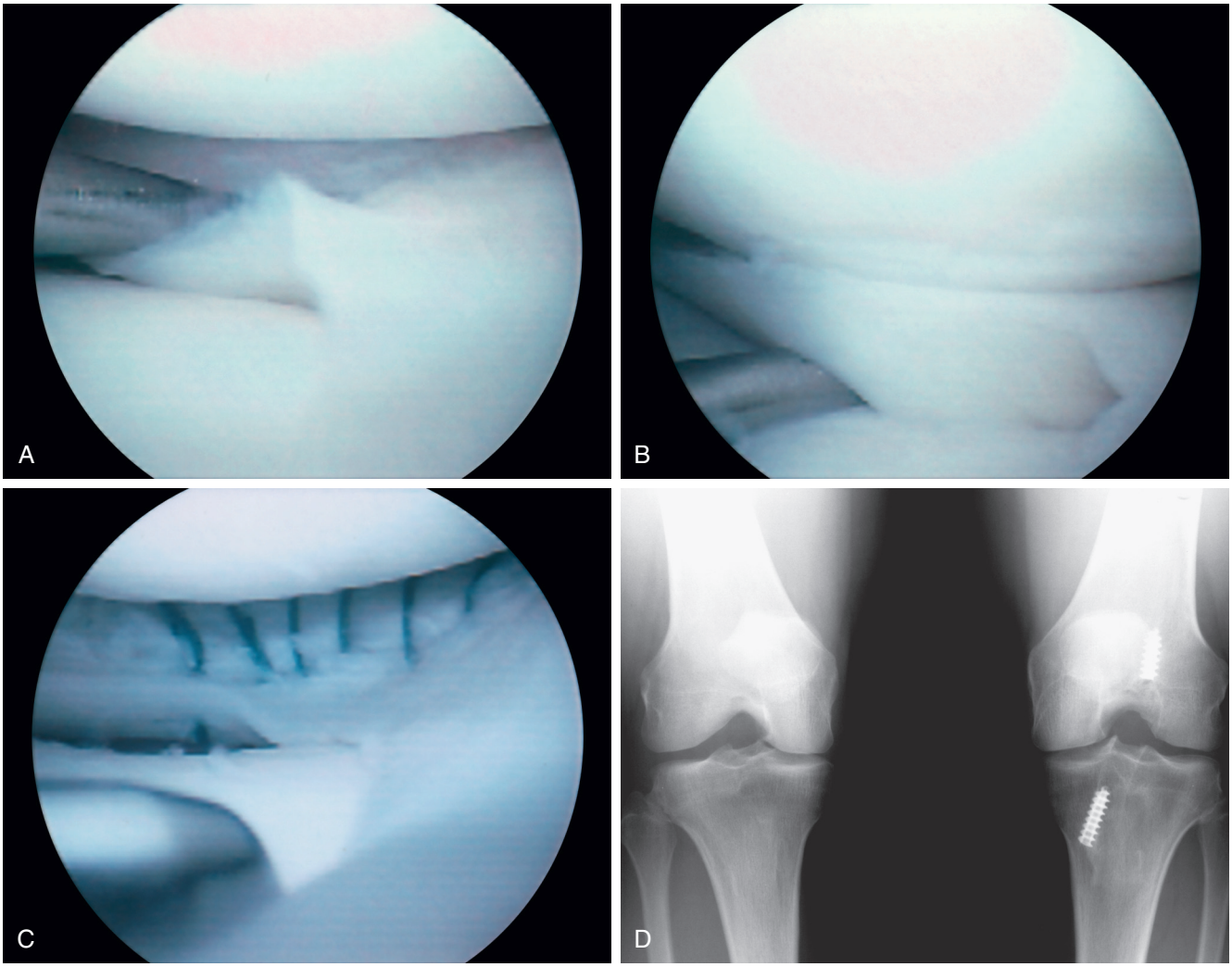


FIG 23-25 Case 6.

At the most recent follow-up evaluation, 14 years postoperatively, the patient reported no symptoms, locking, or catching and rated the overall condition of his knee as normal. Physical examination demonstrated a negative pivot shift test, 3 mm of increased AP displacement on KT-2000 testing, no tibiofemoral joint line pain or crepitus, and a normal range of knee motion. The patient had a sedentary occupation and weighed 265 pounds. Radiographs detected narrowing to the medial tibiofemoral compartment and 2 degrees of varus alignment (Fig. 23-26). MRI revealed deterioration of the medial meniscus, with only a small remnant remaining. The patient was counseled regarding the potential for a future high tibial osteotomy based on medial tibiofemoral compartment symptoms.

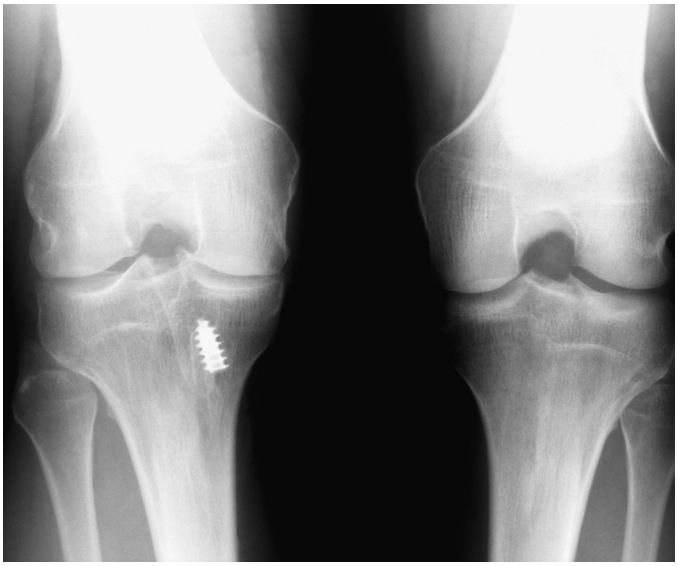


FIG 23-26 Case 7.

Case 8. A 32-year-old man sustained a left knee twisting injury and underwent arthroscopy and removal of the anteromedial bundle of the ACL elsewhere. The patient was treated conservatively for 7 years but gradually developed symptoms and presented for treatment. MRI demonstrated a complex bucket-handle medial meniscus tear. Arthroscopy revealed a complex 20-mm longitudinal tear with an additional vertical tear component. Noteworthy fissuring and fragmentation were found on the medial femoral condyle and in the patellofemoral compartment. Repair of the meniscus tear with multiple divergent sutures was performed.

The patient did well for 1 year until he developed medial joint line pain and catching symptoms. Repeat arthroscopy demonstrated a complex medial meniscus tear extending from the posterior horn to the midbody with horizontal and vertical longitudinal components. A revision meniscus repair was successfully performed with only a small portion of the posterior horn removed. Six years later, the patient reported no problems with light recreational sports and daily activities and rated the overall condition of the knee as good. Physical examination demonstrated a normal range of knee motion, no effusion, no tibiofemoral pain or crepitus, and no meniscus symptoms. Radiographs showed preservation of the medial tibiofemoral joint space (Fig. 23-27).

Case 9. A 22-year old collegiate football player sustained an ACL tear and a lateral meniscus root tear. Arthroscopic visualization of the lateral meniscus root tear is shown in Figure 23-28, A. A 4-mm drill is

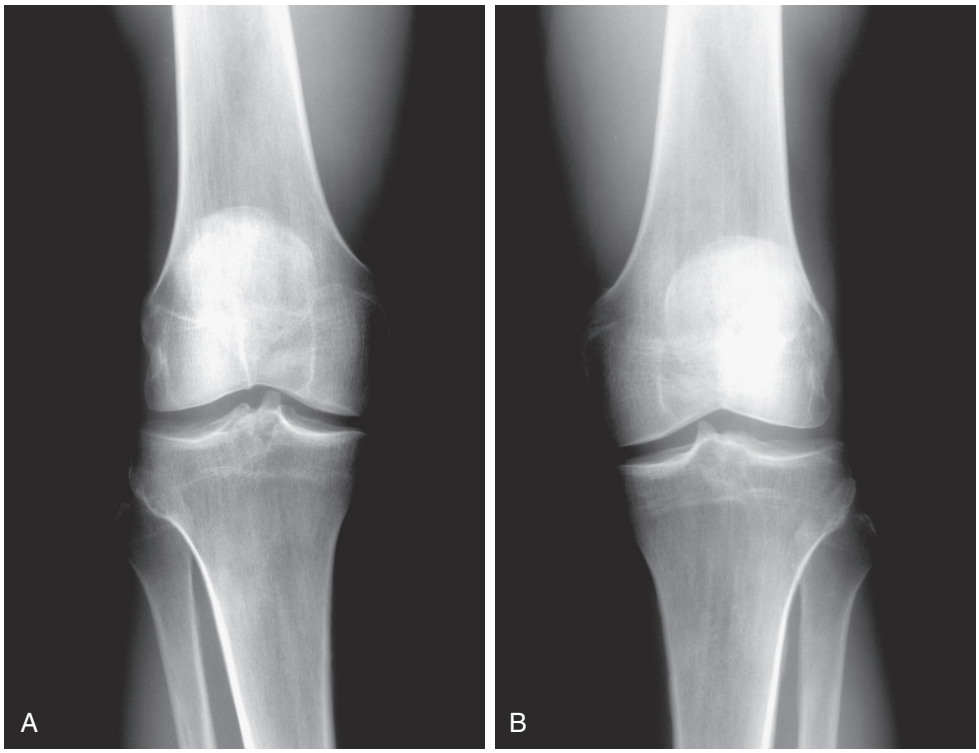


FIG 23-27 Case 8.

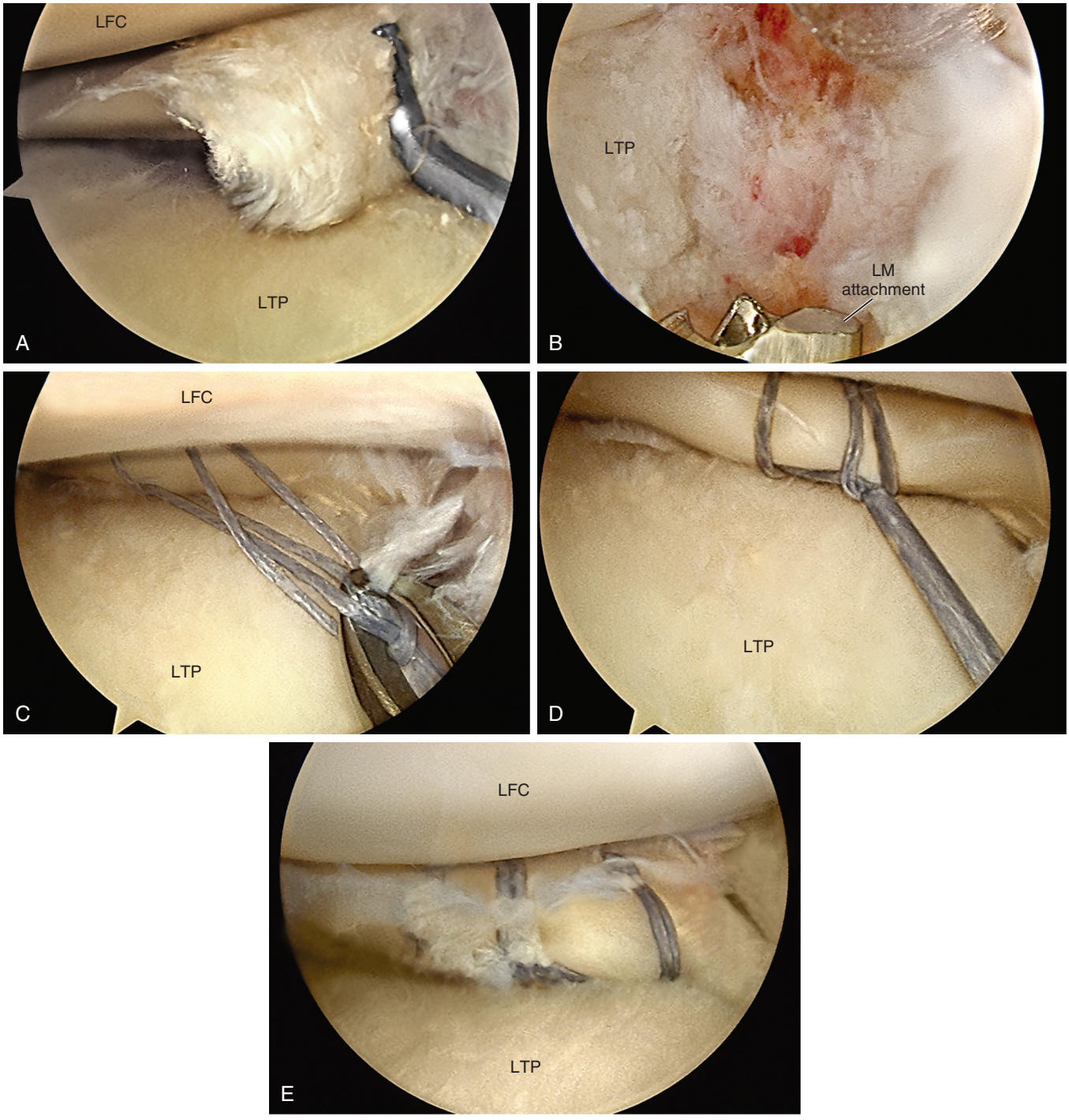


FIG 23-28 Case 9.

placed over a guide pin in the center of the meniscus tibial attachment (Fig. 23-28, *B*). The meniscus root base is curetted to establish a bleeding base for the repair. A central drill hole is created for passage of the sutures that will be tied over a button. A double locking loop stitch (NovoStitch, Ceterix) is placed through the meniscus at the tear site (Fig. 23-28, *C*). Three loop stitches were used in this case to achieve a high strength fixation owing to the large body size of the patient (Fig. 23-28, *D*). Final configuration of lateral meniscus repair with the meniscus pulled flush to the repair site is shown in Figure 23-28, *E*.

Video Content

Video 7-3
Video 23-1
Video 23-2
Video 23-3

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24

Meniscus Transplantation: Diagnosis, Operative Techniques, and Clinical Outcomes

Frank R. Noyes, Sue D. Barber-Westin

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INDICATIONS

The meniscus performs important functions that are vital for the integrity of the articular cartilage of the human knee, including load bearing, shock absorption, stability, and joint nutrition. Although many meniscus tears can be successfully repaired, including complex tears that extend into the central third region,[67,80] not all are salvageable, especially if considerable tissue damage has occurred. The goals of transplantation of human menisci are to restore partial load-bearing meniscus function, decrease patient symptoms, and provide some chondroprotective effects.[23,34,42,65,88,101] However, the procedure remains in an evolving state, as investigations of tissue-processing, secondary sterilization, and long-term function continue to evaluate its effectiveness.[48] Clinical studies have shown that meniscus transplantation decreases tibiofemoral joint pain in the short term.[23,32,34] Many investigations report, however, that most transplants gradually deteriorate, tear, extrude from their normal position, or shrink in size, thereby losing the ability to provide function.[19,30,44,74] Accordingly, the goal is to provide short-term benefits until a more suitable meniscus transplant is clinically available. At best, the transplant provides only partial function, and therefore strenuous sports and high-impact activities are not advised postoperatively even though many younger patients have the desire to return to unrestricted athletics. Education of the patient and family is required so that all understand and accept these current limitations of the procedure.

The optimal candidate is a patient younger than 50 years who has had a total meniscectomy, has pain that limits daily activities, and demonstrates early articular cartilage deterioration in the involved tibiofemoral compartment. There should be no radiographic evidence of advanced tibiofemoral joint arthritis. At least 2 mm of tibiofemoral joint space should be visible on 45-degree weight-bearing posteroanterior (PA) radiographs.[78] Arthroscopic examination performed before meniscus transplantation confirms the patient is a suitable candidate. In the most advanced cases, there should be no or only minimal bone exposed on tibiofemoral surfaces. Few treatment options are available for these individuals, especially those less than 30 years of age. In these cases, the goals in the short term are to decrease pain, increase knee function, allow pain-free activities of daily living (ADLs), and delay the

CRITICAL POINTS Indications

- Prior meniscectomy
- Age ≤50 years
- Pain in the meniscectomized tibiofemoral compartment
- No radiographic evidence of advanced joint deterioration; ≥2 mm of tibiofemoral joint space on 45-degree weight-bearing PA radiographs
- No or only minimal bone exposed on tibiofemoral surfaces
- Normal axial alignment
- BMI within normal range

CRITICAL POINTS Contraindications

- Advanced knee joint arthrosis with flattening of the femoral condyle, concavity of the tibial plateau, osteophytes that prevent anatomic seating of the meniscus transplant
- Uncorrected varus or valgus axial malalignment
- Uncorrected knee joint instability, ACL deficiency
- Knee arthrofibrosis
- Significant muscular atrophy
- Prior joint infection with subsequent arthrosis
- Symptomatic noteworthy patellofemoral articular cartilage deterioration
- Obesity (BMI >30)
- Prophylactic procedure (asymptomatic patient with no articular cartilage damage)
- Untreated full-thickness femoral condylar defect with bone exposure

onset of tibiofemoral arthritis. Normal axial alignment and a stable joint are required. The body mass index (BMI) must be within normal range.

The association of an anterior cruciate ligament (ACL) tear and underlying posterolateral ligament insufficiency (either physiologic or traumatic) results in major abnormal anterior translation of the lateral tibial plateau and, in a case-by-case basis, may warrant meniscus transplantation in addition to ligament reconstruction.

CONTRAINDICATIONS

Patients who have had a meniscectomy are evaluated with 45-degree PA weight-bearing radiographs and magnetic resonance imaging (MRI)[73,74] to determine the status of the joint, articular cartilage, and subchondral bone edema. Contraindications include advanced knee joint arthritis with flattening of the femoral condyle, concavity of the tibial plateau, and osteophytes that prevent anatomic seating of the meniscus transplant. Clinical studies have shown poor results and high failure rates in knees with this amount of joint damage.[26,39,61,74,89]

Untreated lower limb malalignment is associated with failed meniscus transplantation[13,18,93,94]; therefore the patient must be willing to first undergo a staged corrective osteotomy. Axial correction is recommended in knees in which the weight-bearing line is less than 45% (varus) or greater than 55% (valgus), representing a 2- to 3-degree change from normal alignment. Uncorrected knee joint instability, especially ACL deficiency, is also associated with poor outcomes after meniscus transplantation.[94] Patients must undergo concurrent or staged ACL reconstruction to restore normal stability to protect the meniscus transplant.

Preexisting knee arthrofibrosis, significant lower limb muscular atrophy, and a history of prior joint infection with subsequent arthritis are all contraindications for this operation. Symptomatic noteworthy patellofemoral articular cartilage deterioration (subchondral bone exposure) and obesity (BMI >30) are also contraindications.

Prophylactic meniscus transplantation following total meniscectomy is not recommended in asymptomatic patients who do not have articular cartilage deterioration because long-term predictable success rates for transplants are not available. In addition, the operative procedure does carry a slight risk for complications that could make the patient's condition worse.

This clinical problem is often encountered involving patients younger than 30 years of age who have undergone meniscectomy years ago, do not have articular cartilage damage, and are asymptomatic. Clinical studies show that eventual deterioration of the meniscectomized tibiofemoral compartment will most likely occur. These patients are advised that there is no optimal or predictable operative procedure to replace meniscus function and that they should decrease or refrain from participating in high-impact, strenuous activities. There are sensitive and accurate MRI cartilage techniques to determine the status of the articular cartilage in the meniscectomized compartment.[72,73] When early but definite articular cartilage damage is detected, it can be logically assumed that joint deterioration will continue over time and the opportunity exists to perform a meniscus transplantation. This still represents a difficult choice for the patient in terms of undergoing surgery before the onset of major joint symptoms. In addition, the transplant may not function, and further arthroscopic surgery may be required to remove the tissue. Most patients who develop early cartilage damage in the meniscectomized compartment complain of pain with strenuous athletic activities but not with recreational or daily activities. These patients are not truly asymptomatic and desire to lessen the risk of further joint deterioration to the level at which it will affect lower intensity activities. Patient education and a conservative approach to transplant recommendation are important until a more dependable transplant is available.

The presence of a full-thickness femoral condylar defect with bone exposure is a relative contraindication to isolated meniscus transplantation. Concurrent articular cartilage restorative procedures (e.g., osteochondral grafts or autologous chondrocyte implantation) can be successfully performed with meniscus transplantation[3,25,27,32,66,81,82,90] and expand the indications to include knees with these lesions.

CLINICAL BIOMECHANICS

Chondroprotective Effects

The overall goal of meniscus transplantation is to protect the articular cartilage from subsequent deterioration.[88] To date, few experimental investigations have been conducted on large animal models to determine the ability of a transplant to provide chondroprotective effects. Szomor and associates[92] conducted a study in which medial meniscectomy, medial meniscus autografts, and medial meniscus allografts were performed in 24 sheep. The grafts were placed into the anatomic anterior and posterior horn attachment sites and secured to the tibial plateau with three suture anchors. At 16 postoperative weeks, both the allograft and autograft knees demonstrated a 34% to 40% reduction in the score for macroscopic damage to the articular cartilage and an approximate 50% reduction in the area of damage to the articular cartilage compared with the meniscectomized knees. However, neither of the grafts provided complete protection, which the investigators hypothesized could have been caused by nonisometric positioning and tensioning and graft fixation. Histologic analysis revealed that the allografts had fibrinoid degeneration, areas of hypocellularity, and cloning of meniscus cells.

CRITICAL POINTS Clinical Biomechanics

Chondroprotective Effects

- Few large animal model studies have been conducted to date.
- Medial meniscus transplants showed 50% reduction in area of damage to the articular cartilage compared with meniscectomized knees.
- Lateral meniscus transplants increased total contact area by 42% to 65% compared with meniscectomized knees.

Knee Joint Contact Mechanics After Meniscus Transplantation

- Medial meniscus transplants reduced normalized maximum and mean contact pressures by 75% compared with meniscectomized cadaver knees.
- However, the transplants did not restore normal contact mechanics and demonstrated greater variability in normalized maximum and mean pressure than autografts.
- Lateral meniscus transplants sized >10% of native menisci restored contact mechanics close to normal.
- Lateral meniscal transplants increased total contact area by 42% to 65% compared with meniscectomized cadaver knees.

Effect Fixation and Location of Meniscus Transplants

- The method of fixation of meniscus transplants is critical for subsequent load-bearing function and chondroprotective effects.
- Transplant with bone for fixation is required. Soft tissue meniscus transplants, without bone fixation, are not recommended.
- Experimental studies show that implants with either a bony bridge or bone plug fixation of both horns produce contact area, peak contact pressure, and average central pressure results similar to those of an intact meniscus.
- Posterior horn tunnel of medial meniscus allograft should be placed as close to its anatomic position as possible, with a tolerance tighter than 5 mm medial and 5 mm posterior to this location.

Kelly and colleagues[42] developed a meniscus allograft surgical technique that attempted to restore the anatomic anterior tibial and posterior femoral meniscal attachments in a sheep model. Fixation of the allografts was accomplished through bone tunnels. Lateral meniscus allografts were implanted into 17 animals, and lateral meniscectomies were performed in 24 animals. Gross inspection, histologic analysis, biomechanic testing, MRI, and T2 mapping of the central weight-bearing portion of the lateral tibial plateau performed 2 and 4 months postoperatively demonstrated protective effects of the allografts. Significantly decreased cartilage wear and increased cartilage stiffness were found in the allografted joints compared with the meniscectomized knees. However, at 4 months after surgery, the allografted knees had significantly worse values for these outcome measures than the intact knees. The authors noted the successful use of MRI with T2 mapping to detect early articular cartilage degeneration.

Knee Joint Contact Mechanics After Meniscus Transplantation

Alhalki and coworkers[5] measured the maximum pressure, mean pressure, and contact area of the medial tibial articular surface after medial meniscectomy and implantation of ipsilateral medial meniscus autografts and cryopreserved allografts in 10 cadaveric knees (mean age, 70 years). The autografts and allografts were implanted using bone plug fixation through anterior and posterior horn transtibial tunnels. The allografts significantly reduced normalized maximum and mean contact pressures by 75% compared with meniscectomized knees. In addition, the maximum pressure was restricted to a small region of the contact area. The authors hypothesized that a reduction of this magnitude could mitigate the rate of cartilage wear compared with that in a meniscectomized knee. However, the allografts did not restore normal contact mechanics and demonstrated greater variability in normalized maximum and mean contact pressures than the autografts. The authors concluded that the variability in contact mechanics could have been caused by poor matching of the 3-dimensional geometry of the allograft to the recipient knee. Dimensions for the allograft were matched from standard anteroposterior (AP) and lateral radiographs in the transverse plane. Studies by Paletta and associates[70] and Haut and colleagues[33] revealed that measurements made in the transverse plane only weakly predict the cross-sectional shape of the meniscus.

The effect of the size of lateral meniscus allografts (in comparison with native menisci) on tibial plateau contact mechanics was investigated by Dienst and coworkers.[20] Allografts that were 17.5% larger than native menisci had significantly greater contact forces across the articular cartilage. Allografts sized 10% smaller than native menisci resulted in increased forces across the meniscal tissue, which the authors hypothesized could cause early transplant failure. The authors concluded that the surgeon should select lateral meniscus transplants (LMT) that are slightly larger than native menisci (rather than smaller) to reduce the risk of early failure.

Paletta and associates[70] investigated the effects of lateral meniscectomy, cryopreserved lateral meniscus transplantation with bone plug fixation, and lateral meniscus transplantation without fixation of the anterior and posterior horn attachments. The study involved 10 cadaver knees less than 48 years of age. The lateral meniscal transplants increased total contact area from 42% to 65% compared with meniscectomized knees at all flexion angles (0, 30, and 60 degrees), However, there remained a residual 17% to 23% decrease in contact area compared with intact knees. Release of the horn attachments resulted in a contact area that was identical to meniscectomized specimens. McDermott and associates[58] assessed the effects of lateral meniscal transplantation with and without bone block fixation in eight cadaver knees. These investigators reported no difference between the two methods in peak contact pressures compared with intact knees. The cadaver specimens used in the study were ages 81 to 98 years, and all had moderate to severe degenerative changes. In addition, no formal size matching was performed with the allografts and recipient knees.

Effect of Fixation and Location of Meniscus Transplants

The method of fixation of meniscus transplants to the surrounding tissues is believed to be paramount in subsequent load-bearing function and chondroprotective effects. The goal is to reproduce the normal attachment sites, allowing lateral and medial transplants to remain in their anatomic locations and move normally throughout knee motion.[16,76,99] The use of a transplant with bone for fixation incorporated with either a central bone bridge or a two-tunnel technique (as described later in this chapter) is, in our opinion, required to obtain these goals. Soft tissue meniscus transplants, without bone fixation, are not recommended. Although soft tissue transplants are far easier to prepare and implant surgically, scientific data are inadequate to support that the soft tissue ends of the meniscus implant will heal and provide the circumferential tension in the meniscus that is required for function (Fig. 24-1).[28,57]

The importance of securing the anterior and posterior horns of an LMT was documented by Chen and colleagues,[15] who investigated a variety of surgical methods for meniscus implantation. Using an

autograft cadaver model, the study revealed that a transplant that had either a bony bridge or bone plug fixation of both horns produced contact area, peak contact pressure, and average central pressure results similar to those of an intact meniscus. Procedures in which either only one horn was secured or neither horn was secured demonstrated a loss of mechanical function and subsequent expected benefit from the transplant.

Alhalki and coworkers[4] compared three fixation methods of medial meniscus autografts in cadaver knees to determine which method restored tibial contact mechanics closest to normal. The experimental design tested bone plug fixation alone, bone plug fixation combined with peripheral suturing of the transplant to the native rim, and suturing of the horns through bone tunnels combined with peripheral suturing of the transplant to the native rim. The study revealed that bone plug fixation produced contact mechanics closest to normal; however, the maximum pressure was significantly greater than that in the intact knee. There was no benefit in adding peripheral sutures to the bone plug fixation model. Importantly, fixation with sutures only did not restore normal contact mechanics and was not recommended by the investigators.

Verma and associates[103] measured medial compartment peak pressure, mean pressure, and contact area in eight cadaver knees to determine whether a difference existed between medial meniscus transplants (MMTs) implanted with a bone plug technique and those with a bone trough technique. The data indicated no difference between the two techniques for all three variables, which were restored to values similar to those measured in the intact knees. The authors cited clinical advantages with the trough technique for both medial and lateral meniscus transplantation.

The effect of variations in placement of the posterior horn attachment of an MMT were investigated by Sekaran and colleagues.[83] Using a cadaver autograft model, the posterior horn tunnel was placed either in its anatomic position or 5 mm posterior to the anatomic location. The study showed that placing the posterior horn tunnel 5 mm medial to its anatomic position caused an increase in normalized maximum pressure, a posterior shift in the location of the center of the contact area, and an increase in the normalized mean pressure. Placing the posterior horn tunnel 5 mm posterior was not as detrimental; however, this location resulted in a significant shift in the centroid of contact area. The authors concluded that surgeons should place the posterior horn tunnel as close to its anatomic position as possible, with a tolerance limit of less than 5 mm medial and 5 mm posterior to this location.



FIG 24-1 Visual inspection of meniscus transplant before implantation.

CLINICAL EVALUATION

A thorough history including assessment of prior operative records and current symptoms and functional limitations is taken. A comprehensive knee examination is performed. This includes assessment of knee flexion and extension, patellofemoral indices, tibiofemoral pain and crepitus, muscle strength, and gait abnormalities. Also, the appropriate clinical tests for the ACL, posterior cruciate ligament (PCL), medial, and posterolateral structures are performed.

MRI is obtained using proton-density-weighted, high-resolution, fast-spin-echo sequences[73,74] to determine the status of the articular cartilage and the previously meniscectomized tibiofemoral compartment. Radiographs include AP, lateral at 30 degrees of knee flexion, weight-bearing PA at 45 degrees of knee flexion, and patellofemoral axial views. Axial lower limb alignment is measured using double-limb standing hip-knee-ankle weight-bearing radiographs[22] in knees that demonstrate varus or valgus alignment.

CRITICAL POINTS Clinical Evaluation

Physical Examination
- Tibiofemoral joint line pain, compression pain, crepitus
- McMurray test
- Knee flexion and extension
- Joint effusion
- Patellofemoral (medial and lateral subluxation, Q-angle, crepitus, compression pain)
- Muscle strength
- Alignment
- Gait

Ligament Subluxation Tests
- Pivot shift, Lachman
- KT-2000 (MEDmetric) 20 degrees of knee flexion, 134-N force
- Posterior drawer, 90 degrees of knee flexion
- Tibiofemoral rotation dial 30 degrees, 90 degrees of knee flexion
- External rotation recurvatum
- Lateral tibiofemoral joint opening 5 degrees, 20 degrees of knee flexion
- Reverse pivot shift
- Medial tibiofemoral joint opening 5 degrees, 20 degrees of knee flexion

MRI
- Proton-density-weighted, high-resolution, fast-spin-echo sequences

Radiographs
- Anteroposterior
- Lateral, 30 degrees of knee flexion
- Posteroanterior, weight-bearing, 45 degrees of knee flexion
- Patellofemoral axial
- Double-limb standing hip-knee-ankle weight-bearing for varus or valgus malaligned knees

Assessment of Symptoms and Functional Limitations With Activity: Cincinnati Knee Rating System
- Sports Activity and Function Form
- Occupational Rating Form
- Symptom Rating Form

Patients complete questionnaires and are interviewed for the assessment of symptoms, functional limitations, sports and occupational activity levels, and patient perception of the overall knee condition according to the Cincinnati Knee Rating System (CKRS).[7]

Knees with associated varus osseous malalignment require a staged corrective osteotomy before the meniscus transplant procedure. Knees with ligament deficiency require a staged ligament reconstruction. Some studies have advocated concurrent ACL reconstruction and meniscus transplantation.[29,84,107] The normal ACL tibia attachment site and the ACL tibial graft tunnel may compromise meniscus transplant tibial fixation. This may occur when the slot technique to be described is selected in patients whose central tibial intercondylar region is not wide enough to accommodate both the meniscus transplant slot and ACL tibial graft tunnel. Because it is not possible in these knees to use the central slot technique, a two-tunnel procedure is selected for the MMT.

PREOPERATIVE PLANNING

Tissue Bank and Sterilization Issues

In the United States, meniscus transplants are obtained from tissue banks accredited by the American Association of Tissue Banking (AATB) and inspected by the U.S. Food and Drug Administration (FDA). Tissues in which serologic testing meets or exceeds the standards of these organizations are selected. Importantly, donor selection criteria may vary among tissue banks, and the surgeon should understand the specific criteria used by the bank chosen to supply the transplant. We recommend that the donor age be less than 30 years to offset any potential age-dependent alterations in biomechanic or biochemical properties of the transplant.[11]

A variety of sterilization techniques have been described for meniscus transplants, including none (fresh-frozen), irradiated, cryopreserved, and proprietary chemical techniques. Some authors[13] advocate combined secondary sterilization using low-dose irradiation (1-2 mrad) and chemical agents. To date, no scientific data exist to select one type of graft processing method over another.

Surgeons should be aware that so-called *sterilization processes* may not prevent contamination and do not guarantee a sterile graft. Prophylactic antibiotics are administered intravenously before surgery, and patients are carefully monitored postoperatively for any signs of infection. The implications of different processing techniques on graft sterility and donor selection issues, allograft harvesting techniques, and disease testing are beyond the scope of this chapter and have been discussed in detail by others.[8,35,98]

CRITICAL POINTS Preoperative Planning

- Obtain transplants from tissue banks accredited by AATB and inspected by the U.S. FDA.
- Transplant processing includes fresh-frozen, irradiated, cryopreserved, and proprietary chemical techniques. No scientific data are available to select one type of graft processing method over another.
- No standard exists for transplant sizing. AP, lateral radiographs are usually obtained to measure width and length measurements for transplant. The surgeon must select, according to his or her own comfort level, the technique preferred from those currently available to determine the transplant size required.
- Request a photograph of the transplant with metric ruler placed adjacent to inspect size and shape of graft.
- Grafts may vary up to 10% in length and width; the surgeon may need to adjust the transplant to fit the patient's tibial plateau.
- Advise the patient that the transplant will be inspected in the operating room before the induction of anesthesia.

Meniscus Sizing Issues

Although there is no standard protocol at present, AP and lateral radiographs are typically used to obtain approximate width and length measurements for the meniscus transplant (based on tibial plateau measurements), as described by Pollard and associates.[71] A number of studies have been recently performed to determine the most reliable sizing method and this issue clearly remains unresolved.[9,21,33,86,91,109,110] Other methods that have been investigated include MRI; 3-dimensional computed tomography (CT); photographs of the transplant; and calculations to predict transplant size based on patient height, weight, and gender.

Berhouet and associates[9] compared direct anatomic measurements of menisci in cadaver knees with measurements obtained from radiographs and photographs of the specimens. No significant difference was found between the anatomic and radiographic method discussed by Pollard and colleagues[71]; the mean overall measurement error for the radiographic method was 7.9% (4.3% on AP views and 11.45% on lateral views). The photographic method was deemed unreliable because it produced significantly different measurements than the direct anatomic measurements and had a mean overall measurement error of 20.1%. Many tissue banks will provide a photograph of the transplant specimen, which is advantageous because it allows the surgeon to inspect the size and shape of the meniscus. Berhouet and colleagues[9] reported that the problem with the photographic method arose from distortions incurred from the position of the camera and ruler, which produced magnification errors. The ruler was placed in line with the bottom of the specimen, the tibial plateau, which was below the plane of the menisci. The recommendation was made that, during transplant harvest, the ruler should be placed in the plane of the menisci to reduce the measurement error.

Yoon and colleagues[109] presented a slightly different radiographic protocol to identify bony landmarks of the lateral tibial plateau to more precisely measure lateral meniscus length. The radiographic beam was angled 10 degrees caudally at neutral rotation. This lateral view enabled the lateral plateau cortical margins to be differentiated from the medial plateau margins. The authors determined a best-fit equation for predicting meniscal size from Pollard's method of bone size: anatomic length = 0.52 × plateau length ± 5.2. Compared with the Pollard method, this investigation's method reduced the deviation from the anatomic dimensions from 4.1 to 1.4 mm, respectively, and increased the accuracy (within 10% of actual length) from 40% to 98%, respectively.

Stone and associates[91] suggested that recipient height, weight, and gender be considered as important matching criteria when selecting meniscus transplants. These investigators measured meniscus and tibial plateau dimensions in 111 patients using MRI and correlated the dimensions with the patients' height, weight, BMI, and gender. Height correlated well with total tibial plateau width ($R = 0.7194$), and females generally had smaller meniscus dimensions than males. In addition, patients with a BMI greater than 25 had larger meniscus dimensions than patients with a lower BMI at any given height. This concept was further advanced by Van Thiel and colleagues[97] who provided a validated regression model that used height, weight, and gender to predict meniscus transplant size based on data from 930 donors and the dimensions of their menisci. Compared with published radiographic and MRI data, the model produced

measurement results that were "slightly more accurate." However, their findings were later refuted by Yoon and coworkers,[110] who found that height, weight, gender, and BMI failed to estimate the size of the lateral meniscus based on a sample of 91 fresh menisci obtained during total knee arthroplasty.

Prodromos and coworkers[75] conducted an investigation to determine the accuracy of MRI performed on the contralateral knee to determine transplant size. Using tissue bank records, the investigators compared the dimensions of right and left knees of 500 donors and determined that 97% were within 3 mm of each other in the AP and medial-lateral directions. Then the menisci of 10 cadaveric knees were directly measured and compared with tibial plateau dimensions obtained from radiographs (Pollard method). The MRI scans had an average error rate of 4.7% compared with 14.4% for the radiographic method. Radiographs oversized 18 meniscal measurements and undersized 23 measurements. The authors concluded that MRI of the contralateral meniscus should be used to determine transplant size.

Donahue and colleagues[21] developed an algorithm for meniscus transplant sizing based on MRI measurements. The authors recommended that tissue banks follow the algorithm, which involves a series of six steps. These include making four transverse and six cross-sectional measurements for each transplant in the bank's inventory using a 3-dimensional coordinate digitizing system, obtaining MRI of the recipient's uninjured knee, and measuring nine parameters for the medial or lateral meniscus, as well as performing a series of calculations to determine the best match.

McConkey and associates[55] recommended 3-dimensional CT scanning to improve the accuracy and reliability of sizing the tibial plateau. In their investigation, CT estimates of plateau size were closer to anatomic measurements in cadaveric knees than AP and lateral radiographs in all dimensions ($P < .0001$). CT scans fell within 5 mm of the anatomic measurements 100% of the time and within 2 mm of the anatomic measurements 76% of the time. In comparison, radiographic measurements fell within 5 mm of the anatomic measurements 76% of the time and within 2 mm of the anatomic measurements 34% of the time.

These studies show that there is no consensus in the literature regarding meniscus sizing criteria. Studies generally show that radiographic techniques tend to overestimate meniscus size, and MRI tends to underestimate size.[14,55,86] The surgeon must select, according to his or her own comfort level, the technique preferred from those currently available to determine the transplant size required. In addition, the surgeon should be aware of the method the tissue bank uses to measure transplant dimensions and understand that the specimen obtained may vary up to 10% in length and width. In these cases, the surgeon may need to adjust the transplant to fit the patient's tibial plateau. The use of the two-tunnel technique allows for this adjustment to be made because the tunnels are placed at the anatomic attachment sites on the respective medial or lateral tibial plateau. The bone end is pulled into the tunnel (3-5 mm) to maintain tension on the implant and prevent extrusion. Judgment is also required during surgery when the meniscus bone bridge technique is performed because it requires good size matching to prevent medial or lateral meniscus extrusion. We prefer to take the added time to use a bone bridge or bone plug technique (bone-meniscus-bone implant), which requires a good geometric and anatomic fit. Alternative techniques are available in which the meniscus is sutured in place without bone plugs, a procedure that is not recommended.

The problem still exists that even though an approximate size can be determined preoperatively, in many knees, the tibiofemoral joint has undergone degenerative changes that produce subtle alterations in joint geometry, leading to permanent alterations in the normal surface stress distribution of the joint surface.[12] A meniscus transplant does not have the ability to restore the native or normal state of the menisectomized compartment. Future studies are required to determine the effect of subtle size and shape mismatch of the transplant on retaining articular cartilage functional properties. A chondroprotective effect of meniscus transplants has yet to be proven. This involves sophisticated questions regarding the chondrocyte function, cartilage collagen, and glycosaminoglycan homeostasis and resultant biomechanic properties.

Certain medial menisci may have a hypoplastic anterior horn that is narrow and inserts distal to the medial tibial surface (type III),[10] which is not acceptable for implantation. The middle third of a medial or lateral meniscus may be 8 to 10 mm in width and suitable only for small patients. The lateral meniscus may have reduced anterior-to-posterior length, less than that calculated on the sagittal radiograph, and not be suitable for implantation.

The patient is advised that the transplant will be inspected in the operating room before the induction of anesthesia. It is rare that the operative procedure cannot be performed as planned; however, there is always the chance that the transplant will not meet the desired criteria.

INTRAOPERATIVE EVALUATION

MMTs are not prepared until the surgeon determines whether the central bone bridge technique (which is preferred) or the two-tunnel technique (separate anterior and posterior bone attachments and tunnels) will be performed, as is described later.

LMTs are prepared before the operative procedure to determine the depth and width required for the tibial slot in the central bone bridge technique. The central bone portion of the LMT incorporates the anterior and posterior meniscal attachments and usually measures 8 mm in width in smaller patients and 9 mm in larger patients. The posterior 6 to 8 mm of tibia bone bridge that protrudes beyond the posterior horn attachment is removed to produce a buttress against the prepared bone slots in the host knee. Commercially available (Stryker Endoscopy and Cryolife) sizing blocks and channel cutters are helpful for appropriate sizing, as is described later.

All knee ligament subluxation tests should be performed after the induction of anesthesia in both the injured and contralateral limbs. The amount of increased anterior tibial translation, posterior tibial translation, lateral and medial joint opening, and external tibial rotation should be documented. A thorough arthroscopic examination should be conducted, documenting articular cartilage surface abnormalities[68] and the condition of the menisci.

CRITICAL POINTS Intraoperative Evaluation

- Inspect the transplant before administration of anesthesia.
- MMT: choose either central bone bridge or two-tunnel technique.
- Lateral meniscus transplant: Prepare implant to determine depth and width required for tibial slot.
- Repeat all knee ligament subluxation tests with the patient under anesthesia on both injured and contralateral limbs.
- Rate all articular cartilage surfaces and inspect menisci for abnormalities.

OPERATIVE TECHNIQUE: LATERAL MENISCUS TRANSPLANT

The patient is placed in a supine position on the operating room table with a tourniquet applied with a leg holder, and the table is adjusted to allow 90 degrees of knee flexion. The opposite lower extremity is placed in a thigh-high elastic stocking and is padded to maintain mild hip flexion to decrease tension on the femoral nerve. After examination under anesthesia, diagnostic arthroscopy confirms the preoperative diagnosis and articular cartilage changes. A meniscus bed of 3 mm is retained when possible, except at the popliteal tendon region where the native meniscus rim is removed. The meniscus bed and adjacent synovium are rasped to aid in revascularization of the transplant.

The tourniquet is inflated for only the two initial operative approaches. A limited 3-cm lateral arthrotomy is made just adjacent to the patellar tendon. Although arthroscopic techniques are available to prepare the tibial slot, the limited arthrotomy provides superior visualization and avoids incising into the patellar tendon, which must be displaced medially to properly place the tibial slot. A common mistake involves placing the anterior aspect of the tibial slot lateral to the normal attachment of the anterior horn of the lateral meniscus.

A second 3-cm posterolateral incision is made just behind the fibular collateral ligament (FCL; Fig. 24-2), similar to that described in Chapter 23 for inside-out lateral meniscus repairs.[59,79] The interval between the short head of the biceps muscle and the iliotibial band is identified and incised. The biceps capsular attachments are gently dissected with Metzenbaum scissors off the posterior capsule and FCL to just above the fibular head. Care is taken at this point because dissection that extends too far anterior or proximal to the joint line would enter the joint capsule. If this occurs, a capsular repair is required to maintain joint integrity during the inside-out meniscal repair procedure.

The inferior lateral geniculate artery, in close proximity, is identified and preserved. The space between the posterolateral capsule and the lateral head of the gastrocnemius is further developed bluntly. An appropriately sized popliteal retractor is placed directly behind the lateral meniscus bed and anterior to the lateral gastrocnemius muscle. Care is taken during the subsequent inside-out suture passage that the retractor remains anterior to the lateral gastrocnemius muscle to protect the peroneal nerve, which lies posterior to the muscle.

The width of the transplant is determined. A template made out of aluminum foil of the transplant's width and length is cut and inserted into the lateral compartment to determine the proper placement of the bone slot. This sizing step is important to ensure there is no lateral overhang (extrusion) of the meniscal body produced by placing the bone slot too far laterally. If there is a mismatch that results in lateral extrusion, the procedure may be converted from the bone bridge technique to one using two separate bone plugs and bone tunnels. The posterior bone plug is located directly at the lateral meniscus attachment. The anterior bone plug is placed more medially by a few millimeters to prevent lateral extrusion. The use of the bone bridge technique does require adequate size matching, and judgment is required at surgery in using the central bridge or separate bone plug technique. This same concept applies to MMTs. A rectangular bone slot is prepared at the anterior and posterior meniscus tibial attachment sites to match the dimensions of the prepared transplant.

The sequence of steps to prepare the lateral tibial slot is shown in Figure 24-3. The tibial bone slot is 1 to 2 mm wider than the transplant to facilitate implantation. The anterior and posterior horns of the transplant are placed into their normal attachment locations, adjacent to the ACL. It is important to note that a prior ACL reconstruction in which the tibial tunnel was placed in a lateral position may produce a technical problem in creating the tibial slot.

A starter chisel and finishing chisels provide an alternative technique to create and fashion the tibial slot to its final depth and width (Fig. 24-4, *A*). A tibial slot sizing guide is used to check the length and depth (see Fig. 24-4, *B*). A sizing block (see Fig. 24-4, *C*) confirms that the transplant bone bridge is of the correct width and depth.

A dovetail technique may also be considered, which has the advantage of providing added stability to the fixation at the tibial bone portion of the transplant (Fig. 24-5). This procedure entails cutting a trapezoidal bone block that includes a narrower 7-mm bone bridge and requires additional time to prepare the transplant.

The transplant is inserted into the slot, and the bone portion of the graft is seated against the posterior bone buttress to achieve correct anterior-to-posterior placement of the attachment sites. A vertical suture in the posterior meniscus body is passed posteriorly to provide tension and facilitate transplant placement. The suture is tied later in the procedure. The knee is flexed, extended, and rotated to confirm that correct placement of the transplant has been obtained. Sutures are placed into the anterior third of the meniscus, attaching it to the prepared meniscus rim under direct visualization.

Two fixation methods are available for the central bone attachment. Two 2-0 non-absorbable sutures may be placed retrograde into the tibial slot, passed over the central bone bridge before transplant

CRITICAL POINTS Operative Technique: Lateral Meniscus Transplant

- Diagnostic arthroscopy confirms preoperative diagnosis, articular cartilage changes.
- Limited 3-cm lateral arthrotomy just adjacent to patellar tendon
- Patellar tendon displaced medially to properly place tibial slot
- Second 3-cm posterolateral incision made just behind fibular collateral ligament
- Interval between short head of biceps muscle and iliotibial band is identified and incised.
- Biceps capsular attachments are gently dissected off the posterior capsule.
- Inferior lateral geniculate artery is identified and preserved.
- Space between posterolateral capsule and lateral head of the gastrocnemius is further developed bluntly.
- Width of transplant is determined, and template is inserted into lateral compartment to determine proper placement of bone slot.
- Sizing step ensures there is no lateral overhang of the meniscal body.
- Tibial bone slot 1-2 mm wider than transplant to facilitate implantation. Anterior and posterior horns of implant placed into normal attachment locations.
- Transplant sizing block confirms transplant bone bridge is correct width and depth.
- Dovetail technique or rectangular bone technique is chosen.
- Implant is inserted into slot; bone portion of graft is seated against posterior bone buttress to achieve correct anterior-to-posterior placement of the attachment sites.
- Transplant is sutured to native meniscus rim.
- Two fixation methods for the central bone attachment: two 2-0 nonabsorbable sutures are placed retrograde into the tibial slot, passed over the central bone bridge, and tied to tibial post (preferred).
- Place a 7 × 25 mm interference screw adjacent medially to the bone bridge.
- Arthrotomy is closed, and inside-out meniscal repair is completed with multiple vertical divergent sutures.

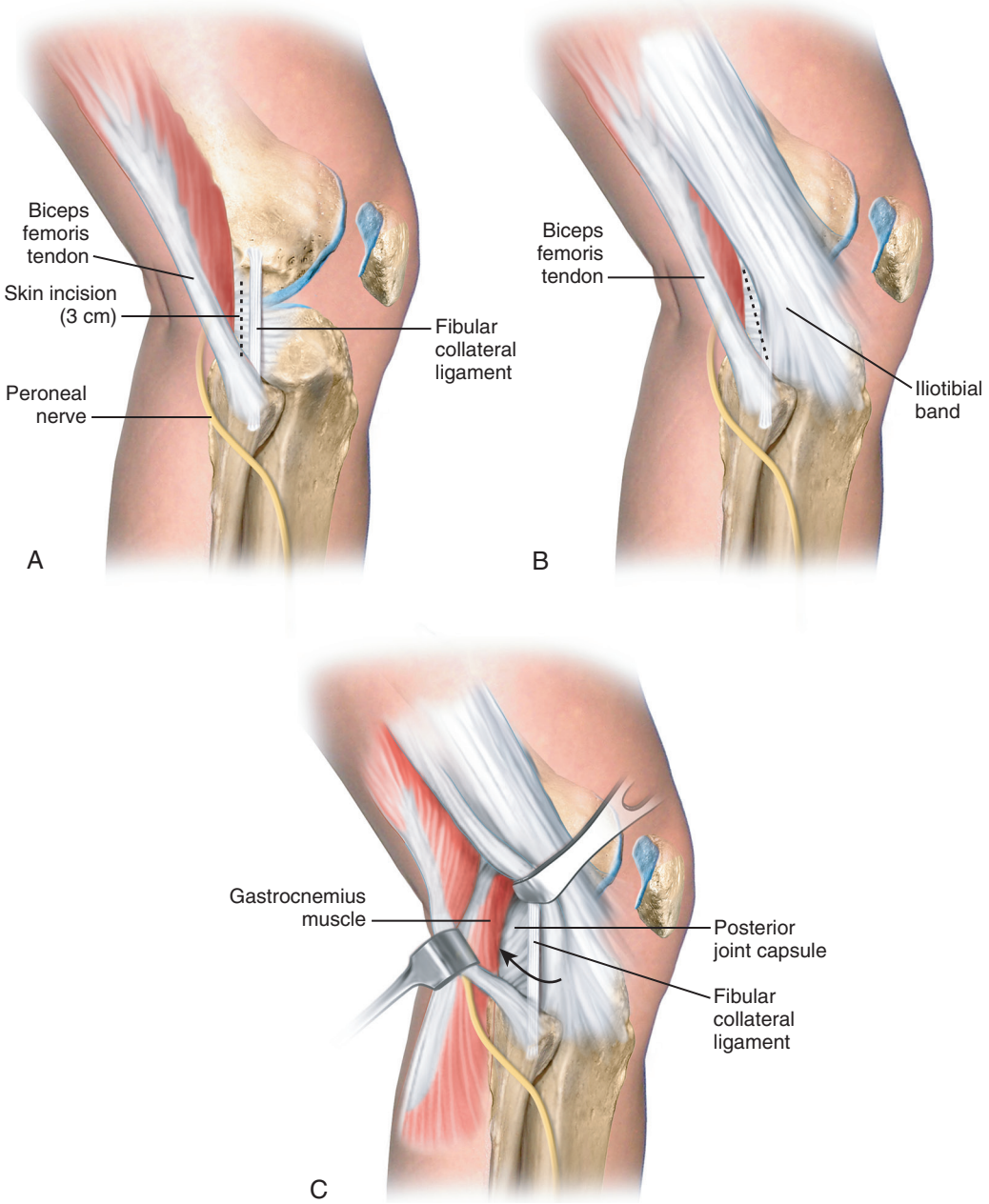


FIG 24-2 **A,** Site of the posterolateral incision for a lateral meniscus transplant. **B,** Incision site in the interval between the posterior edge of the iliotibial band and the anterior edge of the biceps tendon. **C,** The interval between the lateral gastrocnemius and posterolateral capsule is opened bluntly, just proximal to the fibular head to avoid entering the joint capsule proximally.

passage, and tied to a tibial post. The sutures securely hold the transplant in the tibial slot and, along with the peripheral sutures, provide fixation. This is the preferred technique because it is simple and effective. Another option is to place a 7 × 25 mm interference screw composed of an absorbable composite material medially adjacent to the bone bridge.[24] A tap is inserted over the guidewire to create a path for the interference screw with the bone bridge held in place manually. This technique is not used if there is tibial bone osteopenia or if a prior ACL graft tunnel exists because inadequate fixation will occur.

The arthrotomy is closed, and the inside-out meniscal repair completed with multiple vertical divergent sutures that are placed first superiorly to reduce the meniscus (Fig. 24-6) and then inferiorly in the outer third of the transplant. Sutures are not placed in the middle and inner thirds to avoid weakening the transplant owing to its limited healing capability in these regions (Fig. 24-7). Although all-inside suture techniques have been used in some studies, we do not recommend this procedure because multiple superior and inferior vertical divergent sutures provide excellent fixation that allows immediate range of motion and 25% weight bearing.

OPERATIVE TECHNIQUE: MEDIAL MENISCUS TRANSPLANT

The patient is placed in a supine position on the operating room table with a tourniquet applied using a leg holder, and the table is adjusted

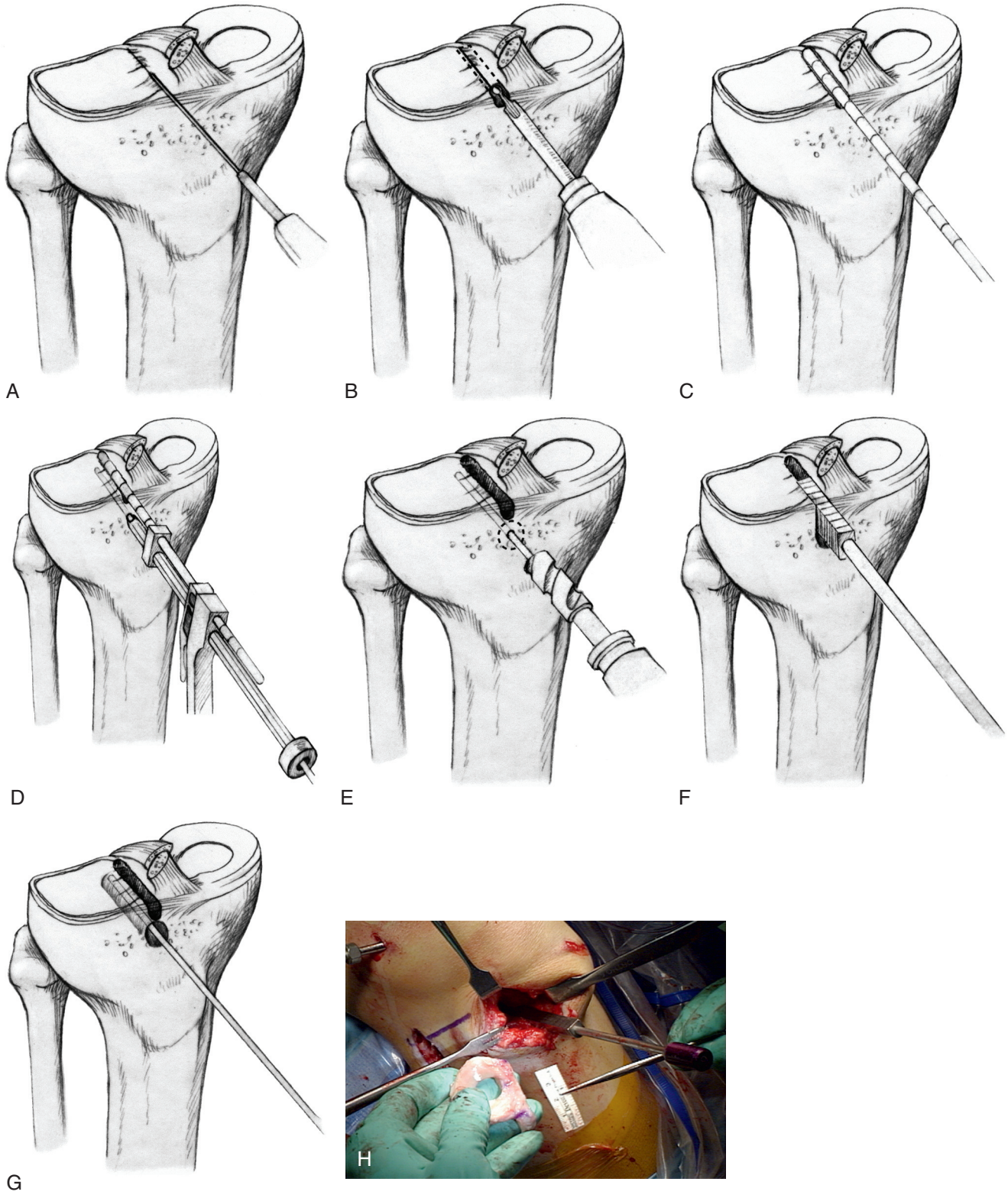


FIG 24-3 **A,** Tibial slot technique for lateral meniscus transplantation. An arthroscopic-assisted technique or minilateral arthrotomy may be used in this procedure. We prefer the miniarthrotomy because it offers superior visualization and avoids incising the patellar tendon. Establish a line connecting the center of the anterior and posterior horn attachments using an electrocautery device. In the mini-open arthrotomy, a template of the meniscus coronal width is used to verify the medial-to-lateral width of the transplant to move the slot appropriately to prevent tibial overhang of the transplant. **B,** A burr removes the tibial spine and creates a 4-mm straight anterior-to-posterior reference slot along the plane of the tibial slope. **C,** This calibrated guide pin sits flush with the articular cartilage. **D,** The drill guide uses a guide pin that has been marked with a laser to set the depth of a second guide pain, allowing a drill to ream 5 mm less to retain the posterior portion of the tibial slot. **E** to **G,** The 8-mm drill bit with a collar at the defined depth is used, followed by use of a box cutter to create a rectangular slot of the desired depth and width. **H,** The lateral meniscus transplant with the central bone bridge technique is ready to be placed into the tibial slot. (**A** to **H,** From Noyes FR, Barber-Westin SD, Rankin M. Meniscal transplantation in symptomatic patients less than fifty years old. Surgical technique. *J Bone Joint Surg Am.* 2005;87(suppl 1[pt 2]):149-165.)

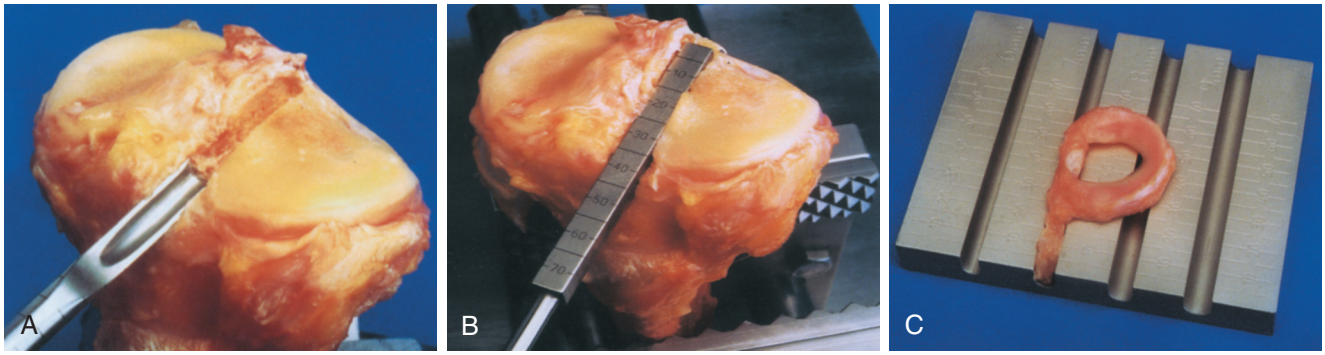


FIG 24-4 **A,** An alternative technique uses a starter chisel and finishing chisels to fashion the tibial slot to its final depth and width. **B,** A tibial slot sizing guide is used to check the length and depth. **C,** The allograft sizing block confirms that the allograft bone bridge is of the desired width and depth. (**A** to **C,** From Noyes FR, Barber-Westin SD, Rankin M. Meniscal transplantation in symptomatic patients less than fifty years old. Surgical technique. *J Bone Joint Surg Am.* 2005;87(suppl 1[pt 2]):149-165.)

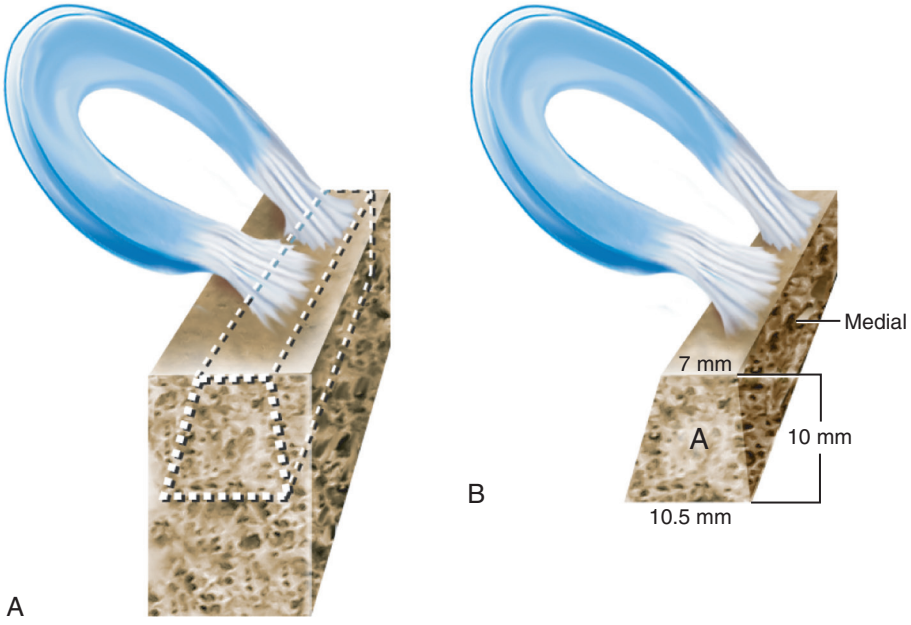


FIG 24-5 Dovetail meniscus allograft technique. **A,** An outline of the dovetail bone block is drawn on the end of the bone plug. A transplant jig system is used to hold the meniscus transplant and produce the desired bone cuts. **B,** Final appearance showing typical dimensions for the trapezoidal bone block before transplant insertion.

to allow 90 degrees of knee flexion. The opposite lower extremity is placed in a thigh-high elastic stocking and is padded to maintain mild hip flexion to decrease tension on the femoral nerve. After knee examination and diagnostic arthroscopy, the meniscus bed is prepared by removing remaining meniscal tissue. It is important to preserve, whenever possible, a 3-mm rim to help contain the meniscus and prevent extrusion. Although there are techniques for suturing the meniscus implant without bone plugs, we prefer to take the added time to secure a bone-meniscus-bone implant. Biomechanic studies[4,5,15,70] support this concept and have shown that sutured meniscus implants, without additional bony fixation, do not restore normal joint contact pressures, although one study did not agree.[58] Any loss of meniscus tissue to its bony attachment may result in loss of function. Sekaran and colleagues[83] showed that even a 5-mm malposition in the medial meniscus posterior bone plug adversely affects joint contact pressure. The meniscus bed and synovium are rasped to aid in revascularization of the transplant.

The tourniquet is inflated only for the anteromedial and posteromedial surgical approaches. For the anterior arthrotomy, a 4-cm skin anteromedial incision is made adjacent to the patellar tendon. A second 3-cm vertical posteromedial incision is made, similar to that described for inside-out meniscus repairs (Fig. 24-8).[59] The fascia is incised anterior to the sartorius muscle, and the pes anserine muscle group is retracted posteriorly. Great care is taken to identify and avoid injury to the infrapatellar branches of the saphenous nerve. The interval between the semimembranosus tendon and the capsule is dissected.

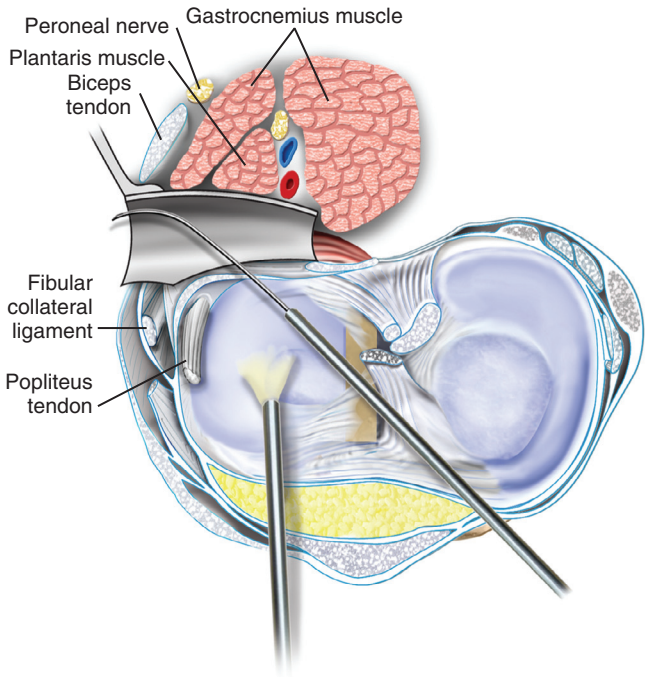


FIG 24-6 Cross-section showing popliteal retractor between the lateral gastrocnemius and the posterior capsule. A single cannula is introduced from the adjacent portal to facilitate placement of the vertical sutures into the periphery of the meniscus transplant.

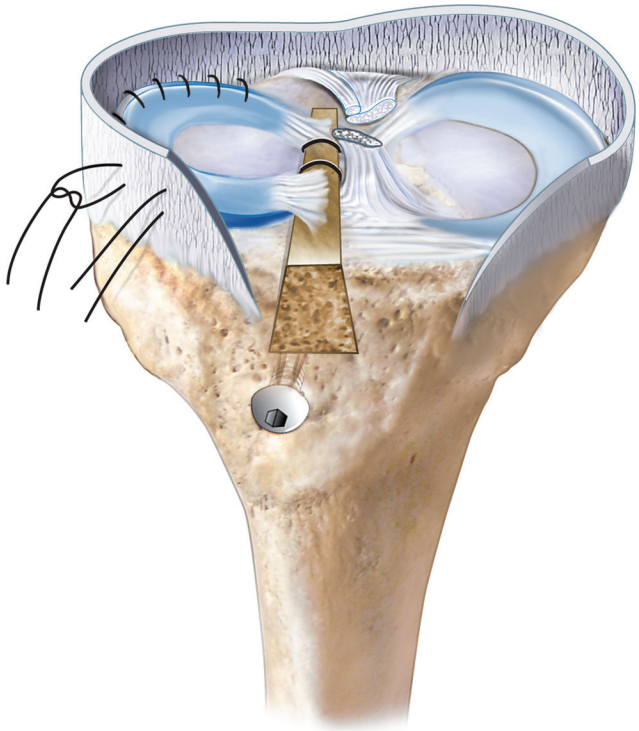


FIG 24-7 Lateral meniscus graft in place and sutured.

The tendon sheath of the semimembranosus is incised to facilitate exposure. The layer between the medial gastrocnemius tendon and the posterior capsule is separated with blunt dissection. A meniscus retractor is placed in the interval anterior to the gastrocnemius tendon and directly posterior to the meniscus bed and posterior capsule. The two

CRITICAL POINTS Operative Technique: Medial Mensicus Transplant

- Diagnostic arthroscopy confirms preoperative diagnosis and articular cartilage changes.
- Tourniquet is inflated only for anteromedial, posteromedial surgical approaches.
- 4-cm skin anteromedial incision adjacent to tibial tubercle and patellar tendon.
- 3-cm vertical posteromedial incision.
- Identify and avoid injury to the infrapatellar branches of the saphenous nerve.
- Tendon sheath of the semimembranosus is incised to facilitate exposure.
- Meniscus retractor is placed in the interval anterior to gastrocnemius tendon, directly posterior to meniscus bed, posterior capsule.
- Aluminum foil template of the MMT is made, measured according to anterior-posterior, medial-lateral dimensions.
- Template is inserted through anterior arthrotomy to measure medial tibial plateau.
- Position of central bone slot is marked.
- Surgeon determines whether meniscus implant will be properly positioned; if so, central bone bridge technique is used.
- If implant requires adjustment for improper fit in medial compartment, two-tunnel technique is selected.

approaches are performed with the tourniquet inflated to 275 mm and usually require less than 15 minutes; otherwise, the tourniquet is not used.

The goal of the operative procedure is to transplant the medial meniscus and bone attachments into the normal anterior and posterior attachments and to suture the transplant to maintain the desired position in the knee joint. An aluminum foil template of the MMT is measured according to its anterior-to-posterior and medial-to-lateral dimensions and is inserted through the anterior arthrotomy to measure the medial tibial plateau. This allows the position of the central bone slot to be marked and to determine whether the meniscus transplant will be properly positioned adjacent to the ACL tibial attachment without medial tibial overhang.

The anterior and posterior meniscus attachment locations are verified to be at the anatomically correct sites. The central bone bridge technique removes 4 to 6 mm of the medial intercondylar tubercle. If the transplant is suitable and no medial tibial overhang is present, the central bone bridge technique may be used. If the transplant needs to be adjusted to fit to the medial tibial plateau to avoid medial extrusion, then the two-tunnel technique is selected. This sizing step is critical to obtain proper placement of the MMT into the host tibia.

In many knees, the central slot technique will not be possible owing to a sizing problem that results in excessive medial displacement of the meniscus body or that would compromise the ACL tibial attachment. Once the appropriate technique has been determined, the meniscus transplant is prepared.

Medial Meniscus Central Bone Bridge Technique

The technique is similar to that already described for LMT. The meniscus transplant is prepared using either a rectangular or dovetail technique. A reference slot is first made on the tibial plateau in the anterior-to-posterior direction. A guide pin is positioned in the slot, inferiorly on the tibia, and a cannulated drill bit is placed over the pin to drill a tunnel. An alternative technique is to use osteotomes and chisels to prepare the tibial slot. The ACL attachment is directly lateral

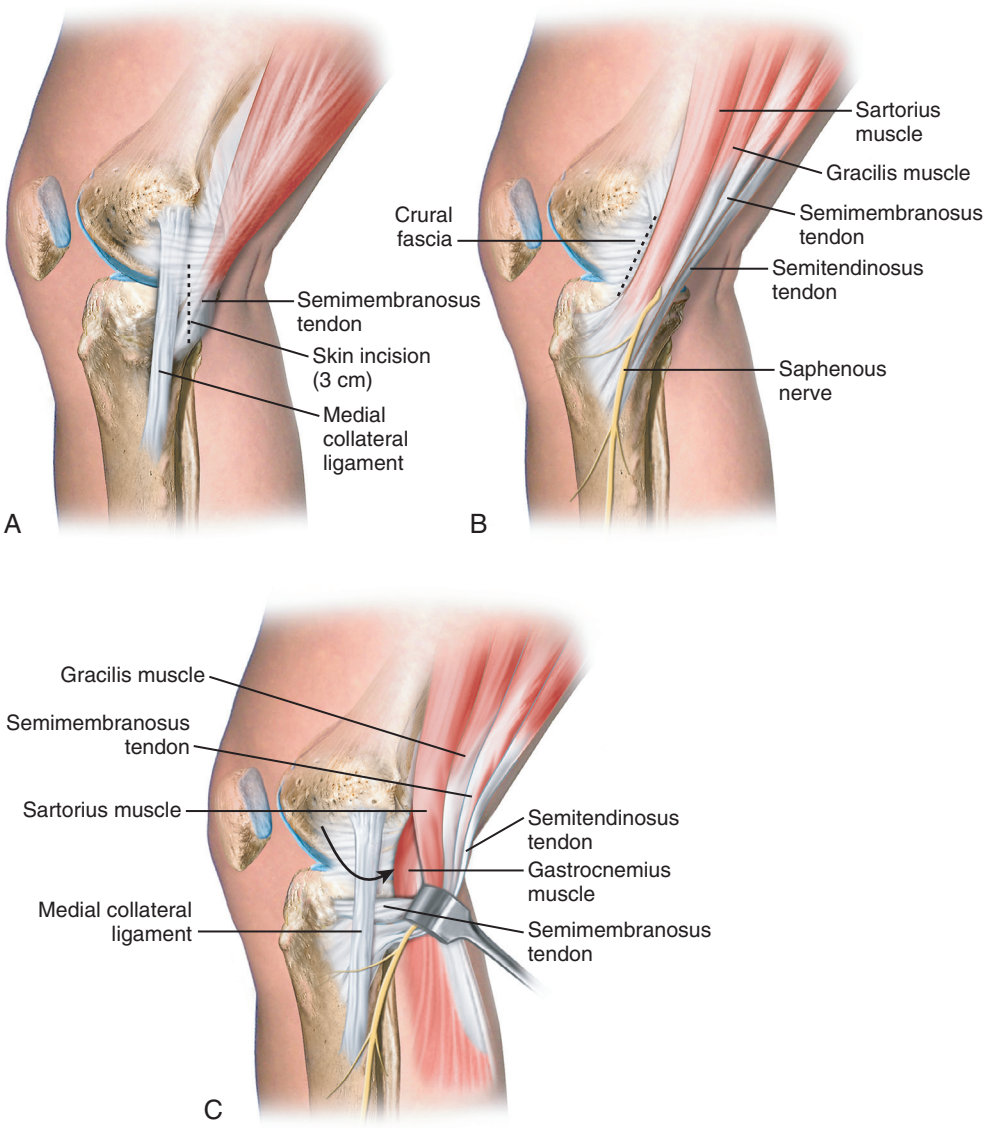


FIG 24-8 The accessory posteromedial approach is shown for a medial meniscus transplant. **A,** Site of the posteromedial skin incision. **B,** The incision is shown through the anterior portion of the sartorius fascia. **C,** The interval is opened between the posteromedial capsule and the gastrocnemius tendon, just proximal to the semimembranosus tendon (*arrow*). The fascia over the tendon is excised to its tibial attachment to facilitate retrieval of the meniscus sutures.

to the tibial slot, and no more than 2 mm of its attachment may be compromised. The final tibial slot is 8 to 9 mm in width and 10 mm in depth. A rasp is used to smooth the slot to allow insertion of the transplant central bone bridge.

In the dovetail technique, the central bone bridge of the transplant is sized to a width of 7 mm (1 mm less than the dimension at the tibial site) and a depth of 10 mm.[24] The dovetail technique requires less central bone resection and therefore is more protective of the ACL attachment.

A vertical suture is placed through the posterior meniscus horn and advanced through the capsule to exit through the posteromedial incision. The meniscus is passed through the arthrotomy into the knee with tension placed on the posterior suture to facilitate proper positioning in the knee joint. Care is taken to align the meniscus bone bridge with the recipient tibial slot. The adjustment of the central bone bridge position is performed in the anterior-to-posterior direction to fit in the anatomically correct position relative to the femoral condyle. The knee is taken through flexion, extension, and tibial rotation to align the transplant. Occasionally, there will be an osteophyte on the anterior portion of the medial tibial plateau, which must be resected to avoid meniscal transplant compression.

The fixation of the central bone bridge is accomplished with two sutures that are passed through a tunnel in the central tibial slot or with an interference absorbable screw, as already described. The anterior horn of the meniscus is sutured with vertical sutures (2-0 Ethibond) under direct visualization (Fig. 24-9). The anterior arthrotomy is closed, and the inside-out vertical divergent sutures are placed, as described, to suture the meniscus to the meniscus bed, removing any

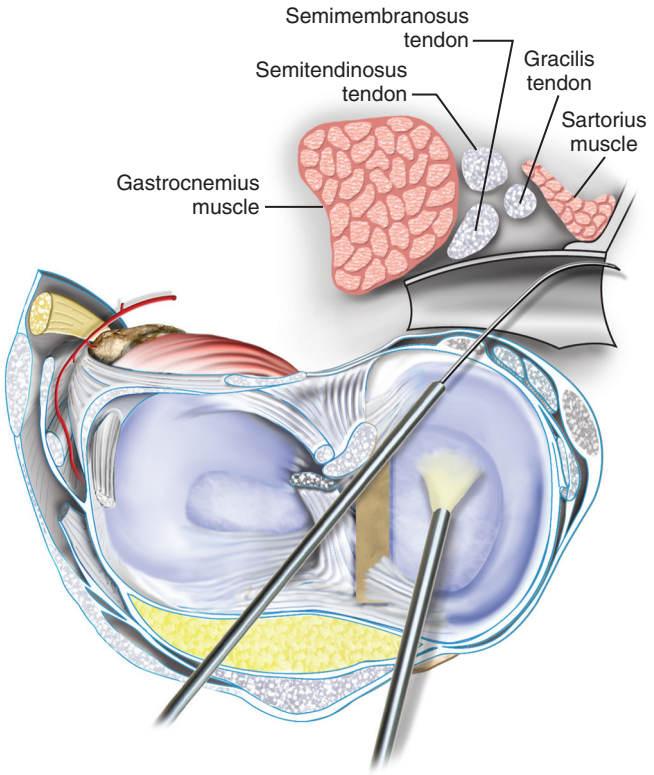


FIG 24-9 Cross-section showing the arthroscope, needle cannula, and popliteal retractor in place. The meniscus is passed through the arthrotomy into the knee with tension placed on the sutures to facilitate proper positioning in the knee joint. Using a single-barrel cannula, the suture is advanced through the capsule at the corresponding attachment site of the meniscus and exits through an accessory incision.



FIG 24-10 Weight-bearing posteroanterior radiograph of a 36-year-old woman 6 years after medial meniscus central bone bridge implantation shows incorporation of the bone bridge into the host, with preservation of the medial joint space. (From Noyes FR, Barber-Westin SD, Rankin M. Meniscal transplantation in symptomatic patients less than fifty years old. Surgical technique. *J Bone Joint Surg Am.* 2005;87(suppl 1[pt 2]):149-165.)

CRITICAL POINTS Operative Technique: Medial Meniscus Central Bone Bridge Technique

- Transplant is prepared using rectangular or dovetail technique.
- Reference slot is tibial plateau, anterior-to-posterior direction.
- ACL attachment is directly lateral to tibial slot; no more than 2 mm of its attachment may be compromised.
- Final tibial slot should be 8-9 mm wide, 10 mm deep.
- Dovetail technique: central bone bridge sized to a width of 7 mm (1 mm less than the dimension at the tibial site) and a depth of 10 mm.
- Meniscus passed through arthrotomy into knee with tension on posterior suture.
- Align meniscus bone bridge with recipient tibial slot.
- Fixation: Two sutures are passed through a tunnel in the tibial slot or an absorbable bone interference screw.
- Anterior horn is sutured with vertical sutures under direct visualization.
- Anterior arthrotomy is closed, and inside-out vertical divergent sutures are placed to suture transplant to meniscus bed.

transplant undulations and restoring circumferential meniscal tension. A final arthroscopic inspection confirms proper transplant fixation and placement. The central bone bridge of the transplant provides for fixation of the anterior and posterior portions of the transplant and subsequent healing to the host tibia (Fig. 24-10).

Medial Meniscus Two-Tunnel Technique

If it is determined that the central bone bridge technique is not acceptable, the surgeon must prepare separate anterior and posterior bone attachments for the meniscus transplant that will be secured to the normal anatomic attachment sites (Fig. 24-11). The transplant is prepared with a posterior bone plug 8 mm in diameter and 12 mm in length. Although techniques have been described that use only soft tissue fixation of the posterior horn and removal of the posterior bone attachment of the meniscus graft to allow easier graft passage, it is our opinion that this provides less secure fixation, does not adequately restore hoop tension, and leads to a higher failure rate. The anterior bone attachment is 12 mm in width, length, and depth. Two 2-0 nonabsorbable sutures are passed retrograde through each bone attachment, with two additional locking sutures placed in the meniscus adjacent to the bone attachment for secure fixation.

The anteromedial and posteromedial approaches are performed as already described. A guide pin is placed adjacent to the tibia tubercle and directed to the anatomic posterior meniscus attachment. A tibial tunnel is drilled over the guidewire to a diameter of 9 mm. The bone tunnel edges are chamfered and slightly enlarged with a curette to allow easier passage of the graft into the tibial tunnel. A limited medial femoral condyle notchplasty is usually required. At least 8 mm of opening adjacent to the PCL and medial femoral condyle is required to pass the posterior bone attachment of the graft. Rarely, a subperiosteal release of the long fibers of the tibial attachment of the distal medial collateral ligament (MCL) (with later suture anchor repair) is required to sufficiently open the medial tibiofemoral joint. This

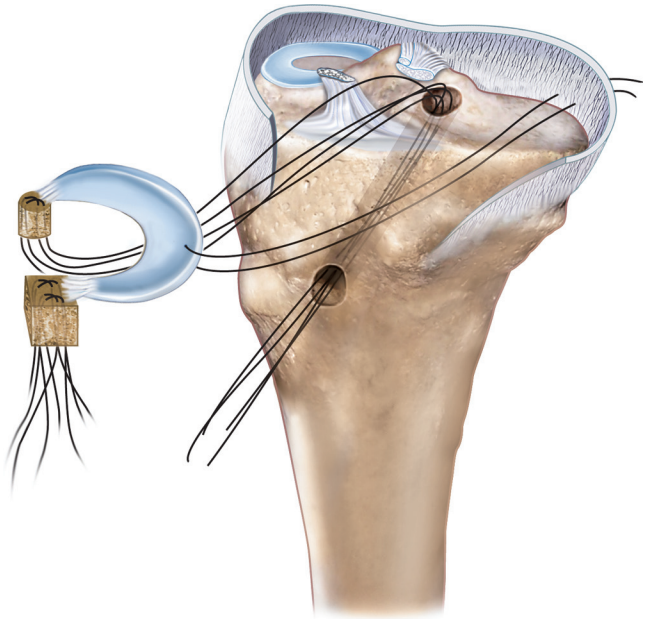


FIG 24-11 Two-tunnel technique for medial meniscus transplantation. The illustration shows insertion of transplant, including the posteromedial suture placed to facilitate meniscus reduction. The anterior and posterior bone attachments of the medial meniscus transplant are fixed into separate tibial tunnels.

technique is preferred over "pie crust" techniques to weaken the MCL because MCL repair restores normal tension.

The graft is passed through the anteromedial arthrotomy. The surgeon is seated with a headlight in place, and the knee is flexed to 90 degrees. A guidewire is passed retrograde through the tibial tunnel, and the sutures attached to the posterior bone are retrieved. A second suture is placed into the posterior horn and is passed inside out through the posteromedial approach to guide the meniscus.

The knee is flexed to 20 degrees under a maximum valgus load to pass the posterior bone plug with the meniscus body suture held by an assistant. A nerve hook or blunt instrument is used to gently assist the passage of the graft. With direct visualization, it is possible to confirm appropriate meniscus graft passage and positioning into the medial tibiofemoral compartment. Care is taken not to advance the posterior meniscus body into the tibial tunnel but only to seat the bone portion of the graft to not shorten the overall circumferential length of the meniscus graft.

The posterior meniscus bone attachment sutures are tied over the tibial post to provide tension to the posterior bone attachment. One or two sutures are passed to secure the posterior horn. The knee is flexed and extended to assess meniscus fit and displacement. The optimal location for the anterior meniscal bone attachment is identified to restore proper meniscus position and prevent medial transplant overhang. In the majority of cases, this should be at the anterior anatomic attachment. The knee is placed in full extension, and correct positioning of the transplant is verified.

A 12-mm rectangular bone attachment is fashioned in the tibia to correspond to the anterior bone attachment of the meniscus graft. A 4-mm bone tunnel is placed at the base of this bone slot and exits at the anterior tibia just proximal to the posterior bone tunnel. The sutures are passed through the bone tunnel, and the anterior horn is seated. Full knee flexion and extension are again performed to determine proper graft placement and fit. Tension is applied to the anterior bone sutures, which are not tied at this point but are used to maintain tension in the graft during the inside-out suture repair. This meticulous seating of the meniscus transplant under circumferential tension with bone attachment of both the anterior and posterior horns is believed to be crucial for meniscus weight-bearing position and function.

The anterior arthrotomy is closed and the arthroscope placed in the anteromedial portal. The suture cannula is then inserted into the anterolateral portal for the meniscal repair. The meniscal repair is performed in an inside-out fashion, starting with the posterior horn, with use of multiple vertical divergent sutures of 2-0 nonabsorbable material both superiorly and inferiorly, constantly tensioning the meniscus from posterior-to-anterior to establish circumferential tension. The assistant is seated with a headlight and retrieves the suture needles through the posteromedial approach. Each suture is placed and tied, bringing the meniscus directly to the meniscus bed with observation that correct meniscus placement, fixation, and tension exist. The fixation technique requires a meticulous approach and time to avoid medial meniscus extrusion that has been frequently reported in MRI studies as previously discussed.

Alternative techniques such as all-inside meniscus suture devices are not recommended because these devices lessen the ability to precisely secure and restore tension to the meniscus transplant. The anterior arthrotomy is opened, and final tensioning and fixation of the anterior horn bone attachment is performed. Additional sutures are

CRITICAL POINTS Operative Technique: Medial Meniscus Two-Tunnel Technique

- Transplant is prepared with posterior bone plug 8 mm in diameter, 12 mm in length, anterior bone attachment 12 mm in width, length, depth.
- Approaches are performed, guide pin is placed adjacent to tibia tubercle and directed to anatomic posterior meniscus attachment.
- Tibial tunnel is drilled over guidewire to diameter of 9 mm.
- ≥8 mm opening adjacent to posterior cruciate ligament and medial femoral condyle is required to pass graft posterior bone attachment.
- Graft is passed through anteromedial arthrotomy.
- Knee is flexed 20 degrees under maximum valgus load to pass posterior bone plug. Do not advance the posterior meniscus body into the tibial tunnel; this will shorten the overall circumferential length of the graft.
- Posterior meniscus bone attachment sutures are tied over tibial post to provide tension to posterior bone attachment.
- Knee is flexed and extended to assess meniscus fit and displacement.
- Knee is placed in full extension, and position of transplant is verified to be correct.
- 12-mm rectangular bone attachment is fashioned in tibia to correspond to anterior bone attachment of graft.
- 4-mm bone tunnel is placed at base of anterior tibia proximal to posterior bone tunnel.
- Tension is applied to anterior bone meniscus sutures during inside-out suture repair.
- Anterior arthrotomy is closed, and suture cannula is inserted into lateral portal for meniscal repair.
- Meniscal repair is performed inside out, starting with posterior horn, using multiple vertical divergent sutures. Each suture is placed and tied to bring meniscus directly to meniscus bed.
- Observe correct meniscus placement, fixation, and tension.
- Anterior arthrotomy opened, final tensioning, and fixation of anterior horn bone attachment.
- All-inside suture devices are not recommended.

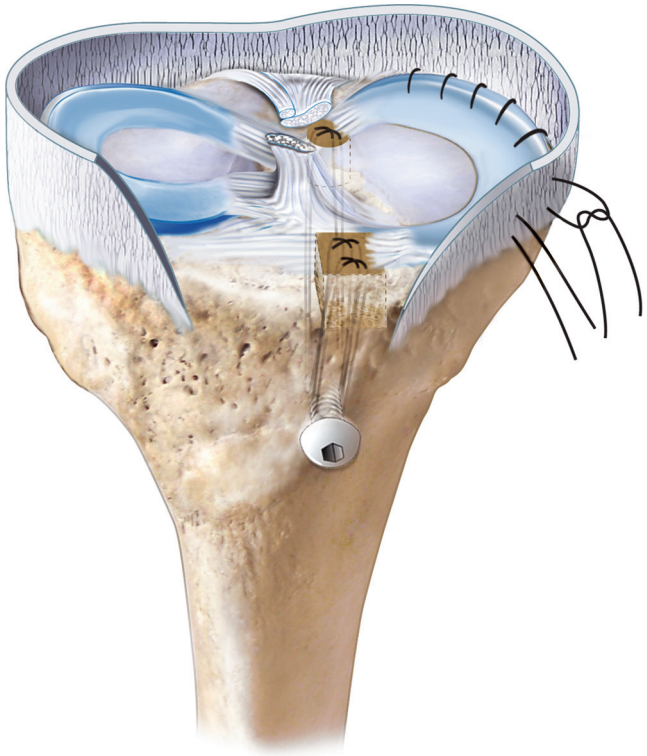


FIG 24-12 Final anterior and posterior tunnel fixation appearance of medial meniscus transplant and vertical divergent sutures.

required to secure the most anterior third of the meniscus to the capsular attachments, which is performed under direct vision (Fig. 24-12). An alternative method of fixation is to use a 3.5-mm cancellous screw with a washer for fixation of the anterior horn meniscus-bone attachment. After final inspection of the graft with knee flexion, extension, and tibial rotation, the operative wounds are closed in a routine fashion.

OUR CLINICAL STUDIES

Clinical Outcomes: Initial Studies

The clinical outcome of 40 consecutive cryopreserved and 96 fresh-frozen irradiated MMTs and LMTs were previously described in detail.[61,64,65,76] A 100% follow-up was obtained in these prospective studies.

Forty cryopreserved meniscus transplants were implanted into 38 patients from November 1995 to March 2000.[65] Four of the meniscus transplants failed and were removed before the minimum 2-year follow-up study period; these cases were included in the overall failure rate. Thirty-five patients were followed (36 meniscus transplants; 18 lateral, 16 medial, one bilateral) a mean of 3.3 years (range, 2-5.7 years) postoperatively. There were 18 males and 17 females whose mean age at surgery was 30 years (range, 14-49 years).

A mean of 11.6 years (range, 1-31 years) had elapsed between the knee injury and the meniscus transplant. A total of 128 prior operative procedures had been done, including 61 partial or total meniscectomies, 13 ACL reconstructions, 4 PCL reconstructions, 1 FCL reconstruction, 5 high tibial osteotomies (HTOs), and 3 osteochondral autograft transfer procedures.

At the time of the LMT, a concurrent osteochondral autograft transfer of the lateral femoral condyle was done in 13 knees for full-thickness articular cartilage defects. Knee ligament reconstructions were done before the meniscus transplant in four knees and at the same time as the transplant in another four knees. In six knees, ACL reconstructions were done using either bone-patellar tendon-bone (B-PT-B) or semitendinosus-gracilis autografts. A PCL two-strand quadriceps tendon autograft reconstruction[60] was done in one knee, and both the PCL and ACL were reconstructed in another knee.

Abnormal articular cartilage surfaces (lesion >15 mm in diameter with fissuring and fragmentation extending greater than half of the depth of the cartilage or subchondral bone exposed) were detected in the meniscectomized tibiofemoral compartment in 31 knees (88%) at the time of meniscus transplantation. Subchondral bone exposure was found in 18 knees, and extensive fissuring and fragmentation were noted in 13 others.

The subjective and functional results were assessed with the CKRS. A classification system of meniscus transplant characteristics was developed on the basis of MRI, clinical examination, follow-up arthroscopy (when performed), and tibiofemoral symptoms (Table 24-1). The International Knee Documentations Committee (IKDC) classification system was used to determine knee ligament graft function.

Before surgery, 27 patients (77%) had moderate to severe pain with daily activities, but at follow-up, only two (6%) had pain with daily activities (Fig. 24-13, $P < .0001$). All patients had pain in the meniscectomized tibiofemoral compartment preoperatively, but at follow-up, only 10 (29%) had some component of tibiofemoral pain.

CRITICAL POINTS Our Clinical Studies: Clinical Outcomes Initial Studies

- $n = 40$ cryopreserved meniscus transplants in 38 patients followed a mean 3.3 yr (range, 2-5.7 yr).
- Average 11.4 yr from knee injury to transplant
- Concurrent osteochondral autograft transfer done in 13 knees.
- Staged or concurrent cruciate reconstructions done in 8 knees: 6 ACL, 1 PCL, 1 ACL + PCL.
- 88% knees had abnormal articular cartilage surfaces.
- 73% meniscus transplants assessed with MRI 12-67 mo postoperative.
- Meniscus transplant characteristics determined with classification system: MRI, clinical examination, follow-up arthroscopy (when performed).
- Pain with daily activities: 77% before surgery, 6% at follow-up.
- Pain in meniscectomized tibiofemoral compartment: 100% before surgery, 29% at follow-up.
  - Pain at follow-up rated as light by majority.
- 94% patients believed knee condition improved by operation.
- Sports without problems: 3% before surgery, 77% at follow-up (mostly low-impact activities).
- Reoperation rate for meniscus transplant symptoms: 25%.
- Meniscus transplant characteristics: 42.5% normal, 30% altered, 27.5% failed.
- Correlation between arthrosis rating on MRI and the transplant characteristics ($P = .01$).
  - 16 transplants in knees with mild arthrosis: 10 normal characteristics, 6 altered characteristics.
  - 12 transplants in knees with moderate arthrosis: 3 normal characteristics, 4 altered characteristics, 5 failed.
- $n = 96$ irradiated meniscus transplants, 82 patients, historical study. Correlation MRI arthrosis rating and transplant failure rate.
  - No/mild arthrosis: 6%
  - Moderate arthrosis: 45%
  - Advanced arthrosis: 80%

TABLE 24-1 Meniscus Allograft Classification

MAGNETIC RESONANCE IMAGING EVALUATION (*N* = 29)				CLINICAL EXAMINATION: TIBIOFEMORAL (*N* = 39)		FOLLOW-UP ARTHROSCOPY (*N* =13)
Allograft Classification	**Peripheral Attachment**	**Position in Joint***	**Signal Intensity**	**Meniscus Signs**	**Pain, Clinical Symptoms**	**Meniscus Tears**
Normal	Healed	Normal (0%-25% of meniscus width)	None	None	None	None
Altered		Displacement (26%-50% of meniscus width)		Grades 1, 2	Mild pain, improved over preoperative	Partial meniscectomy (<1/3; removed)
Failed	Not healed	Major displacement (>50% of meniscus width)	Grade 3 (tearing, signal intensity extended to articular surface)	Obvious signs of meniscus tear	Definite pain, not improved over preoperative	Partial or total meniscectomy (>1/3; removed)

One abnormal result was considered failed.
*Coronal and sagittal planes, percentage of displacement of posterior or medial plateau margin perpendicular to the joint line.

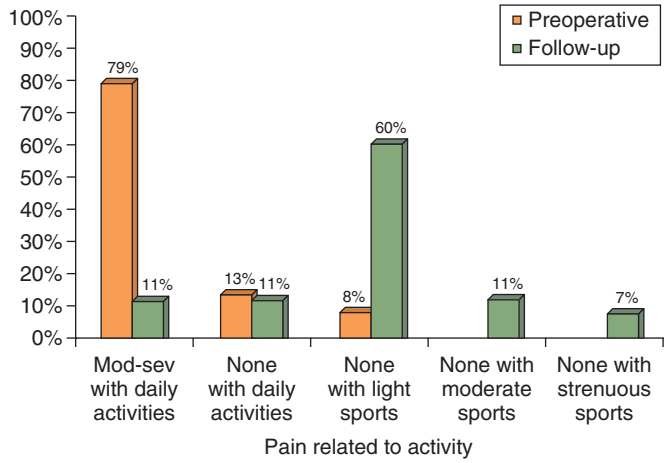


FIG 24-13 The pain scale shows the highest level of activity possible without the patient experiencing knee pain. The difference between preoperative and follow-up was statistically significant ($P < .0001$). *Mod-sev,* moderate to severe. (From Noyes FR, Barber-Westin SD, Rankin M. Meniscus transplantation in symptomatic patients under fifty years of age. *J Bone Joint Surg Am.* 2004;68:1392-1404.)

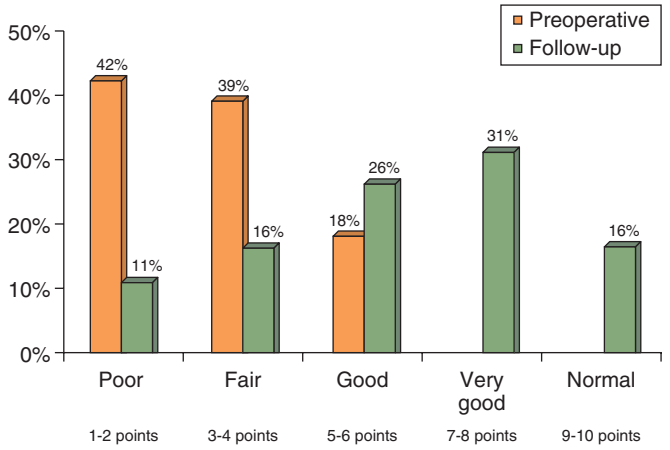


FIG 24-14 Distribution of patient perception of the overall knee condition. The difference between preoperative and follow-up was statistically significant ($P < .0001$). (From Noyes FR, Barber-Westin SD, Rankin M. Meniscus transplantation in symptomatic patients under fifty years of age. *J Bone Joint Surg Am.* 2004;68:1392-404.)

Thirty-three of 35 (94%) patients stated their knee condition had improved on self-assessment ratings (Fig. 24-14). The mean preoperative patient perception score (scale, 1-10) of 3.1 points (range, 1-6 points) improved to a mean of 6.2 points (range, 1-9 points) at follow-up (Table 24-2, $P < .0001$). Preoperatively, only 1 patient was able to participate in sports without problems. At follow-up, 27 patients (77%) were participating in light, low-impact sports without problems, and 1 patient was participating with symptoms against advice (Table 24-3).

Before the operation, 15 patients had symptoms and limitations during work activities (Table 24-4), but at follow-up, only 2 patients continued to have problems related to the knee condition at work.

One patient had signs of a meniscus transplant tear at follow-up. One patient had tibiofemoral joint line pain and increased palpable crepitation compared with the preoperative examination. All patients had a normal range of knee motion.

All knees that had an ACL reconstruction had normal or nearly normal anterior stability restored except one in which the reconstruction failed. The PCL reconstructions restored nearly normal function in both knees at 20 and 90 degrees of flexion, except for one knee in which partial function was restored at 90 degrees of flexion.

Five patients had follow-up arthroscopy for symptoms related to the transplant. In three patients, tears in the periphery of the meniscus transplant at the capsular junction were successfully repaired. In two patients, small tears in the transplant were resected. None of these patients had further complaints. One other patient had a total knee replacement 35 months after the meniscus transplant for unresolved knee pain. With the six patients described above, and the four meniscus transplants that required early postoperative removal, the reoperation rate for meniscal transplant symptoms was 25% (10 of 40 meniscus transplants).

Seventeen of the meniscus transplants (42.5%) had normal characteristics, 12 (30%) had altered characteristics, and 11 (27.5%) failed.

TABLE 24-2 Pain and Function Scores Before and After Meniscal Transplantation

Factor/Scale	Preoperative*	Follow-up*	*P* Value†
Scale, 0-10 points			
Pain	2.5 ± 1.4	5.8 ± 2.2	.0001
Swelling	3.7 ± 2.6	5.8 ± 2.0	.0003
Full giving-way	5.8 ± 2.8	6.4 ± 2.0	NS
Scale, 1-10 points			
Patient perception	3.2 ± 1.3	6.2 ± 2.1	.0001
Scale, 0-40 points			
Walking	29 ± 9	37 ± 10	.0008
Stair climbing	24 ± 12	30 ± 14	.008
Squatting	10 ± 14	17 ± 16	.04
Scale, 40-100 points			
Running	44 ± 9	57 ± 22	.0001
Jumping	43 ± 7	51 ± 20	.01
Twisting/turning	43 ± 8	52 ± 19	.008

*Values shown are mean ± standard deviation.
†Paired *t* test between preoperative and follow-up data.
NS, Not significant.

TABLE 24-3 Sports Activity Levels of Patients Before and After Meniscal Transplantation

Type of Sport	Preoperative (*n*)	Follow-up (*n*)
Jumping, hard pivoting, cutting	0	1
Running, twisting, turning	0	4
Swimming, bicycling	7	24
None	31	9
Change in Sports Activities		
Increased level, no symptoms	0	25
Same level, no symptoms	0	2
Decreased level, no symptoms	1	1
Playing with symptoms	6	1
No sports, knee-related reasons	31	8
No sports, non–knee-related reasons	0	1

TABLE 24-4 Occupational Levels of Patients Before and After Meniscal Transplantation

Occupational Level	Preoperative (*n*)	Follow-up (*n*)
Disabled	5	3
Very light or light	12	21
Moderate	2	1
Heavy or very heavy	4	5
Student or homemaker	15	8
Change in occupational level		
Increased level, no symptoms	0	5
Same level, no symptoms	2	15
Decreased level, no symptoms	1	5
Working with symptoms	15	2
No work, knee-related reasons	5	3
No work, non–knee-related reasons	15	8

Of the 20 LMTs, nine had normal characteristics, seven had altered characteristics, and four failed. Of the 20 MMTs, eight had normal characteristics, five had altered characteristics, and seven failed. There was a correlation between the arthritis rating on MRI and the transplant characteristics ($P = .01$). Of the 16 transplants in knees with mild arthritis, 10 had normal characteristics and six had altered characteristics. Of the 12 transplants in knees with moderate arthritis, three had normal characteristics, four had altered characteristics, and five failed.

The results of 96 consecutive irradiated meniscus transplants implanted into 82 patients were previously described.[64] Twenty-eight menisci in 27 patients required early arthroscopic resection owing to lack of meniscal healing a mean of 10 months (range, 2-20 months) postoperatively. These 28 menisci were included in the overall failure rate. In addition, 1 patient died of causes unrelated to the knee condition before the 2-year follow-up. This left 67 menisci (57 medial, 10 lateral) in 62 patients (63 knees) who all returned for follow-up a mean of 3.6 postoperative years (range, 1-9.2 years).

The patients were divided into three groups for analysis of the meniscus transplant. Group 1 had normal to mild articular cartilage arthritis on MRI, group 2 had moderate arthritis, and group 3 had severe arthritis. The meniscus transplant failure rates were 6% (1 of 18 knees) in knees with normal or only mild arthritis on MRI, 45% (14 of 31 knees) in knees with moderate arthritis, and 80% (12 of 15 knees) in knees with advanced arthritis (Fig. 24-15). The relationship between the meniscus transplant failure rate and increasing severity of joint arthritis was significant ($P < .001$).

Histologic evaluations were conducted by independent examiners on the 28 meniscus allografts with early postoperative failure. Nine specimens (five medial, four lateral) that included the peripheral meniscal–capsular junction and an intact meniscal body were critically analyzed (Fig. 24-16). These allografts had been removed a mean of 11 months (range, 2-21 months) postoperatively, and the tibiofemoral and inner-outer orientations were easily identifiable. There was no evidence of a cellular reaction suggestive of a rejection phenomenon in any of the tissues examined. The specimens consistently demonstrated minimal, if any, cellular repopulation of the femoral and tibial surfaces or central core of the meniscus (Fig. 24-17, *A* and *B*). The predominant cell type was a fibrocyte (Fig. 24-17, *C*). Remodeling with abnormal collagen orientation was found in 6 specimens. The remodeling phenomenon resulted in a loss of the normal surface radial collagen architecture and a loss of the normal circumferential fibers within the meniscal substance (see Fig. 24-17, *D*).

The role of low-dose irradiation (2.0-2.5 mrad) in terms of increasing the failure rate of meniscus allografts is not scientifically known. From a historic standpoint, this study provided needed information on patient selection criteria for meniscus transplants. Patients with advanced arthritis, alterations in joint geometry (major tibial

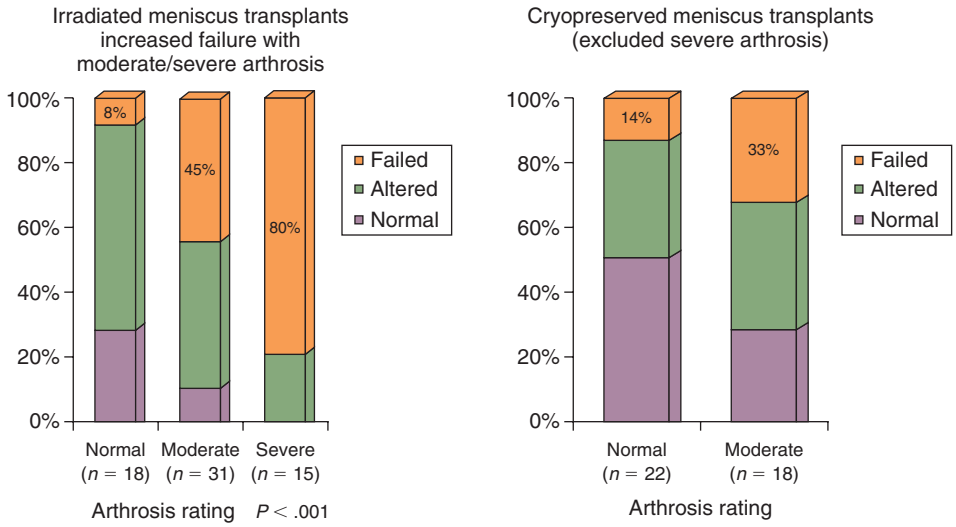


FIG 24-15 Distribution of meniscus transplants rated on magnetic resonance imaging as normal, altered, and failed for our clinical investigations.

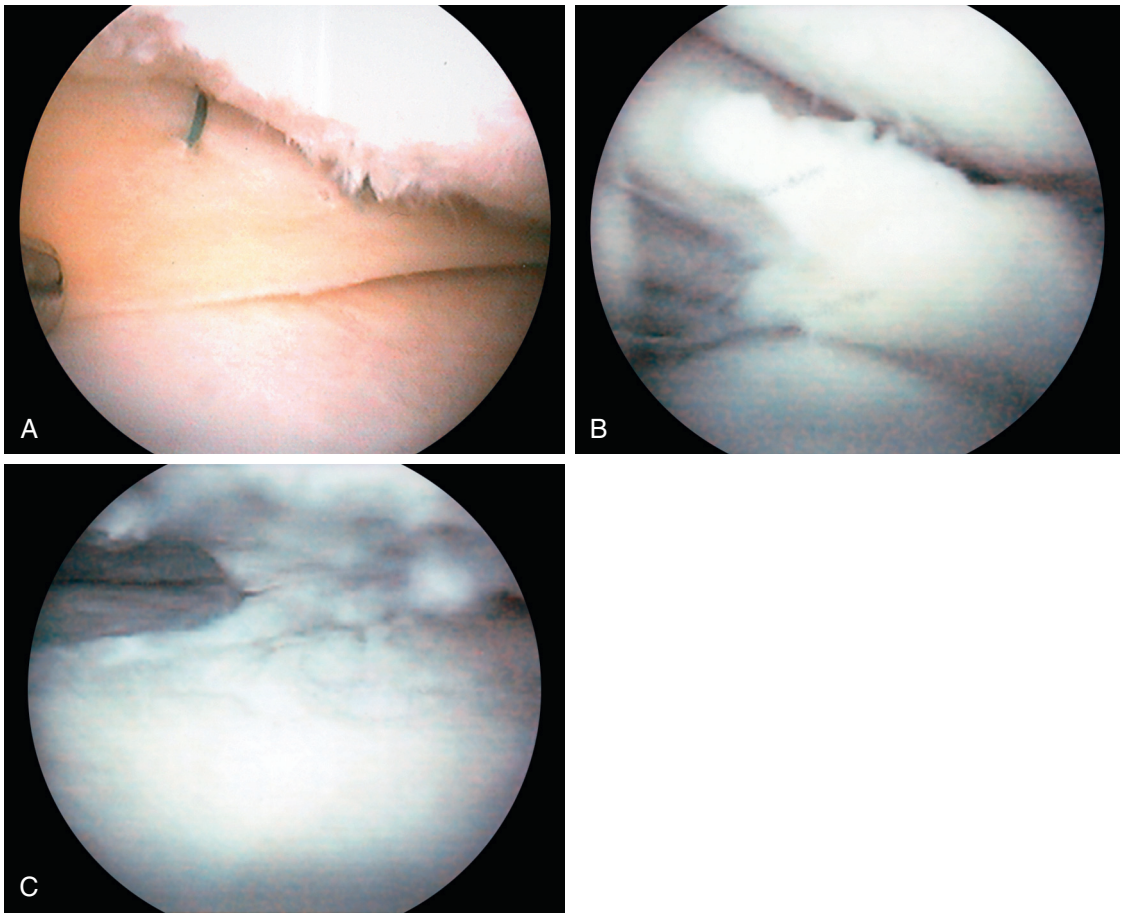


FIG 24-16 **A,** Irradiated medial meniscus-bone transplant upon initial implantation. **B** and **C,** At follow-up arthroscopy 7 months later, the medial meniscus transplant had torn and failed and was removed. This case was included in the histologic assessment of failed meniscus transplants.

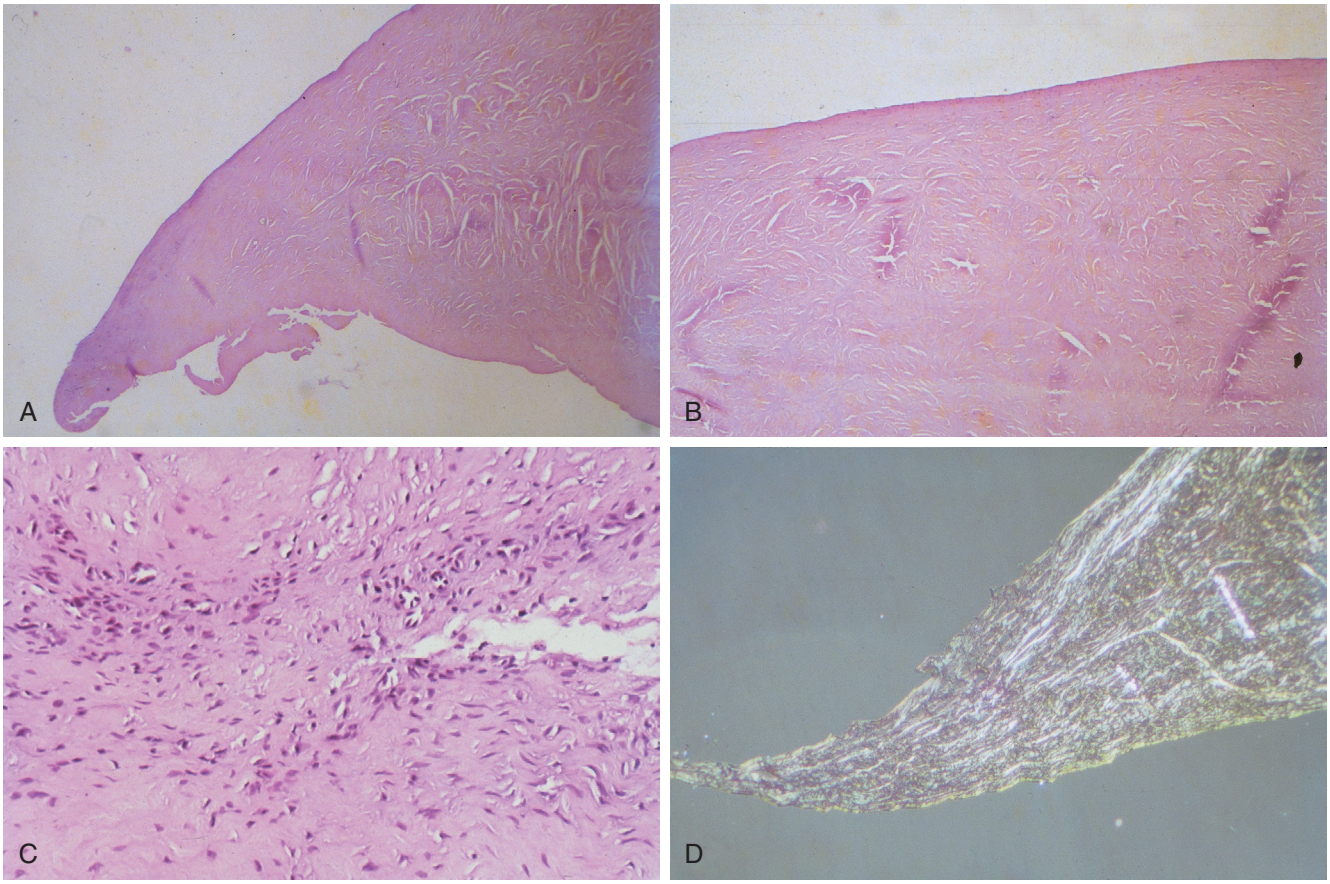


FIG 24-17 Coronal section of a meniscus allograft 17 months after implantation. Photomicrographs show incomplete repopulation of the femoral surface (**A,** ×40) and the remaining tissue acellular (**B,** ×40), with some cells resembling fibrochondrocytes (**C,** ×200). **D,** Polarized light micrograph shows fibers aligned parallel to the surface, with poorly organized collagen fibers at the remodeling site. There is a loss of normal radial and circumferential collagen orientation in the body of the allograft, which has not undergone remodeling (×4).

concavity, femoral condyle flattening) with exposed bone surfaces over the majority of the tibiofemoral compartment are not candidates for meniscus transplantation.

Magnetic Resonance Imaging Analysis: Meniscus Transplant Characteristics

A total of 29 cryopreserved meniscus transplants (73%) were analyzed with MRI using the research protocol previously described in detail[65,76] an average of 2.9 years (range, 1-5.5 years) postoperatively. The films were reviewed and measured by independent orthopedic surgeons blinded to patient information. The height, width, and displacement of the transplants were determined during full or partial weight-bearing conditions.

The mean displacement of the 29 meniscus transplants was 2.2 ± 1.5 mm (range, 0-5 mm) in the coronal plane (Table 24-5). Seventeen transplants (59%) had no displacement, 11 had minor displacement, and 1 could not be evaluated. In the sagittal plane, the mean displacement of the posterior horn of the transplants was 1.1 ± 2.0 mm (range, 0-9 mm). Twenty-five transplants (86%) had no displacement of the posterior horn, 3 had minor displacement, and 1 had major displacement (9 mm). The mean displacement of the anterior horn of the transplants was 1.2 ± 1.7 mm (range, 0-6 mm). Twenty-five transplants had no displacement of the anterior horn, three had minor displacement, and one had major displacement (6 mm). Intrameniscal signal intensity was normal in 1, grade 1 in 13, grade 2 in 11, grade 3 in 3, and could not be evaluated in one case.

TABLE 24-5 Results of Magnetic Resonance Imaging Studies of 29 Meniscus Allografts

Structure	Imaging Plane	Height (mm)	Width (mm)	Displacement (mm)
Posterior horn	Sagittal	7.7 ± 1.9	10.4 ± 2.6	1.1 ± 2.0
Anterior horn	Sagittal	7.1 ± 1.4	10.1 ± 1.8	1.2 ± 1.7
Allograft midbody	Coronal	7.8 ± 1.9	11.7 ± 3.7	2.2 ± 1.5

Data are mean ± standard deviation.

A subset of eight meniscus transplants in 7 knees were studied 1.2 to 2.8 years postoperatively[76] in an open configuration Signa SP MRI System (General Electric Medical Systems). This system is a 0.5-T superconducting magnet in which the windings are located in separate but communicating cryostats. The vertical orientation of the scanner allows the patient to stand between the cryostats with the knee at the isocenter (Fig. 24-18). Single-slice sagittal and coronal images were obtained on both knees at 0, 30, 60, and 90 degrees of knee flexion.

TABLE 24-6 Height and Width Measurements of Eight Meniscus Allografts and Native Menisci in the Sagittal Plane

	HEIGHT (MM)				WIDTH (MM)			
	POSTERIOR HORN		ANTERIOR HORN		POSTERIOR HORN		ANTERIOR HORN	
Knee Flexion Angle	Allograft	Native	Allograft	Native	Allograft	Native	Allograft	Native
0 degrees	8 ± 3	9 ± 3	7 ± 1	6 ± 1	14 ± 3	15 ± 2	12 ± 3	13 ± 2
30 degrees	8 ± 2	7 ± 2	8 ± 1	6 ± 1	15 ± 1	15 ± 2	14 ± 4	14 ± 1
60 degrees	8 ± 1	7 ± 1	8 ± 1	7 ± 1	14 ± 2	15 ± 2	15 ± 3	14 ± 2
90 degrees	8 ± 1	8 ± 1	7 ± 2	8 ± 2	14 ± 3	15 ± 1	14 ± 4	14 ± 2
Change from 0-90 degrees	0.4 ± 2.1	0.4 ± 3.6	0.5 ± 1.5	2 ± 2	0 ± 3	–0.5 ± 1.9	1.9 ± 3.4	1.3 ± 2.7

CRITICAL POINTS Our Clinicl Studies: MRI Analysis Meniscus Transplant Characteristics

- *n* = 29 transplants analyzed MRI mean of 2.9 yr (range, 1-5.5 yr) under full or partial weight-bearing conditions
- Films reviewed and measured by independent orthopedic surgeons blinded to patient information
- Mean meniscus extrusion
  - Meniscus body: 2.2 ± 1.5 mm (range, 0-5 mm).
  - Posterior horn: 1.1 ± 2.0 mm (range, 0-9 mm).
  - Anterior horn: 1.2 ± 1.7 mm (range, 0-6 mm).
  - 1 transplant major extrusion (9 mm)
- Signal intensity
  - Normal: 1
  - Grade 1: 13
  - Grade 2: 11
  - Grade 3: 3
  - Could not be evaluated: 1
- *n* = 8 transplants full-standing, sagittal and coronal images of both knees at 0, 30, 60, and 90 degrees of flexion
  - Mean height, width of anterior and posterior horns of the transplants similar to native menisci
  - Extrusion similar to native menisci
  - Anterior horn native menisci moved mean 5 mm more anterior to posterior



FIG 24-18 An open configuration 0.5-T superconducting magnet. The vertical orientation of the scanner allows the patients to stand and images to be taken under full weight-bearing conditions. (From Rankin M, Noyes FR, Barber-Westin SD, et al. Human meniscus allografts in-vivo size and motion characteristics: Magnetic resonance imaging assessment under weightbearing conditions. *Am J Sports Med.* 2006;34:98-107.)

In this subgroup, the mean height and width of the anterior and posterior horns of the transplants were similar to those of native menisci (Table 24-6). The millimeters of coronal displacement of motion of the midbody was also similar between the transplants and native menisci. The anterior horn of the native medial menisci moved an average of 5 mm more (total anterior-to-posterior translation, $P < .05$) than the transplants. The posterior horn of the native medial menisci and both horns of the native lateral menisci also tended to move more than the corresponding horns of the transplanted menisci (Fig. 24-19), although this could not be confirmed statistically, given the number of menisci studied.

We are currently studying the outcome of fresh-frozen meniscus transplants and will compare the results with those historically obtained to evaluate the effect of chemical and irradiation processing as just described. The rigorous evaluation matches that conducted previously and includes preoperative and serial postoperative MRI, yearly clinical evaluations and standing PA radiographs, and completion of IKDC and CKRS forms.

Clinical Outcomes: Long-Term Study

We evaluated the long-term outcomes and determined survivorship rates for the cohort of 40 knees that underwent cryopreserved meniscus transplantation.[62] All patients in whom the meniscus transplant had initially survived from the first study and had not undergone a subsequent procedure related to the transplant were contacted to return for a follow-up evaluation. The long-term evaluations began when the patients were at a minimum of 10 years after surgery. Eleven of 40 meniscus transplants failed in the initial study. Subsequently, 11 other transplants failed and required reoperations. This left 18 transplants in 18 patients who completed a long-term evaluation a mean of 14.1 years after surgery (range, 10.3-17.3 years).

Kaplan-Meier survivorship analysis was performed to estimate time-defined probabilities for survival of all 40 meniscus transplants at 5, 7, 10, 13, and 15 years postoperatively. Two survivorship analyses were performed. The first used transplant removal or replacement,

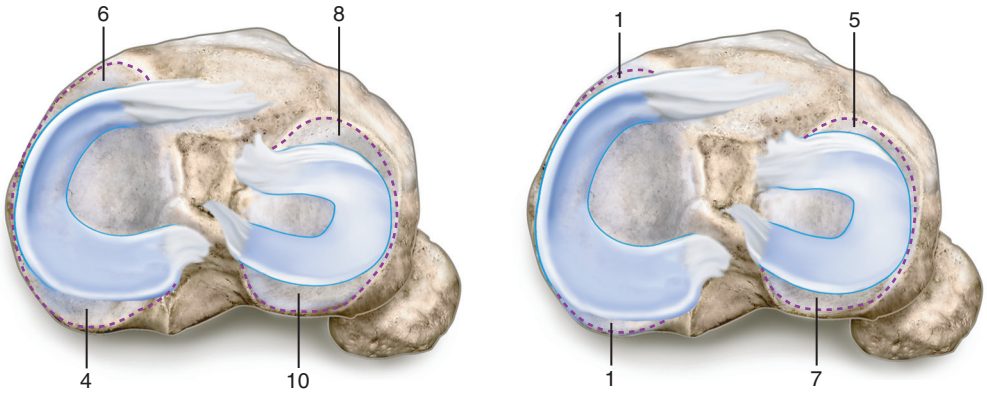


FIG 24-19 Illustrations in the axial plane of the native and transplanted menisci approximating the pattern of meniscal displacement from full extension to 90 degrees of flexion (*dashed lines*; not to scale). (From Rankin M, Noyes FR, Barber-Westin SD, et al. Human meniscus allografts' in-vivo size and motion characteristics: Magnetic resonance imaging assessment under weightbearing conditions. *Am J Sports Med* 2006;34:98-107.)

CRITICAL POINTS Our Clinical Studies: Clinical Outcomes Long-Term Study

- Survival rates determined for 40 cryopreserved meniscus transplants.
- Of initial cohort, 18 knees that had not failed completed long-term evaluation a mean of 14.1 yr (range, 10.3-17.3 yr) postoperatively.
- Endpoints: transplant removal or replacement, revision (total or unicompartmental knee replacement or osteotomy), or pain with daily activities in the involved tibiofemoral compartment.
  - 88% at 5 years, 80% at 7 years, 65% at 10 years, 43% at 15 years
- Worst-case scenario: additional endpoints grade 3 signal intensity or major extrusion (>50% of meniscal width) on MRI, signs of meniscal tear on clinical examination, or complete loss of joint space in the involved tibiofemoral compartment on 45-degree weight-bearing posteroanterior radiographs.
  - 73% at 5 years, 68% at 7 years, 48% at 10 years, 20% at 10 years.

revision (total or unicompartmental knee replacement or osteotomy), or pain with daily activities in the involved tibiofemoral compartment as end points. A worse-case scenario was used in the second analysis where, in patients who did not demonstrate symptoms directly related to the meniscus transplant, additional end points were grade 3 signal intensity or major extrusion (>50% of meniscal width) on MRI signs of meniscal tear on clinical examination, or complete loss of joint space in the involved tibiofemoral compartment on 45-degree weight-bearing PA radiographs. No patients were lost to follow-up, and no transplants were censored.

Statistically significant improvements were detected for pain, swelling, patient perception of knee condition, walking, and stair climbing. Although 72% of the 18 patients had moderate or severe pain with daily activities before the operation, only 11% were continuing to experience such pain at follow-up. Seventy-two percent could participate in sports without pain, although the majority was participating in low-impact athletics only. All regained at least 0 to 135 degrees of knee motion, and none had a knee effusion.

The survivorship analysis revealed an estimated probability of transplant survival of 88% at 5 years (95% confidence intervals [CI], 72%-95%), 80% at 7 years (95% CI, 64%-90%), 65% at 10 years (CI, 48%-79%), and 43% at 15 years (CI, 27%-59%). The worse-case scenario revealed estimated probability of transplant survival of 73% at 5 years (95% CI, 56%-85%), 68% at 7 years (95% CI, 51%-81%), 48% at 10 years (CI, 32%-64%), and 20% at 15 years (CI, 10%-36%). The mean postoperative time at which failures were noted was 7.8 years for medial and lateral transplants.

The 10-year survival probability of 48% is similar to that described by Hommen and associates[36] (45%), who also used multiple endpoints for failure (Lysholm score <65 points, no improvement in the pain score, and grade III signal on MRI). A survival analysis of 63 consecutive cryopreserved meniscal transplants was conducted by van Arkel and de Boer[94] and used persistent pain, a poor Lysholm score, a poor Knee Assessment Scoring System result, or a detached transplant as end points. The cumulative 10-year survival rates of lateral, medial and combined transplants in the same knee were 76%, 50%, and 67%, respectively.

Meniscus Transplant Extrusion

We conducted a systematic review of the medical literature to determine the incidence and clinical significance of postoperative meniscus transplant extrusion.[63] A systematic electronic search was performed using PubMed and Cochrane databases. Inclusionary criteria were English language, clinical trials published from 1984 to 2014, meniscus extrusion measured on MRI, and all evidence levels. The search initially identified 192 original research articles, of which 23 met the inclusionary criteria.* A total of 803 patients underwent 814 meniscus transplants. The MRIs were obtained from 2 days to 10 years postoperatively. The majority of studies used the radiographic method described by Pollard et al[71] to obtain transplant size measurements. Eighteen studies used fresh-frozen meniscus transplants implanted with bone (n = 612) or with suture fixation (n = 116), four studies used cryopreserved transplants, and one used irradiated transplants (Table 24-7).

Twenty-one investigations obtained the MRIs in the supine, non-weight-bearing position. Two studies conducted the scans under partially loaded (50% weight bearing)[65] or fully loaded (100% weight bearing)[76] conditions. Three measurements were used to assess extrusion, and variability was found in each, including absolute millimeters

*References 1, 16, 19, 28, 30, 31, 38, 43-45, 49-51, 65, 74, 76, 89, 95, 100, 102, 108, 111, 112.

TABLE 24-7 Postoperative Extrusion of Fresh-Frozen Meniscus Transplants

Study	*N*	Processing	Fixation	PO MRI (Mean)	Site Extrusion Measured	TRANSPLANT EXTRUSION (MEAN ± SD) (MM)			RELATIVE TRANSPLANT EXTRUSION (%)			TRANSPLANTS EXTRUDED		
						All*	MMT	LMT	All*	MMT	LMT	All*	MMT	LMT
Yoon et al[111] (2014)	35	FF	Bone	0.5-10 yr	NP	NA	2.6	1.7	NA	32%	19 ($P = .01$ vs MMT)	NA	36% >3 mm	25% >3 mm
Lee et al[49] (2012)	49	FF	Bone	2 days	Midbody	NA	NA	3.12 ± 1.17	NA	NA	30.05 ± 11.87	NA	NA	47% >3 mm
Kim et al[44] (2012)	108	FF	Bone	2.4 yr	Site maximum extrusion	3.7 ± 1.8	NA	NA	42.6 ± 21	NA	NA	100% some degree	NA	NA
Koh et al[45] (2012)	99	FF	Bone	2.7 yr	Site maximum extrusion	NA	2.9 (1.2-6.5)	4.7 (1.8-7.7); $P < .001$ vs. MMT	NA	31 (11.6-63.4)	52 (23.8-81.8); $P < .001$ vs MMT	NA	NA	NA
Kim et al[43] (2011)	28	FF	Bone	3.3 yr	Site maximum extrusion	NA	NA	4.0 (0.8-8.4)	NA	NA	45 (8.2 –100%)	NA	NA	100% some degree
Ha et al[31] (2011)	18	FF	Bone	1 yr	Site maximum extrusion	NA	4.35 ± 1.76	NA	NA	43 ± 19.8	NA	NA	NA	NA
Jang et al[38] (2011)	36	FF	Bone	2-3 yr	Site maximum extrusion	3.9 (0-8.8)	4.4 (2.3-6.6)	3.5 (0-8.8)	41 (0-71)	44 (20-69)	39 (0-71)	74% >3 mm	92%	64%
Yoon et al[108] (2011)	11	FF	Bone	1-1.4 yr	NP	NA	NA	1.6 (0.5-2.9)	NA	NA	NA	NA	NA	100% some degree
Choi et al[16] (2011)	23	FF	Bone	0.5 yr	Midbody	NA	NA	3.2 ± 2.3 (0-6.5)	NA	NA	NA	NA	NA	48% >3 mm
Lee et al[50] (2010)	43	FF	Bone	1 yr	Midbody	3.03 ± 0.87	NA	NA	NA	NA	NA	40% >3 mm	NA	NA
Ha et al[30] (2010)	36	FF	Bone	2.6 yr	Site maximum extrusion	3.87 ± 1.94	NA	NA	42.1 ± 17.7	NA	NA	75% >3 mm	NA	NA
Lee et al[51] (2008)	21	FF	Bone	6 wk	Site maximum extrusion	2.87	NA	NA	29	NA	NA	33%	NA	NA
				3 mo		2.95			29			38%		
				6 mo		3.03			32			33%		
				12 mo		2.96			32			33%		
Potter et al[74] (1996)	24	FF	Bone	3 mo to 3.4 yr	All	NA	NA	NA	NA	NA	NA	38%	NA	NA
Gonzalez-Lucena et al[28] (2010)	33	FF	Suture	5 yr	Site maximum extrusion	NA	NA	NA	36.3 ± 13.7	35.9 ± 18.1	38.3 ± 14.4	100% some degree	NA	NA

Verdonk et al[102] (2006)	17	Fresh	Suture	>10 yr	All	NA	NA	NA	NA	NA	NA	70% partial	NA	NA
Verdonk et al[100] (2004)	17	Fresh	Suture	0.5-9.2 yr	All	NA	NA	5.8 ± 2.8 anterior, 2.7 ± 1.5 posterior	NA	NA	NA	NA	NA	100%
De Coninck et al[19] (2013)	16	FF	Suture	1 yr	Midbody	NA	4.7 ± 1	4.0 ± 1.5	NA	NA	NA	NA	100%	90%
	21	FF	Bone				2.4 ± 0.9 (P = .003)	3.4 ± 0.85 (P = .02)					14% (P = .01)	71%
Abat et al[1] (2012)	33	FF	Suture	3.3 yr	Site maximum extrusion	NA	NA	NA	36 (P < .001)	36 (P < .001)	38 (P < .001)	73% (P < .001)	NA	NA
	55	FF	Bone						28	26	30	31% >3 mm		
Rankin et al[76] (2006)	7	Cryo	Bone	2 yr	Ant. horn	1.9 ± 2.5	NA	NA	NA	NA	NA	14%	NA	NA
					Post. horn	2.2 ± 3.1						28% >3 mm		
Noyes et al[65] (2004)	29	Cryo	Bone	2.9 yr	Midbody	2.2 ± 1.5	NA	NA	NA	NA	NA	3% 9 mm	NA	NA
					Ant. horn	1.2 ± 1.7								
					Post. horn	1.1 ± 2.0								
Stollsteimer et al[89] (2000)	12	Cryo	Bone	2 yr	NA	NA	NA	NA	NA	NA	NA	8% 1 mm	NA	NA
Jiang et al[40] (2014)	18	Cryo	Suture	4.2 yr	Midbody	~3.1 (1.7-5.1)	NA	NA	19.2-71.2	NA	NA	100%	NA	NA
van Arkel et al[95] (2000)	16	Cryo	Suture	2.7 yr	Ant. horn, midbody	NA	NA	NA	NA	NA	NA	58% subextruded, 31% extruded	67% subextruded, 17% extruded	54% subextruded, 23% extruded
Zhang et al[112] (2012)	17	Irradiated	Bone	2 yr	Midbody	NA	NA	NA	NA	NA	NA	65% partial	NA	NA

"Some degree," "partial," "subextruded," and "extruded" were not defined by the authors.
*Medial or lateral, not identified in study or combined.
Ant., Anterior; *FF,* fresh frozen; *LMT,* lateral meniscus transplant; *MMT*, medial meniscus transplant; *MRI,* magnetic resonance imaging; *NA*, not applicable; *NP*, not provided; *PO,* postoperative; *Post.*, posterior; *SD*, standard deviation.

CRITICAL POINTS Our Clinicl Studies: Systematic Review of Meniscus Transplant Extrusion

- Systematic search performed using PubMed and Cochrane databases.
- $n = 23$ articles met criteria: English language, clinical trials published from 1984 to 2014, meniscus extrusion measured on MRI, all evidence levels.
- 814 transplants in 803 patients.
- MRI obtained from 2 days to 10 years postoperatively.
- 18 studies used fresh-frozen meniscus transplants implanted with bone ($n = 612$) or suture fixation ($n = 116$).
- 4 studies used cryopreserved transplants, 1 used irradiated transplants.
- Absolute millimeters of extrusion ranged from 0-8.8 mm.
- Relative percentage of extrusion ranged from 0%-100%.
- Percent of transplants that were extruded ranged from 0%-100%.
- No correlation between transplant extrusion and clinical rating scales, joint space narrowing on posteroanterior radiographs, and arthrosis grade progression on MRI and follow-up arthroscopy.
- Nonanatomic placement of lateral meniscus transplants and suture fixation of medial and lateral transplants were associated with greater extrusion.
- Short- to mid-term results were encouraging in regard to knee function with activities of daily living and low failure rates, regardless of the presence or amount of extrusion.

of extrusion (0-8.8 mm), relative percentage of extrusion ([Width of extruded meniscus]/[Width of entire meniscus] × 100; 0%-100%), and the percent of transplants that were extruded (0%-100%). All authors used different indicators to determine the percent of transplants that were extruded, including subjective terms such as *partial* or *some degree*, or an objective measurement such as greater than 3 mm.

There appeared to be no correlation between transplant extrusion and clinical rating scales, joint space narrowing on PA radiographs, and arthrosis grade progression on MRI and follow-up arthroscopy. Nonanatomic placement of lateral meniscus transplants and suture fixation of medial and lateral transplants were associated with greater extrusion.

Recently, Jeon and associates[39] compared meniscus transplant extrusion between 44 patients who had a tibial plateau osteophyte excised concomitantly with the transplant with 44 patients who had an osteophyte that was not excised. One year postoperatively, the nonexcised group had significantly greater absolute transplant extrusion (5.5 ± 1.6 mm vs. 3.5 ± 1.5 mm; $P < .001$) and relative percentage of extrusion (54.7 ± 20.7% vs. 34.1 ± 15.9%; $P < .001$). The total incidence of transplant extrusion (>3.0 mm) was 93% in the nonexcised group and 64% in the excised group ($P < .001$). There were no significant differences in the Lysholm or Hospital for Special Surgery (HSS) scores between the groups at 2 postoperative years. Lee and coworkers[47] reported that ICRS grade 3 or more on the tibia was a significant risk factor for LMT extrusion (bone bridge fixation) in a series of 71 knees (odds ratio 6.9; $P = .001$). Nonsignificant risk factors included patient age, gender, BMI, mechanical axis, and chronicity of injury.

Inconsistencies among studies preclude definitive conclusions regarding the incidence and clinical significance of meniscus transplant extrusion. Even so, the short- to midterm results were encouraging in regard to knee function with ADLs and low failure rates, regardless of the presence or amount of extrusion. Future studies should report absolute transplant extrusion, relative percent of extrusion, the percent coverage (percent of transplant located within the tibiofemoral compartment), and the percent of transplants that were extruded. More sophisticated 3-dimensional MRI modeling should be used if feasible to obtain these values. MRIs should be obtained at the same postoperative time period in all patients.

RESULTS FROM OTHER CLINICAL STUDIES

Since 1984,[52] a multitude of clinical investigations have reported outcomes of meniscus transplant surgery (Tables 24-8 to 24-10). Differences in tissue processing, secondary sterilization, preservation, operative technique, concomitant procedures, and rating systems make comparisons among studies difficult and others have performed lengthy reviews of these investigations.[23,32,34,48,53,54,69,87,88]

The majority of meniscus transplant studies published to date assessed outcome of fresh-frozen grafts (see Table 24-8). Using a minimum of 2 years of follow-up as inclusionary criteria, 15 studies have investigated results of transplants implanted using bone fixation techniques, three studies have assessed transplants implanted using soft tissue suture fixation, and two studies included both bone and suture fixation in their cohorts. Typically, significant improvements have been reported in terms of pain reduction and function with daily activities and the patient perception of knee condition.[25,27,44,46,82,90,102] High levels of patient satisfaction have been noted by several authors.[25,27,46,82,102] Only two studies that assessed the outcome of bone fixation had long-term follow-up (8.5 and 20 years), and nearly all patients underwent combined procedures.[82,104]

In terms of fresh transplants implanted with suture (no bone) fixation, one investigation has reported survival rates at the time of writing. Verdonk and associates[101] followed 100 patients a mean of 7.2 postoperative years. Endpoints for failure were moderate or severe occasional or persistent pain or poor knee function, based on the HSS pain and functional scores. Failure rates for medial meniscus and lateral meniscus transplants were 28% and 16%, respectively, and these occurred at a mean of 4.8 years postoperatively. The average cumulative survival time (11.6 years) was identical for medial and lateral transplants. MMTs done concurrently with HTO had a higher cumulative survival rate of 83.3% at 10 years.

Stone and colleagues[90] followed 119 fresh-frozen transplants a mean of 5.8 years. All the transplants were accompanied by an articular cartilage restorative procedure. The endpoints for failure were removal of the transplant or progression to unicompartmental or total knee replacement. Overall, 20% of the transplants failed an average of 4.6 years postoperatively. These investigators reported a survival time of 9.9 years for medial and 10.2 years for lateral transplants. Survival was not associated with gender, severity of articular cartilage damage, or the involved tibiofemoral compartment. This study used both fresh-frozen and cryopreserved transplants, and it is unknown if a difference existed in the failure rate between tissue processing techniques.

Cryopreserved meniscus transplants implanted with bone fixation techniques were investigated in five studies that followed patients from 2.8 to 5.4 years postoperatively (see Table 24-9).[17,77,81,85,89] These studies reported failure rates ranging from 0% to 30%. Three other investigations of cryopreserved transplants implanted with suture fixation reported failure rates of 20% to 50% from 5 to 13.8 years postoperatively.[36,90,96] For instance, Hommen and associates[36] followed 20 patients for 9 to 13 years postoperatively and reported a 10-year survival rate of 45% based on poor Lysholm scores (<65 points), no improvement in the pain score, and grade 3 signal on MRI. A survival analysis of 63 consecutive cryopreserved meniscal transplants followed a mean of 5 years was conducted by van Arkel and de Boer[94] followed a mean of 5 years. Criteria for failure were persistent pain, a poor Lysholm score, a poor Knee Assessment Scoring System result, or a detached transplant. The cumulative 10-year survival rates of lateral, medial, and combined transplants in the same knee were 76%, 50%, and 67%,

TABLE 24-8 Clinical Outcome Studies of Fresh-Frozen Meniscus Transplants With Minimum 2-Year Follow-up

Study	Menisci (*n*)	Mean Follow-up (yr)	Fixation	Concurrent Procedures (*n*)	Evaluation Methods (*n*)	Results, Conclusions
Getgood et al[27] (2015)	48	6.8	Bone	Osteochondral allograft (all)	Questionnaires, subsequent surgery	23% failed; 5-year survival, 78%, 10-year survival, 69%; mean time to failure, 3.2 years
von Lewinski et al[104] (2007)	5	20	Bone	ACL reconstruction (all), MCL advancement	Clinical examination, MRI, x-rays	Severe shrinkage of all transplants on MRI; all patients in varus (no HTO performed); 3 patients moderate/severe radiographic degenerative changes
Saltzman et al[82] (2012)	22	8.5	Bone	Articular cartilage restorative (11), ACL reconstruction (3)	Clinical examination (6)	12% failed; significant improvements in subjective knee function IKDC, KOOS, SF-12; 91% would have surgery again
Lee et al[50] (2010)	43	5.1	Bone	None	Clinical examination, MRI, x-rays	No progression of joint space narrowing; significant improvement in Lysholm scores
McCormick et al[56] (2014)	172	4.9	Bone	Articular cartilage procedure (4), cartilage procedure + HTO (14), ACL reconstruction (23), HTO (8)	Subsequent surgery	32% required follow-up operative procedures, 69% for debridement; 4.7% failed. At 5 years, patients requiring subsequent surgery had an 88% survival rate; those who did not had a 98% survival rate. Patients requiring subsequent surgery had an odds ratio of 8.4 for future TKA or transplant revision.
Farr et al[25] (2007)	29	4.5	Bone	ACI (all), HTO (6), ACL reconstruction (8)	Clinical examination	12% failed; significant improvements in Cincinnati and Lysholm scores, patient satisfaction score
Kim et al[43] (2011)	29	4.4	Bone	None	Clinical examination, MRI, x-rays, arthroscopy (7)	No progression of joint space narrowing; significant improvement in Lysholm, HSS scores; 31% rated fair/poor according to MRI or follow-up arthroscopy
Kim et al[44] (2012)	110	4.1	Bone	ACL reconstruction (23)	Clinical examination, MRI (108), arthroscopy (20)	Significant improvements in Lysholm, Knee Society pain scores; 92% showed varying degrees of degeneration on MRI; 18% rated fair/poor according to MRI, follow-up arthroscopy, Lysholm score
Yoon et al[111] (2014)	91	3.3	Bone	Articular cartilage procedure (37), ACL recon (32), ACL recon ± ACI (5)	Clinical examination, MRI (35), arthroscopy (27)	No difference in outcome of MMT vs. LMT; significant improvements in IKDC, Lysholm, Tegner scores; 4% failed
Yoldas et al[107] (2003)	34	2.9	Bone	ACL reconstruction (20)	Clinical examination, x-ray	No failures; good function with daily activities but lower with sports; no baseline data collected
Koh et al[45] (2012)	99	2.7	Bone	ACL reconstruction (15), OAT (9)	Clinical examination, MRI	Significant improvement in Lysholm score

Continued

TABLE 24-8 Clinical Outcome Studies of Fresh-Frozen Meniscus Transplants With Minimum 2-Year Follow-up—cont'd

Study	Menisci *(n)*	Mean Follow-up (yr)	Fixation	Concurrent Procedures *(n)*	Evaluation Methods *(n)*	Results, Conclusions
Ha et al[28] (2010)	36	2.5	Bone	ACL reconstruction (11), posterolateral reconstruction (3), PCL reconstruction (2), microfracture (2), ACI (2)	Clinical examination, MRI, x-rays, arthroscopy (18)	Significant improvement in Lysholm score; no progression of joint space narrowing
LaPrade et al[46] (2010)	40	2.5	Bone	ACL reconstruction (10), microfracture (5), osteochondral allograft (3), femoral osteotomy (3)	Clinical examination	Significant improvement in IKDC, Cincinnati scores; 91% pain relief and improved function; 5 transplants tore
Ha et al[30] (2011)	22	2	Bone	ACL reconstruction (15), PCL reconstruction (2), posterolateral reconstruction (4)	Clinical examination, MRI, x-rays, arthroscopy (11)	Significant improvement in IKDC, Lysholm scores; 1 failed according to MRI
Potter et al[74] (1996)	24	3-41 mo	Bone	ACL reconstruction (16), HTO (1)	Clinical examination, MRI (24), arthroscopy (19), histology (18)	71% focal degeneration transplant; correlation of displacement/ degeneration with joint arthrosis
Kazi et al[41] (2015)	86	15	Suture	Valgus osteotomy (27), Varus osteotomy (26), ACL reconstruction (7)	Examination, x-ray	29% failed; median survival 11.6 yr for MMT and osteotomy, 15.3 yr for LMT and osteotomy
Gonzalez-Lucena et al[26] (2010)	33	6.5	Suture	ACL reconstruction (8), microfracture (8)	Clinical examination, MRI, x-ray	No progression of joint space narrowing; significant improvement in Lysholm, Tegner scores; 33% follow-up surgery for meniscus problems; 21% retear rate; 9% failed
Stone et al[90] (2010)	119	5.8	Suture	Articular cartilage procedure (all), osteotomy (15), ACL reconstruction (17)	Clinical examination	20% failed at mean 4.6 yr; survival time 9.9 yr (endpoints: transplant removal, TKA, UKA); survival not affected by gender, severity of cartilage damage, involved compartment; fresh frozen (94), cryopreserved (24), irradiated (1)
Wirth et al[106] (2002)	23	14	Bone or suture	ACL reconstruction (all), MCL advancement (19)	Clinical examination, x-ray, MRI (9), arthroscopy (19)	Clinical results for frozen transplants better than lyophilized; frozen maintained size, lyophilized reduced size on arthroscopy and MRI; lyophilized (17) or frozen (6)
Abat et al[2] (2013)	88	5	Bone or suture	ACL reconstruction (18), microfracture (15)	Clinical examination, x-ray	Suture-only fixation (33): 33% complications, 9% failed; bone fixation (55): 16% complications, 3% failed

ACI, Autologous chondrocyte implantation; *ACL*, anterior cruciate ligament; *HSS*, Hospital for Special Surgery; *HTO*, high tibial osteotomy; *IKDC*, International Knee Documentations Committee; *KOOS*, Knee Injury and Osteoarthritis Outcome Score; *MCL*, medial collateral ligament; *MRI*, magnetic resonance imaging; *LMT*, lateral meniscus transplant; *MMT*, medial meniscus transplant; *OAT*, osteochondral autograft transfer; *PCL*, posterior cruciate ligament; *SF-12*, Short Form 12; *TKA*, total knee arthroplasty; *UKA*, unicompartmental knee arthroplasty.

TABLE 24-9 Clinical Outcome Studies of Cryopreserved Meniscus Transplants With Minimum 2-Year Follow-up

Study	Menisci (*n*)	Mean Follow-up (yr)	Fixation	Concurrent Procedures (*n*)	Evaluation Methods (*n*)	Results, Conclusions
Rath et al[77] (2001)	22	5.4	Bone	ACL reconstruction (11)	Clinical examination, x-ray, histologic (4)	36% failed; tissue showed reduced cellularity, reduced cytokine expression compared with normal menisci
Stollsteimer et al[89] (2000)	23	3.3	Bone	None	Clinical examination, x-ray, MRI (12)	35% additional surgery related to transplant (1 total removal, 5 partial removals, 1 refixation bone plug, 1 repair). Correlation between clinical results and Outerbridge scores. Mean meniscus size, 63% (31%-100%) compared with normal menisci.
Rue et al[81] (2008)	31	3.1	Bone	ACI (16), osteochondral allograft (15), HTO (1)	Clinical examination	7% failed; significant improvements in functional scores; 76% satisfied, 90% would have surgery again
Cole et al[17] (2006)	44	2.8	Bone	Articular cartilage procedure (9), ligament reconstruction (6), osteotomy (1)	Clinical examination	16% failed; significant improvement in subjective scores; 77% satisfied; trend to greater improvement with LMT over MMT
Sekiya et al[84] (2003)	28	2.8	Bone	ACL reconstruction (all)	Clinical examination, x-ray	0% failed; 86% normal/nearly normal IKDC subjective scores
van der Wal et al[96] (2009)	57	13.8	Suture	ACL reconstruction (2)	Clinical examination	29% failed at mean 7.9 years: 35% medial, 25% lateral. 15-year survival rate of 52.5% (endpoint: complete resection of transplant). Mean 16 years between meniscectomy and transplant; 33% patients had grade 4 damage. Indications improved with experience.
Stone et al[90] (2010)	119	5.8	Suture	Articular cartilage procedure (all), osteotomy (15), ACL reconstruction (17)	Clinical examination	20% failed at a mean 4.6 years; survival time 9.9 years (endpoints: transplant removal, TKA, UKA). Survival not affected by gender, severity of cartilage damage, or involved compartment. Fresh frozen (94), cryopreserved (24), irradiated (1).
van Arkel & de Boer[94] (2002)	63	5	Suture	None	Clinical examination, arthroscopy (16)	Cumulative success rates: 88% LMT, 63% MMT. Survival rates: 76% LMT, 50% MMT (endpoints: persistent pain, mechanical damage). Not all ACL-deficient knees reconstructed; correlated with high failure MMT.
Hommen et al[36] (2007)	20	9-13	Bone or suture	None	Clinical examination, x-ray (15), MRI (7), arthroscopy (14)	10-year survival rate 45% (endpoints: Lysholm <65, no improvement in pain score, transplant removal, MRI grade III). Failures noted in 58% (7/12) of MMT and 50% (4/8) of LMT. Retrospective study; variety of surgical techniques and fixation methods used.
Vundelinckz et al[105] (2010)	39	8.9	Bone or suture	Osteotomy (3), microfracture (2)	Clinical examination, x-ray	10% failed. Significant improvements in KOOS, Lysholm, SF-36 scores. Increase radiographic arthritis grade: 24% slight, 18% moderate.
Jiang et al[40] (2014)	18	4.2	Bone or suture	ACL reconstruction (6)	Clinical examination, MRI, x-ray	Patients who received transplants immediately after meniscectomy had higher IKDC subjective scores, better isokinetic muscle strength. MRI: 2 patients grade 3 signal; meniscus body extrusion in all.
Sekiya et al[85] (2006)	25	3.3	Bone (17) or suture (8)	None	Clinical examination (17), x-ray	83% had no symptoms with daily activities. IKDC symptoms in 8 were normal/nearly normal, 12 were abnormal, 5 were severely abnormal. Significantly worse loss knee motion in suture fixation group; all but 1 patient satisfied; no deterioration in joint space.

ACI, Autologous chondrocyte implantation; *ACL*, anterior cruciate ligament; *HTO*, high tibial osteotomy; *IKDC*, International Knee Documentations Committee; *LMT*, lateral meniscus transplant; *MMT*, medial meniscus transplant; *MRI*, magnetic resonance imaging; *OAT*, osteochondral autograft transfer; *SF-36*, Short Form 36; *TKA*, total knee arthroplasty; *UKA*, unicompartmental knee arthroplasty.

TABLE 24-10 Clinical Outcome Studies of Irradiated Meniscus Transplants with a Minimum 2-Year Follow-up

Study	Menisci (*n*)	Mean Follow-up (yr)	Fixation	Concurrent Procedures (*n*)	Evaluation Methods (*n*)	Results, Conclusions
Graf et al[29] (2004)	9	8.5-10.3	Bone	ACL reconstruction	Clinical examination, x-ray, arthroscopy (6)	1 failed; 8 satisfied with outcome; transplants also cryopreserved
Cameron & Saha[13] (1997)	67	2.5	Bone	HTO (35)	Clinical examination, arthroscopy (10)	10% failed. HTO group: 85% good to excellent clinical results. Isolated transplant group: 90% good to excellent results.
Zhang et al[112] (2012)	18	2	Bone	ACL reconstruction (7)	Clinical examination, MRI, arthroscopy	11% failed; 61% transplants partially extruded; 67% satisfied

ACL, Anterior cruciate ligament; *HTO*, high tibial osteotomy; *MRI*, magnetic resonance imaging.

respectively. Failure of lateral transplants occurred an average of 4.4 years after implantation, and failure of medial transplants occurred a mean of 2.1 years postoperatively.

In our opinion, the use of survival criteria based only on the need for subsequent surgery results in a significant overestimation of the long-term function of meniscus allograft transplantation (MAT). This opinion is based on MRI studies of MAT that demonstrate signal intensity alterations[28,74,89,95,106] and high rates of meniscus extrusion.[19,28,30,31,43-45,50,95,102,111,112] For instance, Potter et al[74] investigated 29 meniscal transplants with MRI and clinical examination 3 to 41 months postoperatively. Increased signal intensity was detected on the posterior horn in 15 knees, and peripheral displacement at the body was noted in 11; all of these knees had moderate or severe chondral degeneration. Histologic analysis demonstrated peripheral cellular repopulation but a central core that was acellular or hypocellular with evidence of disorganized collagen fibers. Knees with mild chondral degeneration had no abnormalities noted in the meniscus transplants and demonstrated superior clinical results compared with those with severe chondral degeneration.

Although most authors exclude patients with significant tibiofemoral compartment arthritis from meniscus transplantation, others have combined this procedure with articular cartilage restorative procedures to expand the indications.[25,32,90] As described previously, Stone and associates[90] followed 119 patients a mean of 5.8 years and reported a 9.9-year survival rate. Farr and colleagues[25] reported encouraging results in 29 patients followed a mean of 4.5 years after meniscus transplantation and autologous chondrocyte implantation. Significant improvements were found in several validated rating scales and 91% indicated they would undergo the operation again. Harris and coworkers[32] conducted a systematic review of combined transplant-cartilage procedures that involved six studies comprising 110 patients. During a mean of three postoperative years, failures had occurred in 12% of patients owing mainly to problems with the transplant. Although the short-term knee functional results were improved, a high rate of subsequent surgery (nearly 50%) was found.

CONCLUSION

The biology of meniscus healing and remodeling after implantation determines the final outcome regarding potential load-bearing function and chondroprotective effects. The meniscus transplant heals to the peripheral transplant-host rim junction within a short period of time, usually by 6 weeks, providing initial stability of the transplant in the knee joint. Animal[6] and human[64] studies indicated that an incomplete and disordered remodeling process occurs. This includes minimal cellular repopulation of the central and inner portions of the transplant, disorganization of collagen tissue (which lacks the normal collagen orientation required for load-sharing), and a predominant fibrocyte cellular structure. An increase in water content and a decrease in proteoglycan concentration in meniscus transplants have been documented.[37]

MRI done immediately after meniscus transplantation demonstrates uniform low signal intensity throughout the transplant tissue. Increased signal intensity at the capsular attachments of the transplant to the host meniscus rim is most likely caused by progressive healing. The low signal intensity within the body of the meniscus remains until remodeling of the transplant occurs. It is possible to see retention of

CRITICAL POINTS Conclusions

- Biology of meniscus healing and remodeling after implantation determines final outcome.
- Transplant heals to peripheral transplant-host rim junction within a short period of time providing initial stability of the transplant in the knee joint.
- An incomplete and disordered remodeling process occurs, expected to affect nearly all transplants, which results in altered mechanical properties and potential for tearing, fragmentation, and degeneration under joint-loading conditions.
- Uniform low signal intensity seen up to 4 years after implantation, advantageous in preserving function.
- First goal is to implant meniscus in manner that prevents graft extrusion.
- Results of meniscus transplantation are more favorable when operation is done before onset of moderate or severe tibiofemoral joint arthrosis.
- Procedure acceptable for younger patients, especially those who have symptoms with daily activities, because there are few if any other available treatment options.
- Whether meniscus transplantation provides a chondroprotective effect remains unknown.
- Patients advised that the procedure only has short-term benefits and, in the long term, further surgery will likely be required.

the native meniscus low intensity signal for up to 4 years after implantation, indicating a delayed remodeling response, which is advantageous in preserving the function and integrity of the MAT.

When remodeling occurs, MRI demonstrates an increased signal intensity that represents an ingrowth of mesenchymal and poorly differentiated cells into the transplant, removal of portions of the dense well-formed collagen framework, and replacement with randomized and disorganized collagenous tissues. During this stage, alterations in mechanical properties and decreased load-sharing capabilities of the transplant occur. With further remodeling, there commonly appears a grade 3 signal intensity indicating early degeneration and tears in the transplant. We hypothesize that all meniscus transplants will undergo this deleterious remodeling process, resulting in altered mechanical properties and potential for tearing, fragmentation, and degeneration under joint loading conditions. At this point, the meniscus represents a fibrous tissue interposition transplant.

The first goal of this operation is to implant the MAT in a manner that prevents extrusion. Our previous studies[65,76] showed the operative techniques described in this chapter successfully met this goal. It is recommended that surgeons obtain MRI after surgery to assess meniscus extrusion, which is believed to be deleterious to future expected function. The occurrence of MAT extrusion in the long term is expected in all transplants because of subsequent deterioration as just described.

On the basis of our investigations, the results of meniscus transplantation are believed to be more favorable when the operation is done before the onset of moderate tibiofemoral joint arthritis. A correlation exists between the outcome of meniscus transplants and knee joint arthritis because success rates are higher in knees that have only mild arthritis.

Abnormal limb alignment and ligament instability require simultaneous or staged corrections to warrant meniscus transplantation.

This procedure is acceptable for younger patients, especially those who have symptoms with daily activities, because there are few if any other available treatment options. The short-term results show the majority of patients have improved knee function and relief or decreases in pain in the affected compartment. However, whether or not meniscus transplantation provides a chondroprotective effect remains unknown. The long-term outcome of meniscus transplants is one of eventual deterioration, degeneration, and loss of function. Patients are advised that the procedure only has short-term benefits and, in the long term, that further surgery will likely be required. In our long-term studies, some patients require a second MAT and have achieved beneficial short-term results from the revision procedure.

There are several important research areas that may improve the success rates of meniscus transplantation. These include issues related to transplant remodeling; collagen fiber restoration of microarchitecture to resist tensile, compressive, and shear forces; transplant collagen matrix changes with altered material and structural properties; cellular repopulation and function in maintaining transplant homeostasis; role of fresh transplants with viable cells; and the role of meniscus scaffolds, tissue engineering, and possible meniscus prosthetic devices.

ILLUSTRATIVE CASES

Case 1. A 21-year-old man presented 2 years after an injury sustained to his left knee playing basketball that had been treated with three partial lateral meniscectomies. The patient had lateral tibiofemoral pain and swelling with all athletic activities and had not been able to return to sports. Physical examination revealed moderate lateral tibiofemoral crepitus but no associated ligament deficiency or osseous malalignment. Arthroscopy performed before the meniscus transplantation demonstrated no remaining functional lateral meniscal tissue, diffuse grade 2A damage to the lateral femoral condyle, and a 15- × 20-mm grade 2B lesion on the tibial plateau (Fig. 24-20, *A*). The patient was treated with a cryopreserved LMT (see Fig. 24-20, *B*) and an osteochondral autograft transfer of the lateral femoral condyle.

At the most recent follow-up evaluation, 4 years postoperative, the patient had no lateral tibiofemoral compartment pain and had returned to low-impact activities without symptoms. He rated the overall condition of his knee as very good. MRI demonstrated grade 1 signal intensity and no displacement of the transplant (see Fig. 24-20, *C* and *D*). Using our strict rating system of meniscus transplant characteristics, the implant was classified as normal.

Case 2. A 33-year-old male construction worker presented 19 years after an injury sustained to his left knee playing soccer. His operative history included two lateral meniscectomies and an FCL reconstruction. The patient had lateral tibiofemoral pain and swelling with daily activities, especially during work. Physical examination revealed mild lateral tibiofemoral crepitus and 3 mm of increased lateral joint opening. No other abnormalities were noted.

Arthroscopy performed before meniscus transplantation demonstrated no remaining functional lateral meniscal tissue (Fig. 24-21, *A*), a grade 3A lesion on the lateral femoral condyle, and grade 2B damage to the tibial plateau. The patient was treated with a cryopreserved LMT (see Fig. 24-21, *B*) and an osteochondral autograft transfer of the lateral femoral condyle.

At the most recent follow-up evaluation, 3 years postoperative, the patient had no lateral tibiofemoral compartment pain and had returned to low-impact activities without symptoms. He had changed his occupation to office work. He rated the overall condition of his knee as very good. MRI demonstrated grade 2 signal intensity, and minor displacement of the transplant (see Fig. 24-21, *C*) that was classified as altered. Standing PA radiographs showed no loss of tibiofemoral compartment joint space (see Fig. 24-21, *D*).

Case 3. A 49-year-old woman presented 15 years after an injury to her right knee which had occurred during a fall. She had undergone an ACL allograft reconstruction, two medial meniscectomies, and a microfracture of the medial tibial plateau. She complained of pain, swelling, and partial giving-way with daily activities. Physical examination demonstrated a grade 3 pivot shift, moderate patellofemoral crepitus, and medial tibiofemoral compartment pain. Arthroscopy performed before meniscus transplantation demonstrated no remaining functional medial meniscal tissue, full-thickness defects of the medial femoral condyle and tibial plateau, and noteworthy fissuring and fragmentation of the patellar undersurface. The patient was treated with a cryopreserved MMT (Fig. 24-22, *A*), an osteochondral autograft transfer of the medial femoral condyle, and a proximal patellar realignment. Seven months later, a revision ACL B-PT-B autograft reconstruction was performed as a staged procedure. The MMT had healed and had a relatively normal arthroscopic appearance (see Fig. 22-22, *B*). However, an MRI scan performed 3 years later showed major displacement of the meniscus transplant and a grade 3 signal intensity (see Fig. 24-22, *C*). The meniscus transplant was classified as failed.

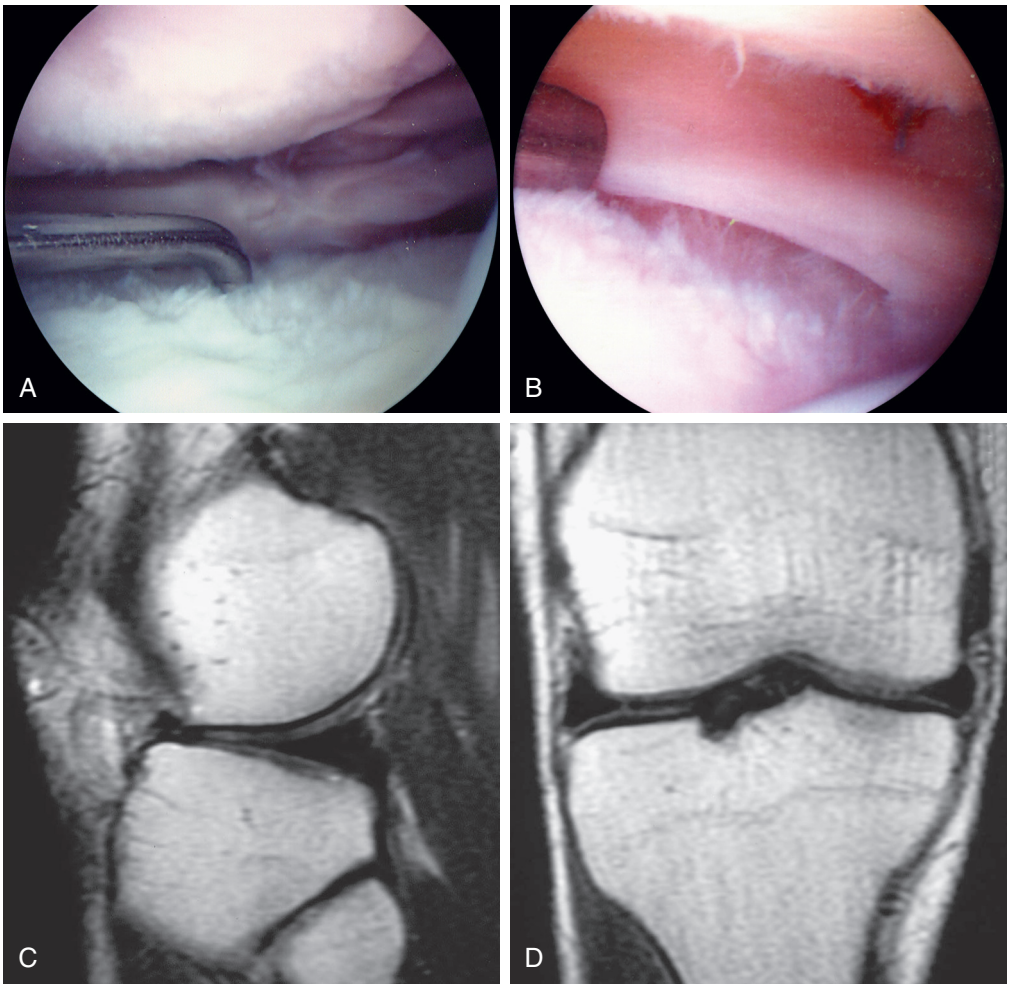


FIG 24-20 Case 1.

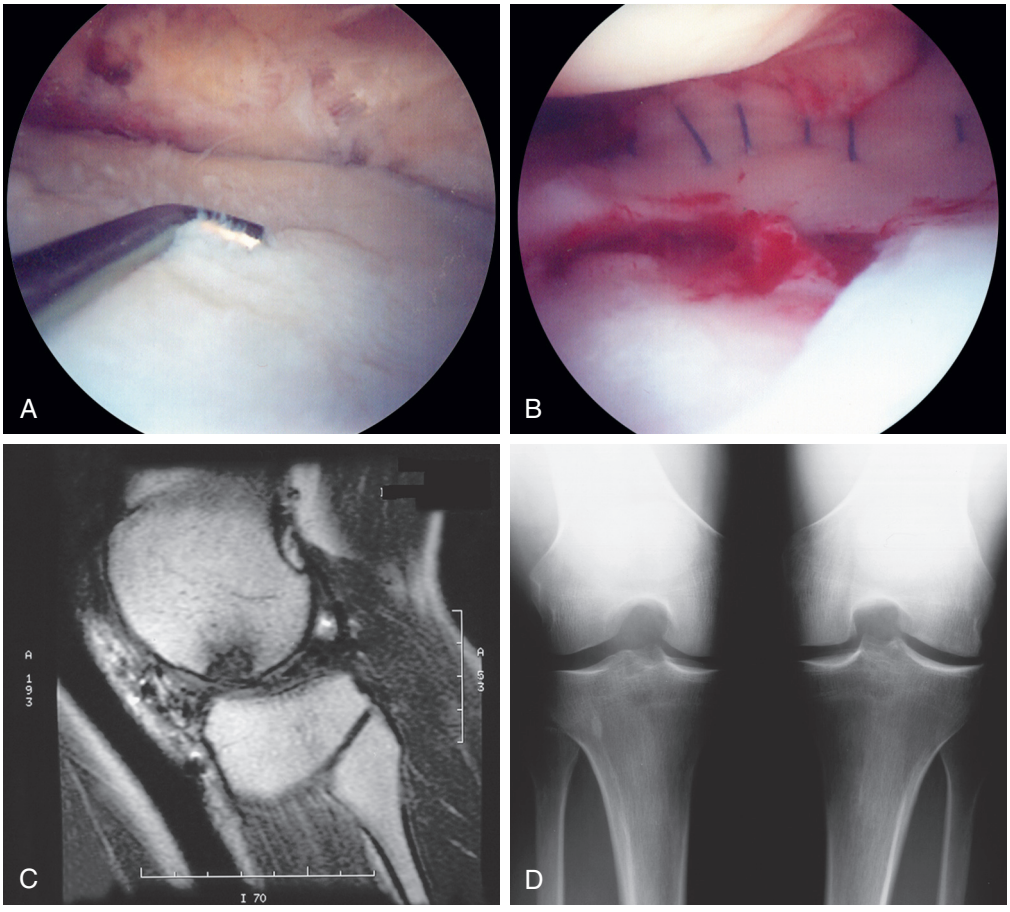


FIG 24-21 Case 2.

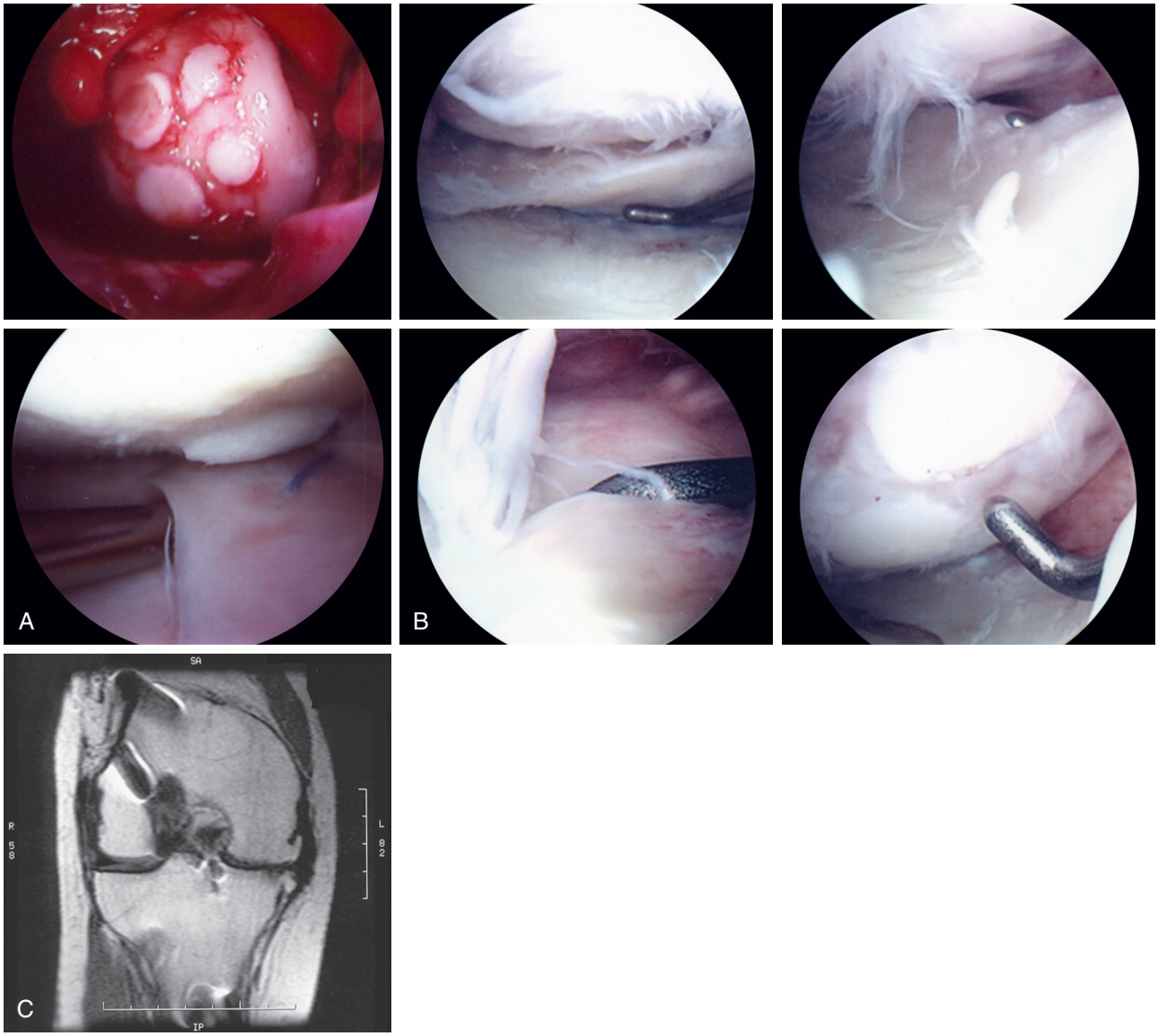


FIG 24-22 Case 3.

At the most recent follow-up evaluation, 5 years postoperative, the patient had no symptoms with low-impact activities and did not complain of medial tibiofemoral compartment pain. She had a grade 1 pivot shift, 3 mm of increased anterior tibial displacement, moderate but asymptomatic patellofemoral crepitus, and a normal range of knee motion. She rated the overall condition of her knee as good despite the lateral tibiofemoral arthritis.

Case 4. A 32-year-old woman presented with left knee medial tibiofemoral pain, locking, and instability with daily activities of 6 months' duration. She had undergone a medial meniscectomy 17 years previously and an ACL allograft reconstruction 7 years before her initial evaluation. Physical examination demonstrated 15 mm of increased AP displacement compared with the contralateral knee on KT-2000 (MEDmetric) testing, no other ligament deficiencies, a marked varus recurvatum deformity, and a hyperextension gait abnormality. Full standing radiographs showed a weight-bearing line of 19%, a mechanical axis of 5 degrees varus, and moderate narrowing of the medial tibiofemoral compartment (Fig. 24-23, *A*). An MRI demonstrated advanced articular cartilage deterioration in the medial tibiofemoral compartment. Owing to the patient's age, she was not considered a candidate for a unicompartmental knee replacement. The treatment recommendation was to first correct the lower limb varus malalignment and then perform meniscus transplantation and ACL revision. The patient underwent a gait retraining program (see Chapter 29) to correct the hyperextension abnormality before proceeding to an HTO.

A closing-wedge osteotomy was performed, with a small 12- to 15-mm area of grade 3A articular cartilage deterioration noted in the medial tibiofemoral compartment at the time of surgery (see Fig. 24-23, *B*). Four months later, an MMT and osteochondral autograft transfer of the medial femoral condyle were performed. An ACL B-PT-B autogenous revision reconstruction was done 3 months later, along with removal of hardware from the osteotomy.

At the most recent follow-up evaluation, 5.5 years posttransplantation, the patient had no symptoms or limitations with daily

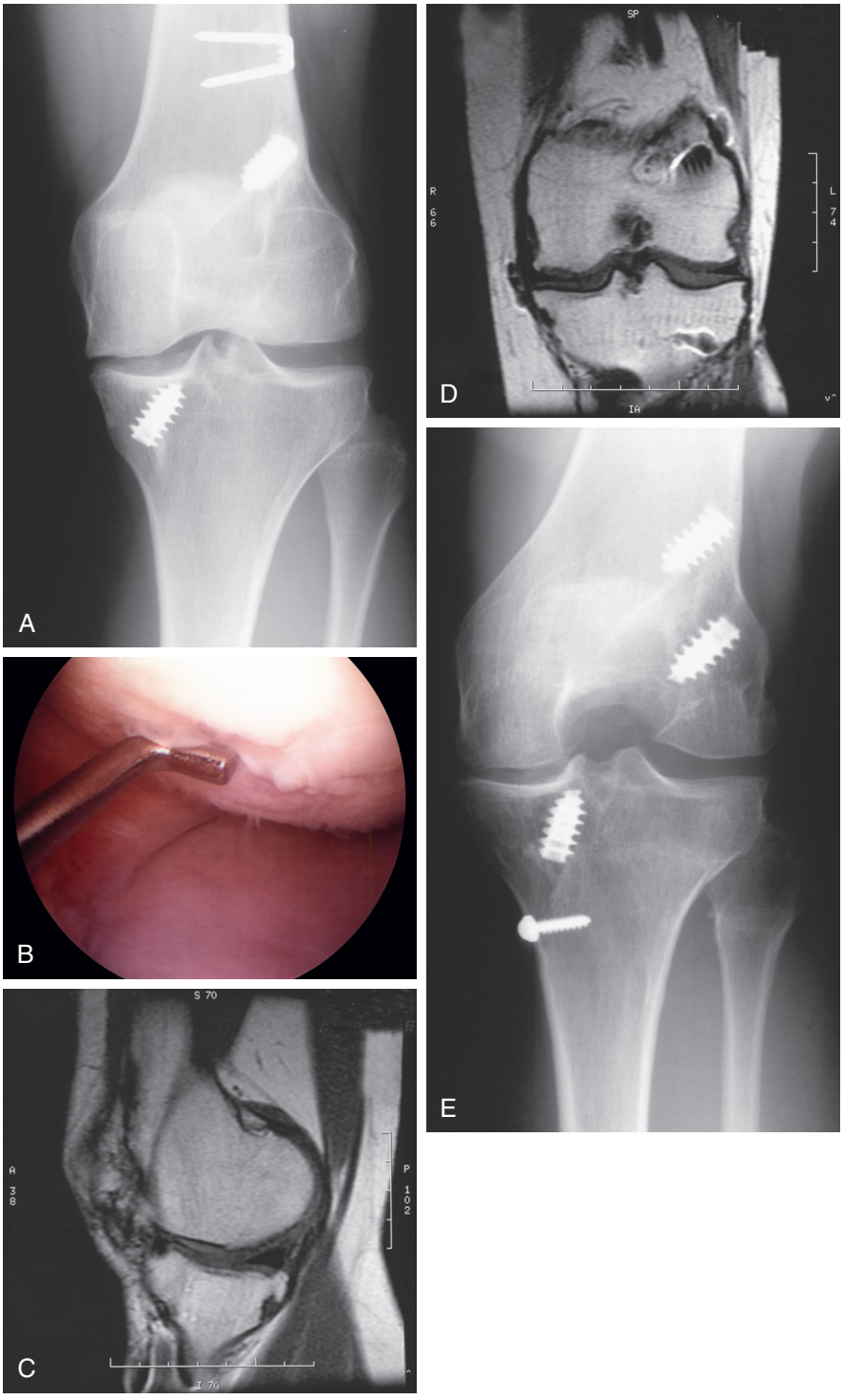


FIG 24-23 Case 4.

activities. She rated the overall condition of her knee as good and had no problems with her occupation in engineering. MRI showed an intact meniscus transplant (see Fig. 24-23 *C* and *D*), still in position in the tibiofemoral joint. There was increased signal intensity noted and some extrusion of the implant. Standing PA radiographs showed no progression of loss of the medial tibiofemoral joint space (see Fig. 24-23, *E*). She had no increase in anterior tibial translation, a negative pivot shift test, and a normal range of knee motion.

Case 5. A 16-year-old female presented 3 years after a right lateral meniscectomy for a symptomatic discoid meniscus. She complained of pain and swelling with all sports activities of 6 months' duration. Her walking tolerance was 1 hour and she was unable to kneel or squat. Physical examination revealed a normal range of knee motion, no ligament deficiencies, moderate pain and crepitation in the lateral tibiofemoral compartment, and an overall valgus alignment. Arthroscopic examination conducted elsewhere 5 months earlier revealed noteworthy articular cartilage deterioration on the lateral tibial plateau. Owing to the patient's young age and rapid deterioration of the lateral compartment (Fig. 24-24, *A*), she was treated with an LMT (see Fig. 24-24, *B*). In addition, an osteochondral autograft transfer of the lateral femoral condyle was performed for a full-thickness defect that measured approximately 7 × 7 mm (see Fig. 24-24, *B* and *C*).

Ten years postoperatively, the patient reported no symptoms with her occupation as an emergency department nurse. She had mild tenderness to palpation of the lateral tibiofemoral compartment, but the remainder of the physical examination was normal. Full standing radiographs demonstrated a valgus alignment (see Fig. 24-24, *D*), and the patient was advised that a femoral osteotomy may be required in the future. Standing PA radiographs showed maintenance of the lateral tibiofemoral joint space (see Fig. 24-24, *E*). However, an MRI showed a meniscus transplant that was decreased in size and displaced, with grade 2 signal intensity (see Fig. 24-24, *F*). The patient was advised to return for yearly examinations to continue to assess the need for a future femoral osteotomy.

Case 6. A 45-year-old man presented 2 years after a left medial meniscectomy. He had medial joint line pain, catching, and partial giving-way with daily activities that had not been resolved by the procedure. Physical examination showed a normal range of knee motion, no ligament instabilities, and mild medial tibiofemoral crepitus. The patient had significant medial joint line tenderness to palpation. Radiographs showed only minor medial joint space narrowing (Fig. 24-25, *A*) and

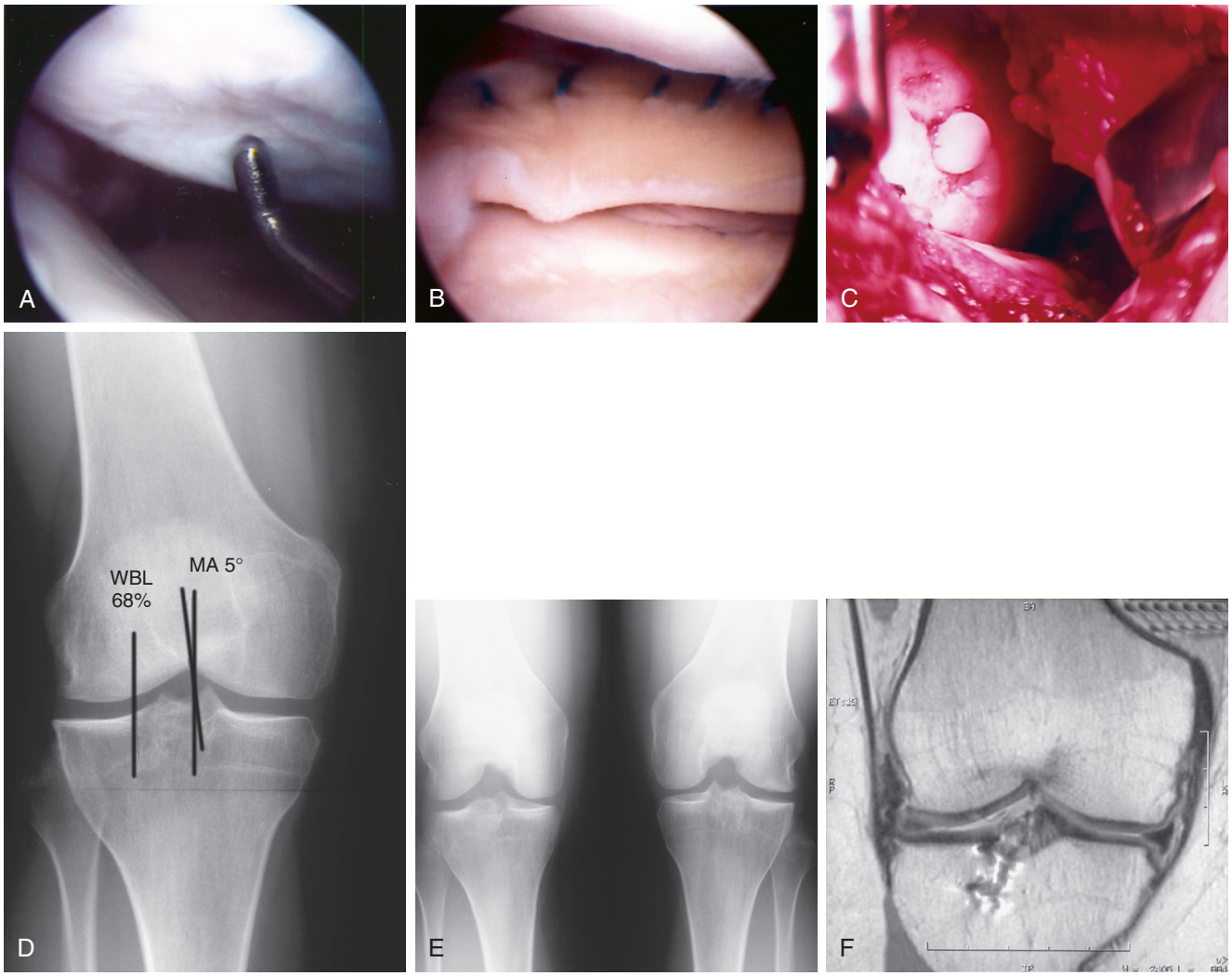


FIG 24-24 Case 5.

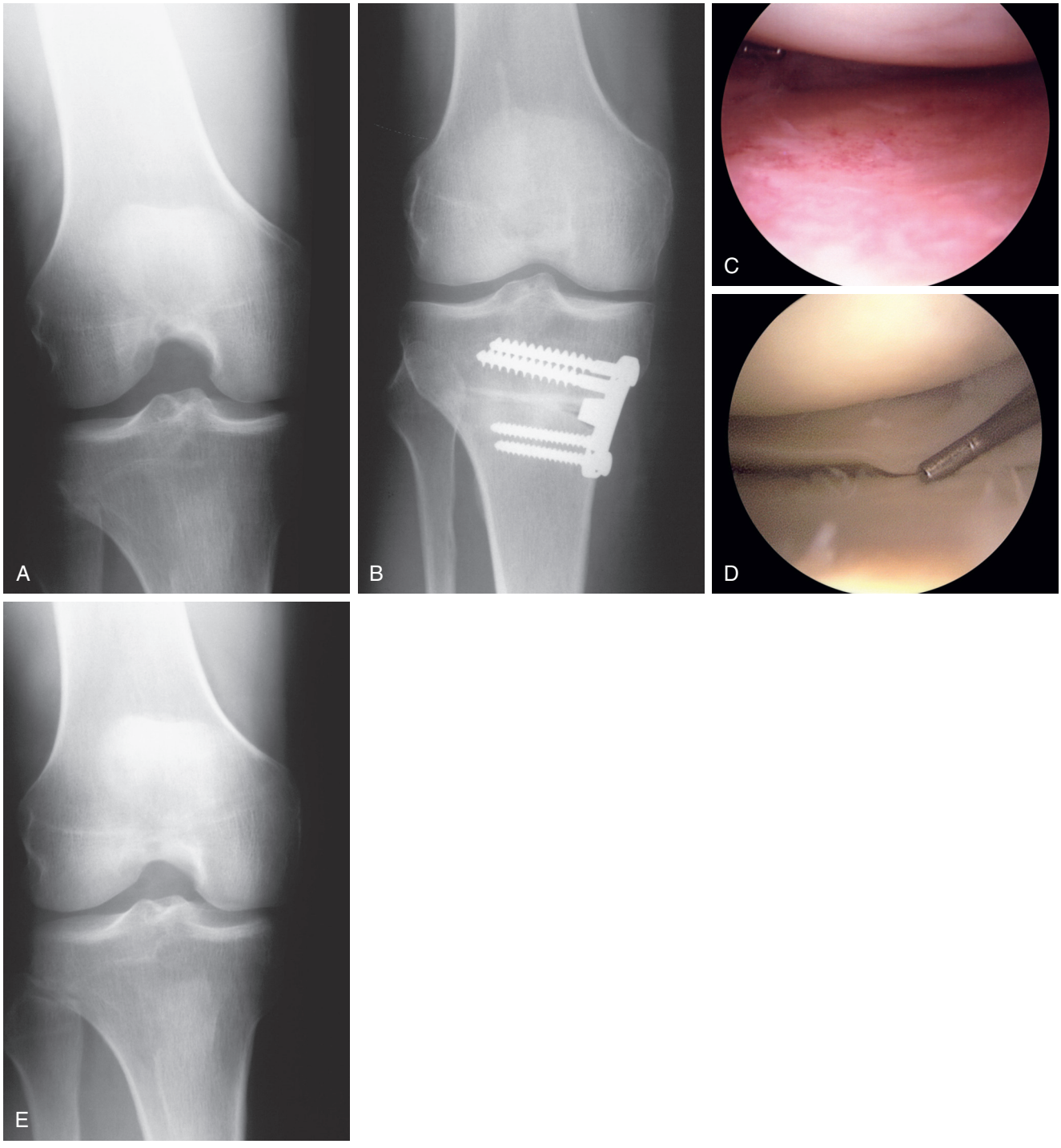


FIG 24-25 Case 6.

a varus malalignment, with the weight-bearing line at the 30% point. The patient ambulated with a varus thrust.

An opening wedge osteotomy was first performed to correct the varus osseous malalignment (see Fig. 24-25, *B*). At the time of surgery, the articular cartilage in the medial tibiofemoral compartment had minor fissuring and no subchondral bone exposed (see Fig. 24-25, *C*). Eight months later, an MMT was performed using a central bone bridge technique. The patient sustained a twisting injury 3 months postoperatively and presented with pain in the medial compartment. Arthroscopy was performed to assess the status of the transplant, which was determined to be normal (see Fig. 24-25, *D*).

Four months later, the patient presented with aching pain in the medial tibiofemoral compartment and pain after walking more than 10 minutes. Radiographs revealed a healed HTO and preserved medial joint space (see Fig. 24-25, *E*). The patient also had burning pain and tenderness to light touch along the anterior tibia. Marked atrophy was noted in the lower extremity. Three months later, the patient had not experienced relief from his symptoms, which were determined to be related to the arthritis and not to a complex regional pain syndrome. The patient subsequently underwent total joint replacement 17 months following the meniscus transplant.

Case 7. A 43-year-old male construction worker presented 4 months after a left medial meniscectomy. The patient complained of medial pain with daily activities and had not been able to return to work. An unloader brace had been prescribed, which provided minimal relief. Physical examination demonstrated normal knee motion, mild pain and crepitation to the medial compartment, no ligament instabilities, a normal lower extremity overall alignment, and moderate patellofemoral pain on compression. At the time of the patient's meniscectomy, noteworthy deterioration had been detected on the medial femoral condyle. Radiographs demonstrated only minimal narrowing of the medial compartment (Fig. 24-26, *A*). The patient was treated conservatively for 5 months with nonsteroidal antiinflammatory medications and physical therapy, but his symptoms continued.

Arthroscopy revealed a 20 × 20 mm area of subchondral bone exposure on the medial femoral condyle (see Fig. 24-26, *B*) and extensive fissuring and fragmentation on the undersurface of the patella. An osteochondral autograft transfer was performed on the medial femoral condyle (see Fig. 24-26, *C*). Eight months later, an MMT was performed, at which time excellent healing of the autograft bone plug in the medial femoral condyle was noted (see Fig. 24-26, *D*).

At follow-up, 5 years postoperatively, the patient had minimal pain and had returned to his construction occupation. No problems were incurred with walking on uneven ground or stair climbing. He had a normal range of motion, no tenderness to palpation to the medial joint line, and no effusion. Radiographs demonstrated preservation of the tibiofemoral compartment (see Fig. 24-26, *E*). An MRI revealed an intact transplant, with no displacement or extrusion and no increase in signal intensity (see Fig. 24-26, *F* and *G*).

Case 8. A 38-year-old man presented 3 months after a falling injury in which he landed directly onto his left knee. His history included a lateral meniscectomy at age 16 years, but he had not experienced knee-related symptoms until his recent injury. The patient had moderate pain and giving-way with activities. Physical examination demonstrated 10 mm of increased posterior tibial translation, 13 mm of increased lateral joint opening, 10 degrees of increased external tibial rotation, tenderness over the medial and lateral joint lines, and moderate crepitus in the lateral tibiofemoral compartment. Standing PA radiographs showed narrowing of the lateral compartment and stress radiographs revealed 6.5 of increased posterior tibial translation compared with the contralateral knee.

A PCL two-strand quadriceps tendon autograft reconstruction, a posterolateral reconstruction, and a lateral meniscus allograft were performed. At the latest follow-up evaluation, 5 years postoperatively, the patient had no symptoms and rated the overall condition of his knee as good. The KT-2000 (MEDmetric) showed 5 mm of increased AP displacement at 20 degrees of knee flexion and 9 mm of increase at 70 degrees of flexion. Physical examination showed no increase in lateral joint opening or external tibial rotation, a normal range of knee motion, no effusion, and no lateral joint line pain.

Case 9. A 19-year-old competitive soccer player sustained a left knee injury during a game that was treated 3 months later with an ACL B-PT-B autogenous reconstruction, a medial meniscus repair for a single longitudinal tear, and a lateral meniscus repair for a complex, double longitudinal tear that was 20 mm in length. She did well and returned to competitive soccer for 3 years until she had a gradual onset of left knee pain. MRI showed a complex tear to the lateral meniscus that was treated with an arthroscopic subtotal meniscectomy. At that time, noteworthy fissuring and fragmentation were found on the lateral tibial plateau, and a 10-mm area of subchondral bone exposure was noted on the lateral femoral condyle. Three months later, an LMT and an osteochondral autograft transfer to the lateral femoral condyle were performed. The patient did well and played soccer (against medical advice) for 7 years. She returned for a routine follow-up evaluation, at which time MRI demonstrated major extrusion of the transplant that was deemed nonfunctional. Because the patient was not experiencing symptoms, she elected conservative treatment and continued playing soccer for another 6 years. Thirteen years after the initial LMT, the patient developed symptoms, and arthroscopy demonstrated a complex tear of the LMT (Fig. 24-27, *A*) that was revised (Fig. 24-27, *B*). Extensive fissuring and fragmentation were noted on the medial and lateral femoral condyles, as well as the entire trochlea. At the latest follow-up evaluation, 2 years postrevision transplant, the patient was asymptomatic and rated her overall knee condition as very good. However, standing PA radiographs showed a moderate loss of joint space in the lateral tibiofemoral compartment (Fig. 24-27, *C*), and the patient was advised of the probability of a future TKA.

Case 10. An 18-year old women sustained a twisting injury playing basketball, underwent a lateral meniscectomy, and presented to our center 5 years later complaining of knee pain with all activities, occasional swelling, and a popping sensation in the anterior aspect of the right knee. Her symptoms were so severe she was unable to walk up and down stairs. A lateral meniscus transplant was performed, at which time a 10 × 10 mm area of erosion of the weight-bearing surface of the lateral condyle directly over the absent lateral meniscus was noted. The medial tibiofemoral and patellofemoral joints were pristine. The patient did well until, 5 years later, she experienced a popping sensation in the lateral aspect of her right knee. After nine additional episodes of locking, arthroscopy was performed. A tear of the lateral meniscus transplant was found and repaired in a satisfactory manner.

Twelve years later, the patient was seen for long-term follow-up (17.3 years posttransplant). She was asymptomatic with her activities that included walking 4 to 5 times a week and golfing. She rated the overall knee condition as very good. Follow-up MRI demonstrated normal joint space, with no meniscus extrusion into the joint (Figs. 24-28, *A* to *C*).

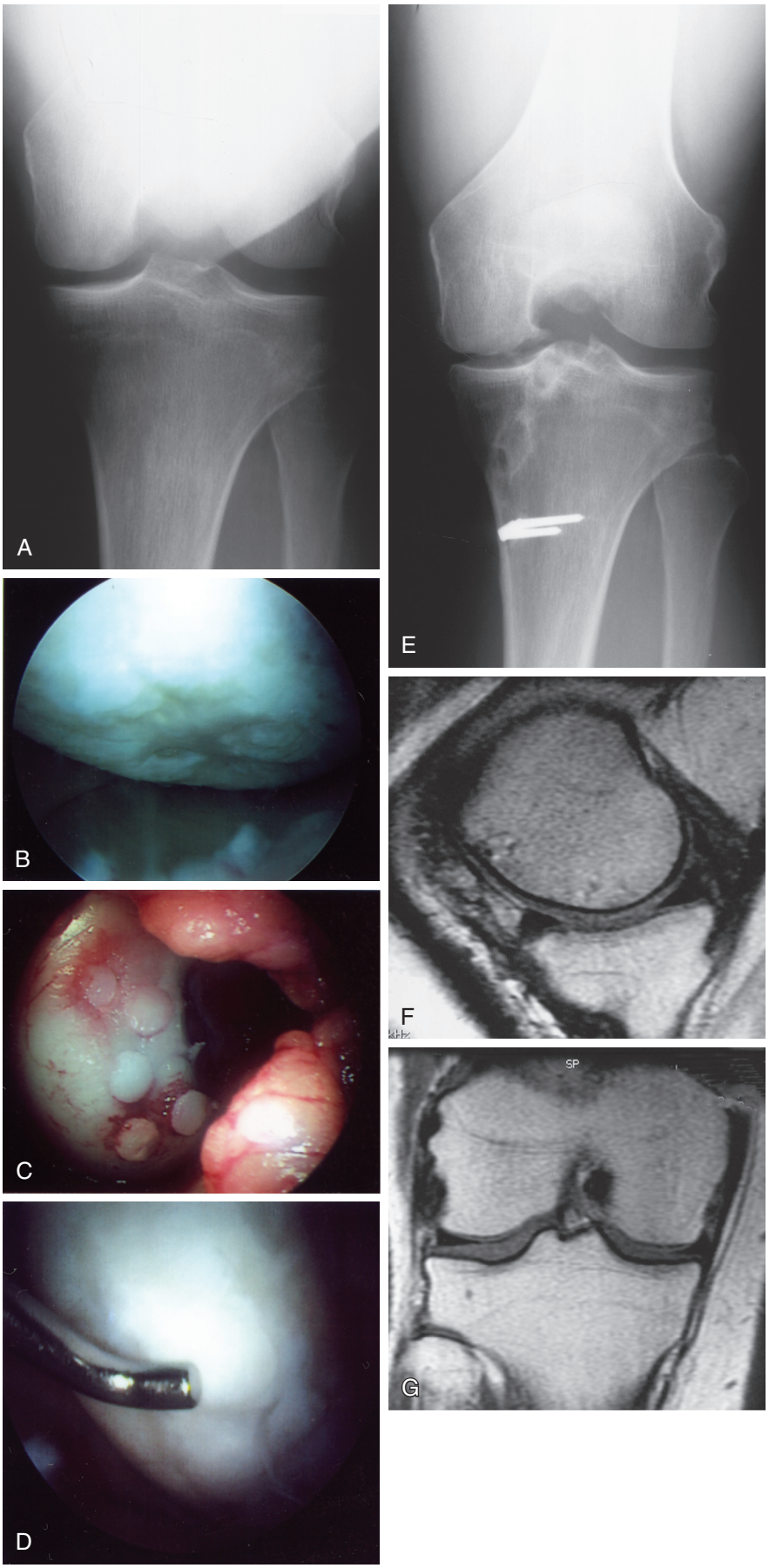


FIG 24-26 Case 7.

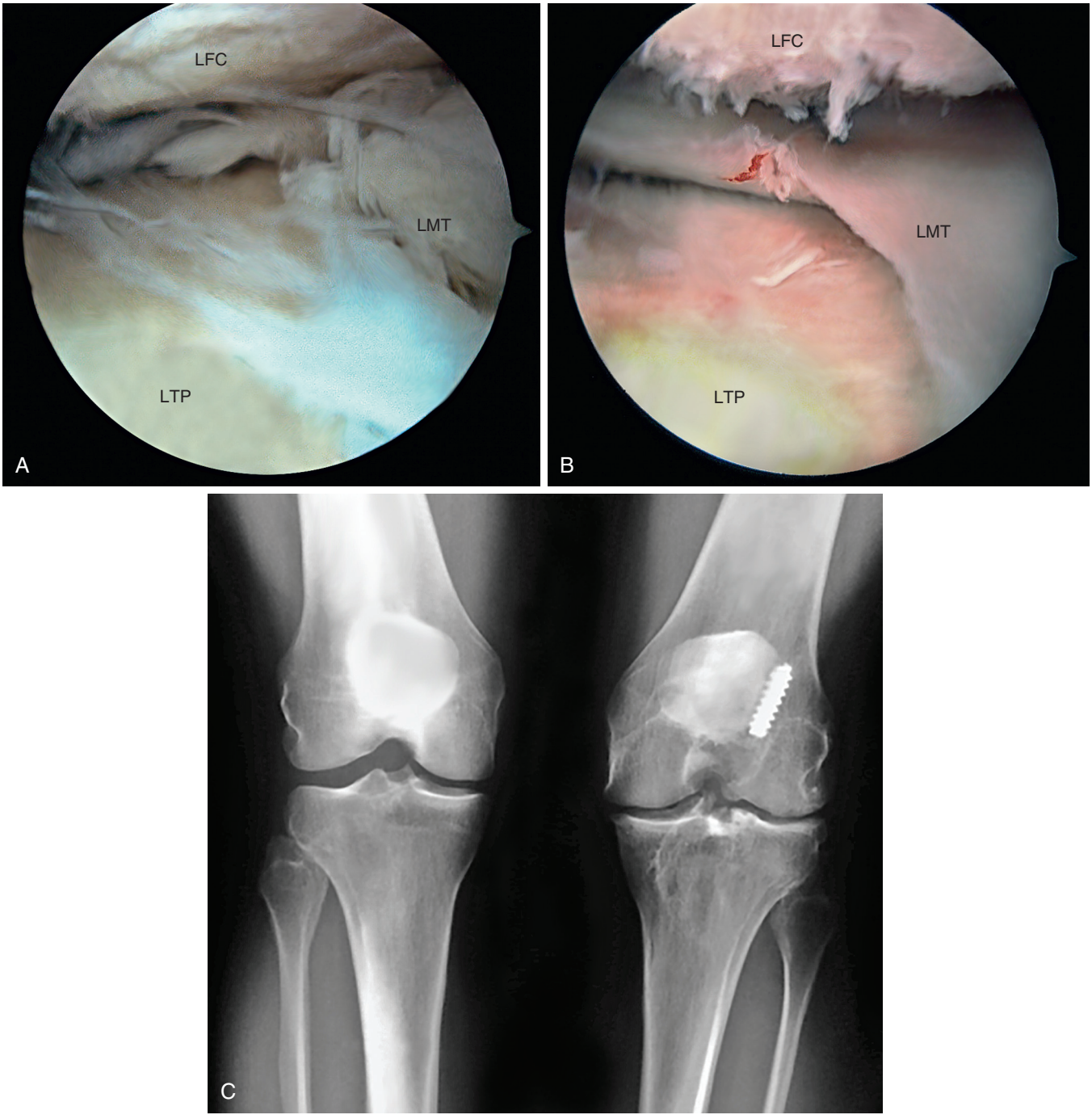


FIG 24-27 Case 9. *LFC,* Lateral femoral condyle; *LMT,* lateral meniscus transplant; *LTP,* lateral tibial plateau.

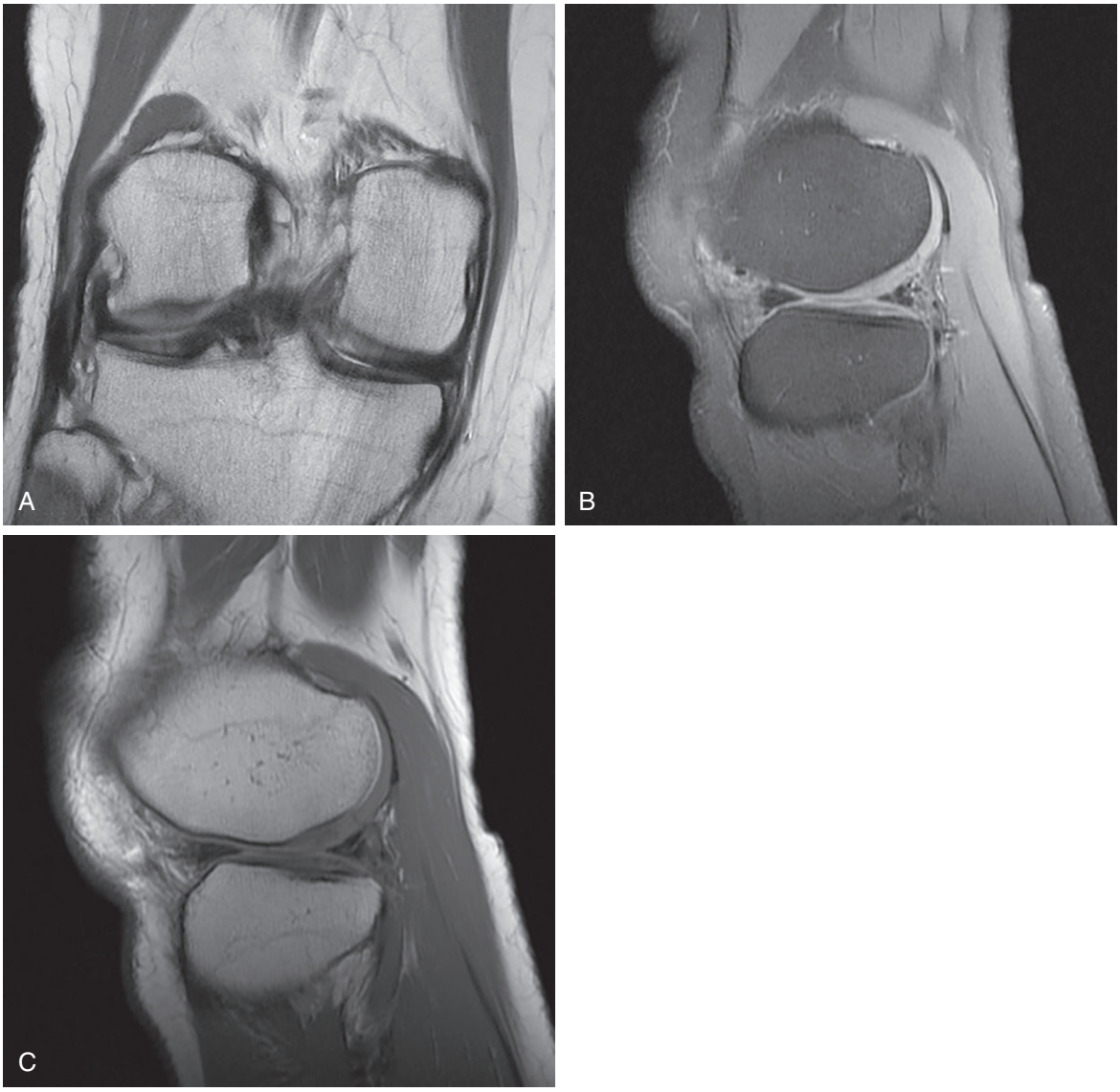


FIG 24-28 Case 10.

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Video Content

Video 23-3
Video 24-1
Video 24-2
Video 24-3
Video 24-4
Video 24-5
Video 24-6

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25

Rehabilitation of Meniscus Repair and Transplantation Procedures

Timothy P. Heckmann, Frank R. Noyes, Sue D. Barber-Westin

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CLINICAL CONCEPTS

The postoperative program for meniscus repair and transplantation is shown in Table 25-1. Because high compressive and shear forces can disrupt healing meniscus repair sites (especially radial repairs) and transplants, the initial goal is to prevent excessive weight bearing. Variations are built into the protocol according to the type, location, and size of the meniscus repair and whether concomitant procedures (such as ligament reconstructions) are performed. The surgeon has the responsibility to inform the physical therapy team of details regarding the type of tear and repair that was performed. Meniscus repairs with all-inside fixators have inferior holding strength and commonly, only a few sutures are used. These repairs require more protection during the first 6 postoperative weeks to allow for healing. Inside-out meniscus repair techniques, on the other hand, involve multiple vertical divergent sutures (see Chapter 23) and have superior holding strength.

Clinicians should be aware that meniscus repairs located in the periphery (outer third red-red [R/R] region) heal rapidly, whereas complex repairs that extend into the central third red-white (R/W) region tend to heal more slowly and require greater caution. In addition, modifications to the postoperative exercise program may be required if noteworthy articular cartilage deterioration is found during the arthroscopic procedure. This rehabilitation program has been used at our institution in hundreds of meniscus transplant and repair recipients, and the results of clinical investigations[3-5,7,8] demonstrate its safety and effectiveness in restoring normal knee motion, muscle, and gait characteristics.

Patients receive instructions before surgery regarding the postoperative protocol. Thus, they have a thorough understanding of what is expected after surgery. Patients are warned that an early return to strenuous activities such as impact loading, jogging, deep knee flexion, or pivoting carries a definite risk of a repeat meniscus tear or tear to the transplant. This is particularly true in the first 4 to 6 postoperative months.

Before surgery, the surgeon screens for any deep vein thrombosis (DVT) risk factors, including a prior patient or family history suggestive of an inherited coagulation defect. In women, all estrogen products and oral contraceptives are stopped 1 month before surgery.

The supervised rehabilitation program is supplemented with daily home exercises. The therapist routinely examines the patient in the clinic to implement and progress the appropriate protocol. Therapeutic procedures and modalities are used as required for successful rehabilitation. On average, patients require 11 to 16 physical therapy visits over a period of 9 to 12 months to produce a desirable result.

Lateral and anteroposterior plain radiographs are obtained 1 week after surgery to verify the position of the osseous component of meniscus transplants and at 6 to 8 weeks to verify healing and retention of the bony portion of the transplant within the slot or tunnels. Any onset of tibiofemoral joint line clicking or pain may indicate failure of the meniscus repair or transplant, and the surgeon should be notified immediately for consideration of refixation.

TABLE 25-1 Rehabilitation Protocol Summary for Meniscus Repairs and Transplants

	WEEKS					MONTHS			
	1-2	3-4	5-6	7-8	9-12	4	5	6	7-12
Long-leg postoperative brace	C, A, T	C, A, T	C, T						
Range of motion minimum goals:									
0-90 degrees	X								
0-120 degrees		X							
0-135 degrees			X						
Weight-bearing:									
Toe touch to 50% body weight	P								
75%-100% body weight		P							
Toe touch to 25% body weight	C, T, A								
50%-75% body weight		C, T, A	C, A						
100% body weight			T	C, A					
Patella mobilization	X	X	X						
Stretching: Hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X	X
Strengthening:									
Quadriceps isometrics, straight-leg raises, active knee extension	X	X	X	X	X	X	X	X	X
Closed-chain: gait retraining, toe raises, wall-sits, minisquats		P	C	X	X	X	X	X	
Knee flexion hamstring curls (90 degrees)			P	C	X	X	X	X	X
Knee extension quadriceps (90-30 degrees)			X	X	X	X	X	X	X
Hip abduction-adduction, multi-hip			X	X	X	X	X	X	X
Leg press (70-10 degrees)			P	P	X	X	X	X	X
Balance/proprioceptive training: Weight shifting, minitrampoline, BAPS, BBS, plyometrics	P	X	X	X	X	X	X	X	X
Conditioning:									
Upper body ergometer		X	X	X					
Bike (stationary)				X	X	X	X	X	X
Aquatic program					X	X	X	X	X
Swimming (kicking)					P, C	X	X	X	X
Walking					X	X	X	X	X
Stair-climbing machine					P, C	P, C	P, C	P, C	X
Ski machine					P	P	P	C	X
Running: straight*						P	P	C	X
Cutting: lateral carioca, figure-eights*							P	P	X
Full sports*							P	P	X

*Return to running, cutting, and full sports is based on multiple criteria (see text). Patients with noteworthy articular cartilage damage are advised to return to light recreational activities only.

A, All-inside meniscus repairs; *BAPS*, biomechanical ankle platform system (Patterson Medical); *BBS*, Biodex Balance System; *C*, complex red-white inside-out meniscus repairs; *P*, peripheral red-red meniscus repairs; *T*, transplants; *X*, all meniscus repairs and transplants.

CRITICAL POINTS Clinical Concepts

Initial rehabilitation goal: prevent excessive compressive and shear forces through limited weight bearing

General Postoperative Healing Expectations

- Rapid healing of peripheral meniscus repairs
- Delayed healing of complex meniscus repairs in middle third region
- Further delayed healing of meniscus transplants (1-2 yr)

Preoperative patient counseling and education during entire rehabilitation program are paramount.

Premature return to high-impact loading activities (jogging, deep knee flexion, pivoting) risks repeat meniscus tear or tear to transplant.

Obtain lateral and anteroposterior x-rays 1 and 6-8 weeks after meniscus transplantation to verify position of osseous component.

IMMEDIATE POSTOPERATIVE MANAGEMENT

Important early postoperative signs for the therapist to monitor include effusion, pain, gait, knee flexion and extension, patellar mobility, strength and control of the lower extremity, lower extremity flexibility, and tibiofemoral symptoms indicative of a meniscal tear (Table 25-2). The protocol to prevent DVT that includes aspirin (325 mg, 2 ×/day), compression dressings, thromboembolic hose, early ambulation, and active ankle pumps (performed hourly) is carefully followed.

Patients present to physical therapy on the first day after surgery on bilateral axillary crutches in a postoperative dressing with a long-leg brace locked in full extension. The postoperative bandage and dressing are changed to allow the application of thigh-high compression stockings and a compression bandage. Early control of postoperative effusion is essential for pain management and early quadriceps reeducation. In addition to compression, cryotherapy is critical during this time period. Patients receive a commercial cooling unit, which is used 6 to 8 times daily at home. In the clinic, the use of various cryotherapy

TABLE 25-2 Postoperative Signs and Symptoms Requiring Prompt Treatment

Postoperative Sign or Symptom	Treatment Recommendations
Continued pain in the medial or lateral tibiofemoral compartment of the meniscus repair or transplant	Physician examination, assess need for refixation or repeat repair
Tibiofemoral compartment clicking or a subjective sensation by the patient of "something being loose" within the tibiofemoral joint	Physician examination, assess need for refixation or repeat repair
Failure to meet knee extension and flexion goals	Overpressure program, early gentle manipulation under anesthesia if 0-135 degrees not met by 6 postoperative weeks
Decreased patellar mobility (indicative of early arthrofibrosis)	Aggressive knee flexion, extension overpressure program, or gentle manipulation under anesthesia to regain full ROM and normal patellar mobility
Decrease in voluntary quadriceps contraction and muscle tone, advancing muscle atrophy	Aggressive quadriceps muscle strengthening program, EMS
Persistent joint effusion, joint inflammation	Aspiration, rule out infection, close physician observation

From Heckmann T, Barber-Westin SD, Noyes FR. Meniscal repair and transplantation: Indications, techniques, rehabilitation, and clinical outcome. *J Orthop Sports Phys Ther.* 2006;36:795-814.
EMS, Electrical muscle stimulation; *ROM*, range of knee motion.

CRITICAL POINTS Immediate Postoperative Management

Early Postoperative Therapist Monitors:

- Knee effusion, pain, gait, flexion and extension, patellar mobility, lower extremity strength and flexibility, tibiofemoral joint symptoms
- Postoperative compression dressing, long-leg brace, compression stockings, cryotherapy, lower limb elevation, pain management

Common Complications:

- Excessive pain or swelling
- Quadriceps shutdown
- Limitation knee flexion, extension
- Saphenous nerve irritation

Early detection and treatment of complications are critical.

machines provides compression simultaneously with the cold program (Fig. 25-1).

Patients are instructed to maintain lower limb elevation as frequently as possible during the first week. A portable neuromuscular electric stimulator may be helpful for quadriceps reeducation and pain management (Fig. 25-2). These devices are used 4 to 6 times per day, 15 minutes per session, until the patient displays an excellent voluntary quadriceps contraction.

The patient's initial response to surgery and progression during the first 2 weeks sets the tone for the initial phases of the rehabilitation program. Common postoperative complications include excessive pain or swelling, quadriceps shutdown or loss of voluntary isometric contraction, range of motion (ROM) limitations, and saphenous nerve irritations for medial repairs. Monitor patient complaints of posteromedial or infrapatellar burning, posteromedial tenderness along the distal pes anserine tendons, tenderness of the Hunter canal along the medial thigh, hypersensitivity to light pressure, and hypersensitivity to temperature change. These abnormal symptoms or signs occur in early cases of complex regional pain syndrome (see Chapter 40) and require immediate medical treatment.



FIG 25-1 A clinical cryotherapy machine that provides compression with the cold program (Game Ready) is used in the initial postoperative period.



FIG 25-2 A portable neuromuscular electric stimulator (EMPI) is effective for quadriceps reeducation and pain management in the early postoperative phase.

BRACE AND CRUTCH SUPPORT

All patients receive a long-leg postoperative brace immediately after surgery to prevent hyperflexion and rotation of the knee that may damage the repair or transplant. The brace is opened from 0 to 90 degrees, but it is locked at 0 degrees of extension at night for the first 2 weeks. Thereafter, the brace is not routinely locked except in patients who cannot maintain 0 degrees of extension. In these cases, the brace

TABLE 25-3 Range of Motion, Flexibility, and Modality Use After Meniscus Repair and Transplantation

Postoperative Time	Frequency	Extension-Flexion Limits	Patellar Mobilization	Flexibility (5 reps × 20 sec)	EMS (20 min)	Cryotherapy (20 min)
1-2 wk	3-4 ×/day, 10-min sessions	0-90 degrees	Medial-lateral Superior-inferior	Hamstring, gastrocnemius-soleus	Yes	Yes
3-4 wk	3-4 ×/day, 10-min sessions	0-120 degrees	Medial-lateral Superior-inferior	Hamstring, gastrocnemius-soleus	Yes	Yes
5-6 wk	3 ×/day, 10-min sessions	0-135 degrees	Medial-lateral Superior-inferior	Hamstring, gastrocnemius-soleus	Yes	Yes
7-8 wk	2 ×/day, 10-min sessions	0-135 degrees	If required	Hamstring, gastrocnemius-soleus, quadriceps, iliotibial band	Yes	
9-52 wk	2 ×/day, 10-min sessions	Should be full	Hamstring, gastrocnemius-soleus, quadriceps, iliotibial band	Yes		

From Heckmann T, Barber-Westin SD, Noyes FR. Meniscal repair and transplantation: indications, techniques, rehabilitation, and clinical outcome. *J Orthop Sports Phys Ther.* 2006;36:795-814.
EMS, Electrical muscle stimulation.

CRITICAL POINTS Brace and Crutch Support

Brace Used for 4 Weeks

- Locked 0 degrees at night for first two postoperative weeks.
- Opened 0-90 degrees during the day.

is locked at 0 degrees of extension as required during the day and night. The brace is used for 4 weeks.

Crutches with partial weight bearing are recommended for the first 4 weeks in all cases. Weight bearing is gradually progressed as shown in Table 25-1, and patients are encouraged to use a normal gait that avoids a locked knee and assumes normal flexion throughout the gait cycle. Patients who had a repair of a radial meniscus tear are kept non–weight bearing for 4 weeks to protect the repair site.

RANGE OF KNEE MOTION AND FLEXIBILITY

Passive knee flexion and passive and active/active-assisted knee extension exercises are begun on the first postoperative day. Active knee flexion is limited to avoid hamstring strain to the posteromedial joint. ROM exercises are performed in seated position initially from 0 to 90 degrees. Flexion is gradually advanced to 120 degrees by the third to fourth week and 135 degrees by the fifth to sixth week (Table 25-3). Patients who had extensive repairs may be required to limit ROM to 0 to 90 degrees for the first 2 weeks. Knee motion exercises are performed 3 to 4 times daily until normal motion is achieved. Hyperextension is avoided in individuals who had anterior horn meniscus repairs.

If 0 to 90 degrees of knee motion is not easily achieved by the end of the first postoperative week, the patient may be at risk of a knee motion complication. Individuals who develop such a limitation are placed into a specific treatment program previously described in detail.[2,6] Overpressure exercises are usually successful in achieving the last few degrees of extension if initiated within the first few weeks after surgery. The patient props the foot and ankle on a towel to elevate the hamstrings and gastrocnemius, which allows the knee to drop into full extension. A 10- to 15-lb weight may be added to the distal thigh and

CRITICAL POINTS Range of Knee Motion and Flexibility

Begin passive flexion, passive and active-assisted extension exercises on first postoperative day, 0-90 degrees.

Advance Flexion

- Goal: 135 degrees by 5-6 weeks

Begin ROM Overpressure Program 1 wk After Surgery if 0-90 Degrees Not Achieved

- Extension: hanging weights, 10-min sessions
- Flexion: chair rolls, wall-slides, ERMI Knee Flexionator device

Patellar mobilization and flexibility exercises are paramount to achieving full ROM.

knee to stretch the posterior capsule (Fig. 25-3). This program is done for 10 minutes at a time, 6 to 8 times per day.

Flexion exercises are performed in seated position using the opposite lower extremity to provide overpressure (Fig. 25-4). Chair rolling, wall-sliding, passive quadriceps stretching, and ROM devices such as the ERMI Knee Flexionator are also helpful in regaining full knee flexion. No squatting exercises should be performed for at least 5 months because these exercises place large tensile forces on posterior meniscus repairs and transplants.

ROM exercises are accompanied by patellar mobilization (in the superior, inferior, medial, and lateral directions), which is paramount to achieve full knee motion (Fig. 25-5). Flexibility exercises, beginning with hamstring and gastrocnemius-soleus, are begun on the first postoperative day and are done 3 times per day. Quadriceps and iliotibial band flexibility exercises are incorporated at 7 to 8 weeks after surgery. Sustained static stretching is performed, with the stretch held for 30 seconds and repeated 5 times.

The knee motion program is effective because no patient in our clinical studies who had an isolated meniscus repair or transplant required further surgery for a knee motion complication. Only 2 of 193 patients who had meniscal repair and 4 of 38 patients who had a transplant required a gentle manipulation for a limitation of flexion.

In these six patients a major concomitant procedure, such as a cruciate ligament reconstruction, had been performed.

Close supervision and additional exercises to successfully restore normal knee motion may be required in patients who undergo combined procedures. No difference exists between medial and lateral meniscus repairs or transplants regarding knee motion complications.

BALANCE, PROPRIOCEPTION, AND NEUROMUSCULAR TRAINING

Restoration of normal neuromuscular function after meniscus repair and transplantation is paramount for a successful outcome. Knee joint proprioception and balance are crucial elements of neuromuscular function. Therefore balance and proprioception exercises are initiated as soon as patients achieve partial weight bearing, typically the first week after surgery. Crutches are used for support during these exercises until full weight bearing is allowed. Initially, patients perform weight shifting from side to side and front to back. Then gait retraining, including cup walking, is encouraged. This helps develop symmetry between the surgical and contralateral limbs, hip and knee flexion, quadriceps control during midstance, hip and pelvic control during midstance, and adequate gastrocnemius-soleus control during push-off (Fig. 25-6).

Tandem balance is begun during the partial weight-bearing phase to assist with position sense and balance. This is progressed to a single-leg balance exercise, which is done by pointing the foot straight ahead, flexing the knee to between 20 and 30 degrees, extending the arms outward horizontally, and positioning the torso upright with the shoulders above the hips and the hips above the ankles. The patient stands in position until balance is disturbed. A minitrampoline is used to make this exercise more challenging after it is mastered on a hard surface.

Many devices are available to assist with balance and gait retraining, including Styrofoam half rolls and whole rolls, and the Biomechanical Ankle Platform System (BAPS). Patients walk (unassisted) on Styrofoam half rolls to develop a center of balance, quadriceps control in midstance, and postural positioning. The BAPS board is used in double-leg and single-leg stance to promote proprioception. More sophisticated devices are also available (Fig. 25-7), including the Biodex



FIG 25-3 Extension overpressure hanging-weight exercise.



FIG 25-4 Flexion exercise using the opposite knee to apply pressure.



FIG 25-5 Patellar mobilization exercises (in the superior, inferior, medial, and lateral directions), which are paramount in regaining full range of motion, are initiated on the first postoperative day.

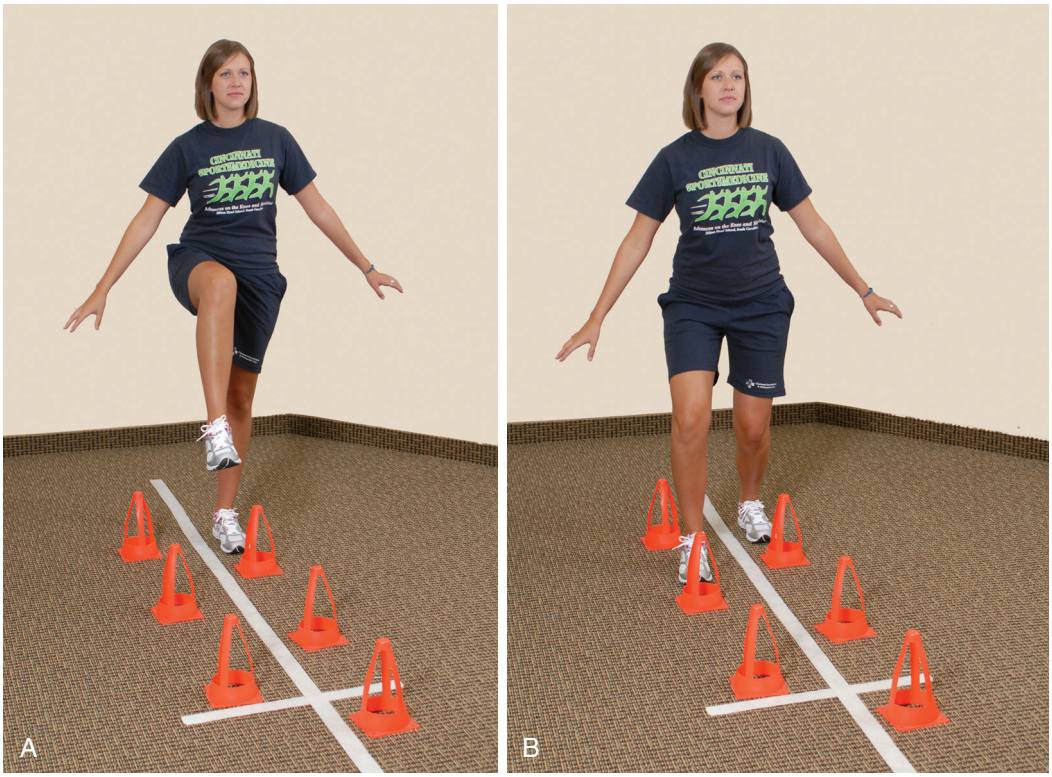


FIG 25-6 Cup walking is used early in postoperative recovery to develop symmetry between the surgical and the contralateral limbs, hip and knee flexion, quadriceps control during midstance, hip and pelvic control during midstance, and adequate gastrocnemius-soleus control during push-off. This exercise also facilitates quadriceps control to prevent knee hyperextension from occurring during gait.

CRITICAL POINTS **Balance, Proprioception, Neuromuscular Training**

Begin Balance, Proprioception Training 1 wk Postoperative

- Side-to-side weight shifting
- Cup walking
- Tandem balance
- Single-leg balance
- Styrofoam half and full rolls
- BAPS board, double-leg and single-leg stance
- Balance systems
- Computerized stability systems

Balance System and Neurocom Balance System. These devices provide visual feedback to assist with a variety of balance activities.

In patients who desire to return to sports activities, more advanced exercises to promote neuromuscular function are necessary. These include front step-downs, lateral step-downs, single-leg balance drills, progressive perturbation training with the therapist, and lunge exercises in various directions using a resistance cord onto an unstable surface. It is crucial that the patient be taught correct posture and form while performing these exercises. This includes avoiding varus or valgus lower limb alignment, maintaining knee flexion to prevent knee hyperextension, avoiding hip adduction and internal rotation, maintaining balance and control throughout the exercise, and landing softly to decrease ground reaction forces. The progression of exercises to running, pivoting/cutting, plyometrics, and return to full activities



FIG 25-7 A sophisticated balance device (Biodex) provides visual feedback to assist with a variety of balance activities.

is based on specific criteria described later. Plyometric exercises are especially important in younger athletic patients who have an associated anterior cruciate ligament (ACL) reconstruction.

STRENGTHENING

The strengthening program is begun on the first postoperative day with quadriceps isometrics, straight-leg raises (Fig. 25-8), and active-assisted knee extension from 90 to 30 degrees (Table 25-4). Initially, straight-leg raises are performed in the flexion plane only. The patient must achieve a sufficient quadriceps contraction to eliminate an extensor lag before adding straight-leg raises in the other three planes (abduction, adduction, and extension). These exercises are performed as 3 to 5 sets of 10 repetitions, and this set/repetition rule allows for systematic progression of ankle weights as tolerated.

At weeks 3 to 4, weight-bearing exercises are begun. Toe raises for gastrocnemius-soleus strengthening, wall-sits, and minisquats for quadriceps strengthening are initiated when patients are 50% weight bearing. Wall-sits (Fig. 25-9) and minisquats (Fig. 25-10) are begun at 5 to 6 postoperative weeks after meniscal transplantation. These activities should be limited from 0 to 60 degrees of flexion to protect the posterior horn of the meniscus.

Wall-sitting isometrics can be made more challenging by modifying the exercise technique. First, the patient can voluntarily set the quadriceps muscle once he or she reaches the maximum knee flexion angle, which is typically between 30 and 45 degrees. This contraction and knee flexion position are held until muscle fatigue occurs. In a second modification, designed to promote a stronger vastus medialis obliquus contraction, the patient performs a hip adduction contraction by squeezing a ball between the distal thighs. In a third variation, the patient holds dumbbell weights in the hands to increase body weight, which promotes an even a stronger quadriceps contraction. The patient can shift their body weight over the involved side to simulate a single-leg contraction, or perform the wall-sit on just one leg.

Minisquats are initially done using the patient's body weight as resistance. Gradually, TheraBand or surgical tubing is used as a resistance mechanism. The depth of the squat is controlled to protect the meniscus repair or transplant and the patellofemoral joint. Quick, smooth, rhythmic squats are performed at a high-set/high-repetition cadence to promote muscle fatigue. Hip position is important to monitor to emphasize work on the quadriceps.

Open kinetic chain non–weight-bearing exercises are begun 5 to 6 weeks after surgery (see Table 25-4). Knee extension progressive resistive exercises (PREs) are initiated from 90 to 30 degrees to protect the patellofemoral joint.[1] By keeping the quadriceps exercises in this protected ROM, minimal forces will be placed along peripheral and midsubstance repair sites. Progression from ankle weights to machines occurs as the patient progresses the amount of weight in the exercise program. Quadriceps control is critical for program progression.

CRITICAL POINTS Strengthening

First Postoperative Day

- Quadriceps isometrics
- Straight-leg raises
- Active-assisted knee extension, 90-30 degrees

Postoperative Weeks 3 to 4

- Toe raises
- Wall-sits (0-60 degrees)
- Minisquats (0-60 degrees)

Delay wall-sits, minisquats until 7 to 8 weeks after meniscus transplantation.

Postoperative Weeks 5 to 6

- Open kinetic chain knee extension 90-30 degrees
- Hamstring curls 0-90 degrees (delayed until 7-8 weeks after complex meniscus repair, 9-12 weeks after transplant)
- Leg press machine 70-10 degrees (delayed 9-12 weeks after transplant)
- Multiangle hip machine



FIG 25-8 Straight-leg raises shown in hip extension (**A**), flexion (**B**), adduction (**C**), and abduction (**D**) planes.

TABLE 25-4 Muscle Strengthening Exercises after Meniscus Repair and Transplantation*

Postoperative Time, Frequency	Quadriceps Isometrics (Active)	Straight-Leg Raises	Knee Extension (90-30 Degrees)	Toe Raises	Wall-Sits (to Fatigue)	Minisquats	Lateral Step-ups (5- to 10-cm Block)	Hamstring Curls (0-90 Degrees)	Multihip (Flex, Ext, Abd, Add)	Leg Press (70-10 Degrees)
1-2 w 3 ×/day, 15 min	1 set × 10 reps (every hour)	Flex; 3 sets × 10 reps	Active-assisted 90-0 degrees all but anterior horn repairs, 90-30 degrees, 3 sets × 10 reps							
3-4 wk 2-3 ×/day, 20 min	Multi-angle 0, 60 degrees; 1 set ×10 reps each	Flex, ext, add; 3 sets × 10 reps	Active-assisted 90-0 degrees all but anterior horn repairs, 90-30 degrees, 3 sets × 10 reps	**Meniscus repairs only** 3 sets × 20 reps	**Meniscus repairs only** 3 sets × 3 reps	**Meniscus repairs only** 3 sets × 20 reps				
5-6 wk 2 ×/day, 20 min	Multiangle 30, 60, 90 degrees; 2 sets × 10 reps	Add ankle weight ≤10% of body weight; 3 sets × 10 reps	Active, 90-30 degrees, 3 sets × 10 reps	**Transplants start** **Meniscus repairs** Add heel raises, 3 sets × 10 reps	**Transplants start** 3 sets × 3 reps	**Transplants start** 3 sets × 20 reps		**Peripheral repairs only** Active, 3 sets × 10 reps	3 sets × 10 reps	**Peripheral repairs only** 3 sets × 10 reps
7-8 wk 2 ×/day, 20 min		Add abd; 3 sets × 10 reps Add rubber tubing, 3 sets × 30 reps	Active, 90-30 degrees with resistance, 3 sets × 10 reps	**Transplants** Add heel raises, 3 sets × 10 reps	3 sets × 3 reps	3 sets × 20 reps	3 sets × 10 reps	**All meniscus repairs** Active, 3 sets × 10 reps	3 sets × 10 reps	**Peripheral repairs only** 3 sets × 10 reps
9-12 wk 2 ×/day, 20 min		3 sets × 10 reps Rubber tubing, 3 sets × 30 reps	Active, 90-30 degrees with resistance, 3 sets × 10 reps		3 sets × 3 reps	Add rubber tubing, 0-40 degrees, 3 sets × 20 reps	3 sets × 10 reps	**Transplants start** Active, 3 sets × 10 reps	3 sets × 10 reps	**Transplants start** 3 sets × 10 reps
13-26 wk 2 ×/day, 20 min		Rubber tubing, high speed, 3 sets × 30 reps	Active, 90-30 degrees with resistance, 3 sets × 10 reps			3 sets × 20 reps		Add resistance, 3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
27-52 wk 1 ×/day, 20-30 min		Rubber tubing, high speed, 3 sets × 30 reps	Active, 90-30 degrees with resistance, 3 sets × 10 reps			3 sets × 20 reps		With resistance, 3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps

*Exercises done by recipients of either meniscus repair or transplantation unless otherwise indicated.
Abd, Abduction; *Add*, adduction; *Ext*, extension; *Flex*, flexion.



FIG 25-9 Wall-sit exercises are begun 3 to 4 weeks after meniscus repair and 5 to 6 weeks after meniscal transplantation. These exercises are limited from 0 to 60 degrees of flexion to protect the posterior horn of the meniscus.



FIG 25-10 Minisquats, begun 3 to 4 weeks after meniscus repair and 5 to 6 weeks after meniscal transplantation, are an effective quadriceps strengthening exercise.

Hamstring curls from 0 to 90 degrees are initiated in patients who had peripheral meniscus repairs at the same time as the knee extension PREs. Care should be taken to avoid hyperextension, which places tension on the posterior capsule. This exercise is delayed until at least 7 to 8 weeks after a complex meniscus repair and until 9 to 12 weeks after meniscus transplantation. Isolated resisted hamstring curls are limited in complex repairs and transplants owing to the medial hamstring insertion along the posteromedial joint capsule. This limitation is designed to lessen potential traction forces being imposed onto the repair site. Initially, hamstring curls are done with Velcro ankle weights; then the exercise is progressed to weight machines.

A leg press machine is initiated in the range of 70 to 10 degrees at 5 to 6 weeks after all meniscus repairs and at 9 to 12 weeks after transplantation. The limitation in flexion is incorporated owing to the increased load placed on the posterior horn of the meniscus after 60 to 70 degrees of flexion.

Side-lying straight-leg raises are initiated early in the rehabilitation program. Later, when patients have access to equipment, the seated abduction-adduction machine and cable column or multihip machine for hip flexion, extension, abduction, and adduction are also included in the exercise program. These activities are implemented at 5 to 6 weeks after surgery.

CONDITIONING

A cardiovascular program may begin as early as 2 to 4 postoperative weeks if the patient has access to an upper body ergometer (Table 25-5). Stationary bicycling is begun 7 to 8 weeks after surgery. The seat height is adjusted to its highest level based on patient body size and a low-resistance level is used. A recumbent bicycle may be substituted in patients that have damage to the patellofemoral joint articular cartilage or anterior knee pain.

Water walking may be implemented during this timeframe. Walking in waist-high water decreases the impact load to the knee by 50%. To protect the healing meniscus, swimming with straight-leg kicking and dry land walking programs are initiated between the ninth and twelfth weeks. At this time, patients who had a meniscus repair may also begin using stair-climbing, elliptical cross-trainers, or cross-country ski machines. Protection against high stresses to the patellofemoral joint is required in patients with symptoms or articular cartilage damage. If a stair-climbing machine is tolerable, a short step is maintained with low resistance levels. The cardiovascular program should be done at

CRITICAL POINTS Conditioning

Postoperative Weeks 2-4
- Upper body ergometer

Postoperative Weeks 7-8
- Stationary bicycling (patellofemoral joint precautions)
- Water walking

Postoperative Weeks 9-12
- Swimming with straight-leg kicking
- Walking
- Stair-climbing machine
- Elliptical cross-trainer
- Cross-country ski machine

Cardio program should be done 3 times/wk, in 20- to 30-min sessions.
Exercise level should be at least 60%-85% of maximal heart rate.

TABLE 25-5 Aerobic Conditioning Exercises After Meniscus Repair and Transplantation*

Postoperative Time, Frequency	UBE	Stationary Bicycle	Water Walking	Swimming	Walking	Stair-Climbing Machine (Low Resistance and Stroke)	Ski Machine (Short Stride and Level and Low Resistance)	Running (Straight)	Cutting	Functional Training
3-4 wk, 1-2 ×/day	10 min									
5-6 wk, 2 ×/day	10 min									
7-8 wk, 1-2 ×/day	15 min	15 min								
9-12 wk, 1 ×/day (select one activity per session)		15 min	15 min	15 min	15 min	Meniscus repairs only, 15 min	Meniscus repairs only, 15 min			
13-26 wk, 3 ×/week (select one activity per session)		20 min	20 min	20 min	20 min	Meniscus repairs only, 20 min	Meniscus repairs only, 20 min			
20 wk, 3 ×/wk, peripheral meniscus repairs only†								Jog ¼ mile, walk ⅛ mile, backward run 20 yards		
27 wk and beyond 3 ×/wk (select one activity per session)		20-30 min	20-30 min	20-30 min	20-30 min	20-30 min	20-30 min		Lateral, carioca, figure-eights, 20 yards	Plyometrics box hops, level, double-leg 15 sec, 4-6 sets, sports-specific drills 4-6 sets
30 wk and beyond								Complex meniscus repairs start 30 wk postoperative; advance program as needed	**Complex meniscus repairs start** >35 wk postoperatively; advance program as needed	**Complex meniscus repairs start** >35 wk postoperatively; advance program as needed
12 months and beyond								Transplants start, with precautions		

From Heckmann T, Barber-Westin SD, Noyes FR. Meniscal repair and transplantation: indications, techniques, rehabilitation, and clinical outcome. *J Orthop Sports Phys Ther.* 2006;36:795-814.

*Exercises done by recipients of either meniscus repair or transplantation unless otherwise indicated.

†Begin running program when ≤30% deficit elicited on isokinetic testing; begin cutting program when ≤20% deficit elicited on isokinetic testing.

UBE, Upper body ergometer.

least three times a week for 20 to 30 minutes and the exercise performed to at least 60% to 85% of maximal heart rate.

RUNNING PROGRAM

A running program is begun at approximately 16 to 20 weeks postoperative in patients who had peripheral meniscus repairs and who have no more than a 30% deficit in average peak torque for the quadriceps and hamstrings on isometric testing performed on a Biodex dynamometer. This program is delayed until approximately 30 postoperative weeks in patients who had complex meniscus repairs and until at least 1 year in patients who had a meniscus transplant.

Isometric muscle testing is initially performed at an angle of 60 degrees of knee flexion, which places the knee in a protected position for both the meniscus and patella. Progression to isokinetic testing at high speeds is important, but the initial goal is to test the integrity of the quadriceps and hamstring musculatures. Other testing parameters worth evaluating include peak torque/body weight ratios, agonist/antagonist ratios, and time to peak torque values.

Patients begin with a walk/run combination program, using running distances of 18, 37, 55, and 91 meters. Initially, patients run at 25% to 50% of their normal speed. Once patients can run straight ahead at full speed, lateral and crossover maneuvers are added. Short distances (such as 18 m) are used to work on speed and agility. Side-to-side running over cups may be used to facilitate agility and proprioception. Figure-eight and carioca running drills are also useful.

CRITICAL POINTS Running and Plyometrics

Running, Begin

- 16-20 postoperative wk in peripheral meniscus repairs
- 30 postoperative wk in complex meniscus repairs
- Minimum 1 yr postoperative in meniscus transplants

Patient must demonstrate ≤30% deficit quadriceps and hamstrings peak torque on isometric testing.

Use Walk/Run Program Initially

- 18, 37, 55, 91 m
- 25%-50% normal running speed, straight
- Progress to 100% speed

Add lateral, crossover, side-to-side, figure-eights, carioca drills for agility.

Plyometric Training

- Patient should be able to run straight ahead at full speed with no symptoms
- Begin at 6-9 postoperative mo after meniscus repair
- Majority of meniscus transplant patients are not candidates for this program

Considerations

- Surface: firm but forgiving such as wooden gym floor; avoid hard surfaces such as concrete
- Footwear: cross-training or running shoe; check wear patterns, outer sole wear
- Warm-up: include light cardiovascular workout

Training Progression

- Begin with level surface box hopping on 4-square grid
- Double-leg jump initially, land in flexion
- Complete four levels
- Single-leg hops
- Vertical box hopping

PLYOMETRIC TRAINING

Progressive plyometric training is initiated upon successful completion of the running program. This training program is typically begun after 6 months of surgery in patients who have had a large peripheral or complex repair. In patients who had a radial meniscus repair, this program may be delayed until 9 months postoperative, owing to the disruption that occurred in the hoop stresses of the meniscus. The majority of patients who undergo meniscal transplantation have noteworthy articular cartilage deterioration and are not candidates for strenuous plyometric training.

Plyometric training starts in individual sessions performed in a manner similar to interval training. Initially, a rest period is incorporated that lasts 2 to 3 times the length of the exercise period; this is gradually decreased to 1 to 2 times the length of the exercise period. Plyometrics are performed 2 to 3 times each week in addition to strength and cardiovascular endurance exercises. Plyometrics should be done on a surface that is firm, yet forgiving, such as a wooden gym floor. Very hard surfaces such as concrete should be avoided. In addition, a cross-training or running shoe should be worn to provide adequate shock absorption as well as adequate stability to the foot. Checking wear patterns and outer sole wear will help avoid overuse injuries.

The program beings with level-surface box-hopping. A four-square grid of four equally sized boxes is created on the floor with tape. The patient first jumps with two legs from box 1 to box 3 (front to back) and then from box 1 to box 2 (side to side). This drill is initially performed using both legs, with the body weight kept on the balls of the feet. The patient jumps as fast as possible with the knees bent and lands in flexion to avoid knee hyperextension. It is important for the patient to focus on limb symmetry during this exercise.

The initial exercise time period lasts 15 seconds, with the patient completing as many jumps between the squares as possible. Three sets are performed for both directions, and the number of jumps is recorded. Progression of the program occurs as the number of jumps, as well as patient confidence, improves. This exercise has four levels. The first level includes front-to-back and side-to-side jumping, as previously described. The second level incorporates both of the directions in level one into one sequence and also includes jumping in both right and left directions (i.e., box 1 to box 2 to box 4 to box 2 to box 1). Level three progresses to diagonal jumps, and level four includes pivot jumps in a 180-degree direction. When the patient can perform level-four double-leg jumps, similar exercises are initiated using single-leg hops.

For patients who undergo a combined meniscus repair and ACL reconstruction, advanced plyometric training is recommended before release to strenuous high-risk sports activities such as soccer and basketball. This program is described in detail in Chapter 14. The program is applicable for both female and male athletes.

RETURN TO SPORTS ACTIVITIES

Sport-specific drills and cutting patterns of 45- and 90-degree angles may be implemented, based on the patient's athletic goals. Repeat isokinetic testing is typically performed monthly, progressing from isometric testing for the first 6 months to isokinetic testing at speeds of 180 and 300 degrees per second. This testing not only provides the patient with feedback on performance but also serves to assist the clinician with program progression. Goals for testing should be at least 70% to begin running and 90% for full activity for the bilateral torque

CRITICAL POINTS Return to Sports Activities

- Sports-specific drills completed based on patient goals
- Successful completion of running and functional training
- ≤10% deficit quadriceps and hamstrings peak torque on isokinetic testing
- No symptoms
- ≤15% deficit single-leg hop tests
- >60% normalized knee separation distance on drop-jump test
- Trial of function recommended; monitor for overuse symptoms
- Majority of meniscus transplant patients not candidates owing to joint damage; encourage low-impact activities, weight control

comparisons and approximately 60% for agonist/antagonist ratios. Torque/body weight ratios are based on age, sex, and body weight parameters.

Return to sports activities is based on successful completion of the running and functional training program. A trial of function is encouraged, during which time the patient is monitored for overuse symptoms. For patients who undergo a combined meniscus repair and ACL reconstruction, the following is recommended for release to unrestricted athletics:

- Isokinetic test 180 degrees/sec and 300 degrees/sec quadriceps, hamstrings: 10% deficit or less
- No pain, swelling, patellofemoral crepitus
- Lachman, KT-2000 (MEDmetric) arthrometer test: less than 3 mm increase over opposite side
- Single-leg hop tests: less than 15% deficit[9]
- Successful completion of advanced plyometric training
- More than 60% normalized knee separation distance on video drop-jump test[10]
- No valgus motion or medial-lateral movement of knee on single-leg squat test[11]

The majority of patients who undergo meniscal transplantation have noteworthy articular cartilage deterioration and are not candidates for strenuous plyometric training or sports activities. Return to low-impact activities is therefore recommended for these individuals.

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Tibial and Femoral Osteotomy for Varus and Valgus Knee Syndromes: Diagnosis, Osteotomy Techniques, and Clinical Outcomes

Frank R. Noyes, Sue D. Barber-Westin

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Video 26-2 High Tibial Osteotomy: Techniques and Surgical Results
Video 26-3 Rehabilitation After High Tibial Osteotomy and Joint Replacement

INDICATIONS

High tibial osteotomy (HTO) has gained wide acceptance as a treatment option for patients with medial tibiofemoral osteoarthritis and varus deformity of the lower extremity. Most candidates are in their third to fifth decade and wish to remain active and avoid unicompartmental or total knee replacement. The recommendations for this procedure are derived from a careful evaluation of subjective symptoms, findings on physical examination, and radiographic evidence of malalignment and arthritis.

The predominant indication for HTO is lower limb osseous malalignment (Fig. 26-1) in younger patients who have medial tibiofemoral joint pain and wish to maintain an active lifestyle. The goal is to correct the mechanical abnormality of excessive loading of the medial tibiofemoral compartment by redistributing weight-bearing loads onto the lateral compartment. Varus malalignment is present when the weight-bearing line (WBL) crosses less than 50% of the mediolateral transverse width of the tibial plateau.

Unfortunately, a prior medial meniscectomy is a major risk factor for progression of arthritis in these knees. Because any underlying arthritis is expected to progress,[190] it is advisable to perform HTO while the joint damage is in the early stages before the development of severe articular cartilage deterioration and loss of tibiofemoral joint space.[62,67,214]

One advantage of performing HTO in young patients who have early medial tibiofemoral arthritis after medial meniscectomy is the opportunity to also perform a meniscus transplant and a cartilage restoration procedure if indicated.

The appropriate level of physical activity that can be recommended after HTO remains questionable. Patient education is important so that activity limitations to be followed postoperatively are well understood. The goal of the osteotomy is to allow an active, pain-free lifestyle that includes low-impact recreational pursuits but not high-loading athletics that involve twisting, jumping, and pivoting.

The majority of patients who undergo HTO are age 50 years or younger with varus malalignment and mild to moderate medial tibiofemoral joint arthritis. Many patients have had a prior medial meniscectomy. Patients older than 60 years are usually candidates for partial or total joint replacement. The difficult decision is the treatment recommendation for patients between 50 and 60 years old. With the increasing longevity of unicompartmental knee replacements, patients who have advanced medial compartment damage with major areas of bone exposure will likely experience symptoms after HTO and are better candidates for partial replacement. Individuals who undergo a unicompartmental replacement may participate in recreational activities similar to those who undergo HTO. Osteotomy is performed in patients 50 years old and younger who are athletically active, have remaining medial tibiofemoral cartilage (although thinned), and wish to maintain reasonable athletic pursuits such as tennis and skiing. These patients have early medial compartment symptoms; however, the joint damage is not advanced to a bone-on-bone state that would warrant unicompartmental replacement. Careful patient selection is the key issue, and the surgeon should not overstate or guarantee results of an HTO because the arthritis will eventually progress. In short, the goal of an HTO is to buy time in younger-aged patients (hopefully 10-15 years) before joint replacement. If there is any question that the arthritis of the medial tibiofemoral compartment is advanced to the point where the HTO will not last 10 years, it is preferable in patients age 50 years or older to perform a partial replacement. This is particularly true for sedentary patients in whom the goals of ambulating activities are achieved with partial joint replacement, avoiding the more prolonged postoperative recovery from an HTO.

There exists a group of varus-angulated knees with associated symptomatic ligament deficiencies requiring reconstruction. These ligament deficiencies most commonly involve the anterior cruciate ligament (ACL) and posterolateral structures (fibular collateral ligament [FCL], popliteus muscle-tendon-ligament unit [PMTL] and posterolateral capsule). In these double and triple varus knees, a normal



FIG 26-1 Bilateral varus malalignment in a 40-year-old man who presented with bilateral medial joint pain after 1 to 2 hours of ambulation.

CRITICAL POINTS Indications

- Varus osseous malalignment: weight-bearing line <50% of tibial width
- Mild to moderate symptomatic arthrosis medial tibiofemoral compartment
- Articular cartilage retained in medial tibiofemoral compartment
- To achieve normal limb alignment before:
  - Medial meniscus transplant
  - Articular cartilage restorative procedures
  - Cruciate ligament or posterolateral reconstruction in double and triple varus knees
- Patients ≤50 years old, athletically active, wishing to maintain reasonable athletic pursuits

axial alignment must be achieved before proceeding with ligament reconstructive procedures. Lower limb varus malalignment is not overcorrected to valgus when there is no damage to the articular cartilage in the medial tibiofemoral compartment. The goal in these patients is to correct the varus to a neutral alignment and then proceed in a staged manner with a cruciate and posterolateral reconstruction as required. Correction of the varus alignment decreases the risks of failure of the ligament reconstructive procedures.[153,155,158,160]

CONTRAINDICATIONS

One commonly debated issue regarding contraindications to osteotomy is the extent of damage to the medial tibiofemoral compartment. In general, HTO is avoided in knees in which there is more than a 15 × 15 mm area of exposed bone on both the tibial and femoral surfaces. There are knees in younger patients in which the area of exposed bone may be greater and partial replacement is not an option. However, as a general rule, remaining articular cartilage should be present over the majority of the medial joint surfaces.

Major concavity of the medial tibial plateau with loss of bone stock is a contraindication to HTO.[115] On standing 45-degree posteroanterior (PA) radiographs,[184] knees that demonstrate no remaining articular cartilage space to the medial compartment are not candidates. An arthroscopic procedure just before HTO helps to assess the amount of remaining articular cartilage and remove symptomatic meniscus fragments and other tissues.

Additional contraindications are a limitation of knee flexion (>10 degrees), lateral tibial subluxation (>10 mm), prior lateral meniscectomy, or lateral tibiofemoral joint damage.[115]

An absolute contraindication for a medial opening wedge osteotomy is the use of nicotine products in any form. The complication of a nonunion is not worth the risk, and a minimum of 8 to 12 weeks of abstinence before surgery is required. The patient is warned that there may still be an increased risk in regard to osteotomy healing.

A relative contraindication is a body weight over 200 lb (91 kg; Fig. 26-2). Although there may be some patients in whom HTO is indicated that weigh up to 225 lb (102 kg), this operation is avoided in patients

CRITICAL POINTS Contraindications

- Medial tibiofemoral compartment bone exposure over an area >15 × 15 mm on femur and tibia
- Major concavity medial tibial plateau, loss of bone stock
- No joint space in medial compartment on standing 45-degree PA radiographs
- Patients 50-60 years old with advanced medial compartment damage (candidates for unicompartmental knee replacement)
- Patient >60 years old (candidates for partial or total joint replacement)
- >10 degrees of limitation of knee flexion
- >10 mm of lateral tibial subluxation
- Prior total lateral meniscectomy, lateral tibiofemoral cartilage damage
- Use of products containing nicotine
- Obesity (body mass index >30)
- Increased slope to affected medal tibial plateau; teeter-totter knee
- Marked symptomatic and advanced patellofemoral arthrosis
- Prior joint infection, diabetes, rheumatoid arthritis, autoimmune diseases, malnutrition state

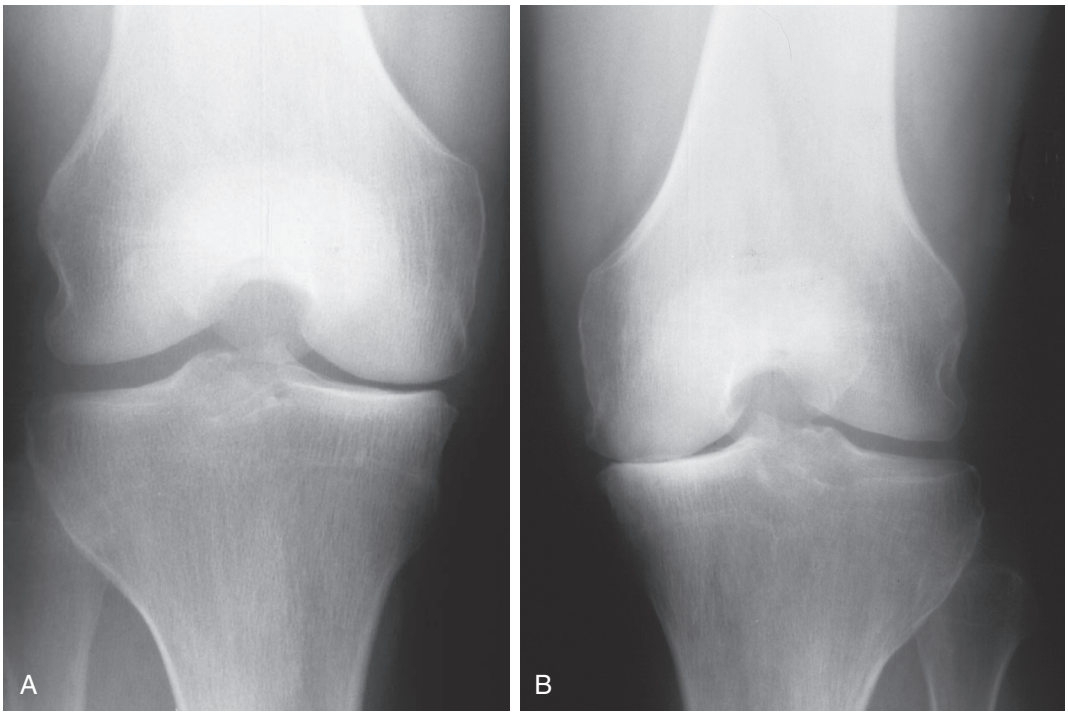


FIG 26-2 Anteroposterior (AP) radiographs of the right (**A**) and left (**B**) knee in a 45-year-old retired professional football player. The patient's weight was 260 lb. His chief complaint was bilateral medial joint pain with walking. The patient was advised to lose a significant amount of weight to decrease body size. In our opinion, high tibial osteotomy (HTO) is contraindicated in the left knee because of the advanced medial compartment arthritis. However, HTO may be an option in the right knee after achieving a normal body mass index. Many athletes of large stature with varus malalignment undergo medial meniscectomy, continue athletic participation, and rather promptly lose the remaining cartilage in the medial tibiofemoral joint. Patient counseling and close follow-up are necessary.

with a higher body weight because the beneficial effect of unloading the medial compartment will not be achieved.[6,67,97,138]

A relative contraindication is increased medial slope to the affected medial tibial plateau in the coronal plane because of advanced medial plateau concavity.[46,115] This finding indicates that it will not be possible to significantly unload the medial compartment with HTO, and the joint will remain with all of the weight bearing confined to the medial compartment. This problem can be tested before surgery with varus-valgus stability tests at 30 degrees of knee flexion. In knees with advanced medial arthritis, there is no neutral point in which there is simultaneous contact of the medial and lateral compartments. The tibia behaves like a teeter-tooter, with contact alternating between the medial and the lateral compartment and obvious separation of the noncontacted compartment.

The issue of concurrent patellofemoral arthritis has been addressed by prior studies.[47,137,186] In general, the symptomatic state should be addressed and the patient warned preoperatively that patellofemoral symptoms may continue or progress. Marked patellofemoral symptoms contraindicate a HTO.[115,186] The finding of asymptomatic articular cartilage changes to the patellofemoral joint is not a contraindication to HTO because clinicians have noted that the end result in terms of longevity of the HTO depends on the symptomatic medial tibiofemoral compartment.[47,114,152]

Medical contraindications to HTO include diabetes, rheumatoid arthritis, autoimmune diseases, and malnutrition states.

LOWER LIMB ALIGNMENT: PRIMARY, DOUBLE, AND TRIPLE VARUS KNEES

An added complexity in the varus-angulated knee with medial compartment arthritis is the presence of ACL deficiency. An associated deficiency of the posterolateral structures may add to the varus angulation and clinical symptoms. Patients who have these combined abnormalities often experience pain, swelling, giving way, and functional limitations that may result in a disabling condition. In these complex knees, multiple abnormalities exist to the lower limb and knee joint that must be correctly diagnosed to outline a rational treatment program. These include the anatomic tibiofemoral osseous coronal and sagittal alignment, abnormal knee motion limits, abnormal knee positions (subluxations of the medial and lateral tibiofemoral compartments), and the corresponding specific deficiencies of the ligament structures (single and combined).

The terms *primary varus*, *double varus*, and *triple varus* knee were devised to classify varus-aligned knees with associated ligament deficiencies (Table 26-1).[152] This classification system is based on the underlying tibiofemoral osseous alignment and the additional effect of separation of the lateral tibiofemoral compartment (because of deficiency of the posterolateral structures) on the overall varus lower limb alignment, as calculated from the WBL.

In patients with a varus-angulated knee, a bilateral physiologic varus tibiofemoral alignment is usually present. In others, a normal

TABLE 26-1 Causes of Varus Angulation in the Anterior Cruciate Ligament–Deficient Knee

Tibiofemoral Alignment or Geometry	Knee Motion Limits	Knee Joint Position	Ligament Deficiency	Comments
Primary varus Physiologic tibiofemoral varus alignment; narrowing or loss of medial joint cartilage	NA ↑ Varus or adduction rotation	NA ↓ Separation of medial tibiofemoral compartment	NA Pseudolaxity or slackness of medial ligament structures	Medial displacement of weight-bearing tibiofemoral line. Effect on varus alignment is more pronounced when preexisting physiologic varus alignment is present.
Double varus Added deficiency of FCL, posterolateral soft tissue structures	↑↑ Varus or adduction rotation Often coupled with lateral tibial translation and secondary support, intercondylar eminence against lateral femoral condyle	Separation of lateral tibiofemoral joint on standing Varus thrust on walking caused by lateral condylar lift-off Increased tension in FCL, posterolateral soft tissues	FCL, lateral capsule, iliotibial band (femorotibial portion) Amount of joint opening depends on slackness of lateral soft tissue restraints Absence of ACL secondary restraint to varus angulation	Weight-bearing tibiofemoral line shifts far enough medially to produce separation of the lateral tibiofemoral joint during walking, sports activities. Under states of maximal muscle contraction (quadriceps, biceps femoris), sufficient compressive forces may exist to prevent lateral condylar lift-off.
Triple varus Added deficiency of all PL structures (FCL, PMTL, PL capsule)	↑↑↑ Varus or adduction rotation Varus recurvatum in extension: Increased external tibial rotation Increased hyperextension Increased external tibial rotation in flexion	↑ Separation of lateral compartment plus varus recurvatum may occur on standing, walking Varus recurvatum thrust if quadriceps and ankle plantar flexors do not prevent knee hyperextension Posterior subluxation of lateral plateau with external tibial rotation	As above, plus PMTL, PL capsule Knee hyperextension increases with associated damage to ACL, PCL (partial to complete)	Gait training is required to teach patient not to walk with varus recurvatum thrust, maintaining 5 degrees of knee flexion on initial weight bearing. Knee hyperextension with physiologic slackness to ACL and PCL may be present without actual injury to cruciates allowing varus recurvatum.

From Noyes FR, Simon R. The role of high tibial osteotomy in the anterior cruciate ligament–deficient knee with varus alignment. In DeLee JC, Drez D, editors: *Orthopaedic Sports Medicine: Principles and Practice*. Philadelphia: WB Saunders; 1994;1401-1443.
ACL, Anterior cruciate ligament; *FCL*, fibular collateral ligament; *PCL*, posterior cruciate ligament; *PL*, posterolateral; *PMTL*, popliteal muscle-tendon-ligament.

CRITICAL POINTS Lower Limb Alignment: Primary, Double, and Triple Varus Knees

Primary varus: amount of varus angulation caused by physiologic tibiofemoral angulation and osteocartilaginous (narrowing) of the medial tibiofemoral compartment

Double varus: amount of varus angulation caused by:

1. Tibiofemoral osteocartilaginous and geometric alignment
2. Separation of the lateral tibiofemoral compartment from moderate deficiency of the posterolateral structures (>5 mm increased lateral joint opening, 10 degrees increased external tibial rotation)

Triple varus: amount of varus angulation caused by:

1. Tibiofemoral osteocartilaginous and geometric alignment
2. Separation of the lateral tibiofemoral compartment
3. Varus recurvatum in extension, severe deficiency posterolateral ligamentous structures

Restraints resisting lateral tibiofemoral compartment separation under dynamic weight-bearing conditions: quadriceps, biceps femoris, gastrocnemius, iliotibial band

tibiofemoral alignment may convert to a varus malalignment after medial meniscectomy. With loss of the medial meniscus and resultant articular cartilage deterioration, narrowing of the medial tibiofemoral compartment occurs along with an increase in varus lower limb alignment. For example, a patient with a physiologic varus alignment of 3 degrees (mechanical axis) with an additional loss of 3 mm of the medial articular cartilage would develop an overall 6 degrees varus tibiofemoral alignment.

The term *primary varus* refers to the physiologic tibiofemoral osseous angulation and any further increase in angulation owing to altered geometry (narrowing) of the medial osteocartilaginous tibiofemoral joint (Fig. 26-3). The tibiofemoral WBL shifts into the medial tibiofemoral compartment as the narrowing progresses and the lateral compartment is unloaded. Three degrees of varus angulation approximately doubles medial compartment pressures.[61,81]

As the WBL shifts into the medial compartment, there are increased tensile forces in the posterolateral soft tissues, including the iliotibial tract and ligament structures. There is corresponding separation of the lateral tibiofemoral compartment during standing, walking, and running activities (lateral condylar lift off).[122,189] This is called a *double varus knee* because the lower limb varus malalignment results from two factors: the tibiofemoral osseous and geometric alignment and separation of the lateral tibiofemoral compartment from deficiency of the posterolateral structures.

A combination of active and passive restraints resists separation of the lateral tibiofemoral compartment under dynamic loading conditions.[78,141] The quadriceps, biceps femoris, and gastrocnemius muscles and iliotibial band act in a dynamic manner to resist adduction moments at the knee joint during gait, and with weight-bearing loads, resist lateral tibiofemoral separation. If these muscle forces do not provide a functional restraint to excessive lateral tensile forces, separation of the lateral tibiofemoral joint occurs.

The FCL normally allows a few millimeters of separation of the tibiofemoral compartment, and pathologic stretching (interstitial injury) may occur to this ligament in chronic varus-angulated knees. Under these circumstances, a transfer of all of the weight-bearing loads to the medial compartment occurs, which can be especially deleterious if damaged articular cartilage or prior meniscectomy is present.

The patient symptoms commonly increase with pain in both the medial compartment and lateral aspect of the knee joint owing to

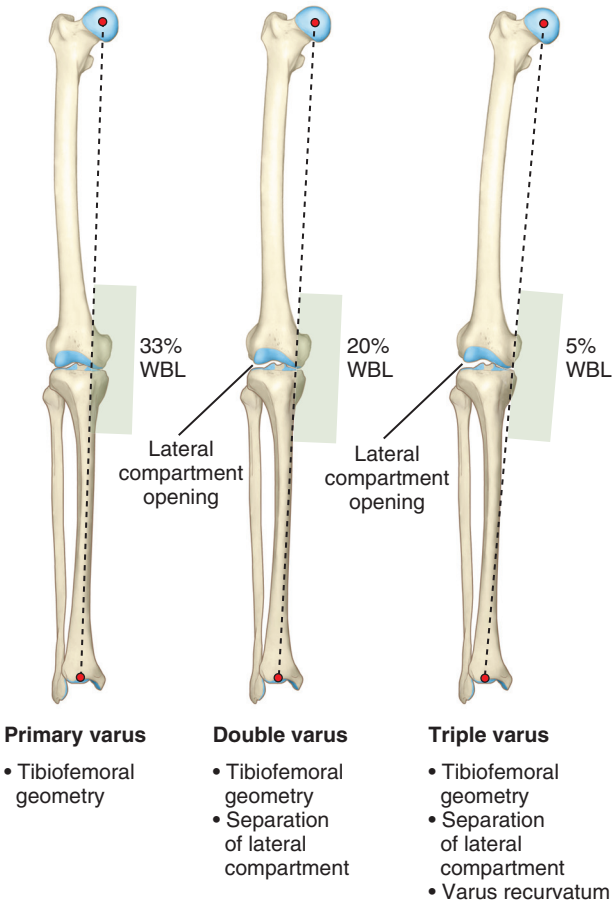


FIG 26-3 Schematic illustration of primary, double, and triple varus knee angulation. *WBL*, Weight-bearing line.

excessive medial compressive and lateral soft tissue tensile forces, respectively.

In a triple varus knee, injury to the FCL and posterolateral structures produces a varus recurvatum position of the limb.[95] A *triple varus knee* results from three causes: tibiofemoral varus osseous malalignment, increased lateral tibiofemoral compartment separation caused by marked insufficiency of the FCL and PMTL, and varus recurvatum in extension. The varus recurvatum occurs because of abnormal external tibial rotation and knee hyperextension, reflecting deficiency of the posterolateral structures and possibly the ACL. Owing to the increase in lateral compartment opening, the WBL shifts further medially as shown in Figure 26-3.

HTO is indicated in patients with varus malalignment who demonstrate a varus thrust on walking. An ACL reconstruction in these knees would not address the instability and would be expected to fail if the varus osseous malalignment was not first corrected owing to the abnormal lateral tibiofemoral joint opening. A varus recurvatum or back-knee instability indicates a triple varus knee in which the posterolateral structures require reconstruction along with the ACL, after first correcting the osseous malalignment.

Eckhoff and coworkers[61] reported important 3-dimensional measurements in 90 individuals (180 limbs) and showed that there is considerable variation in coronal alignment between subjects and between right-left lower limbs (Fig. 26-4). One qualification to the data is that the hip-knee-ankle computed tomography (CT) measurements were obtained under non–weight-bearing conditions.

Given the variation in lower limb alignment in individuals, a frequent question is what is the effect of correcting one limb to neutral or a mild valgus overcorrection on overall gait and the (unoperated) opposite limb, particularly when a marked varus alignment is present bilaterally. In our experience, the opposite extremity does not require HTO, except in a small percentage of patients who have marked bilateral varus alignment and medial tibiofemoral pain.

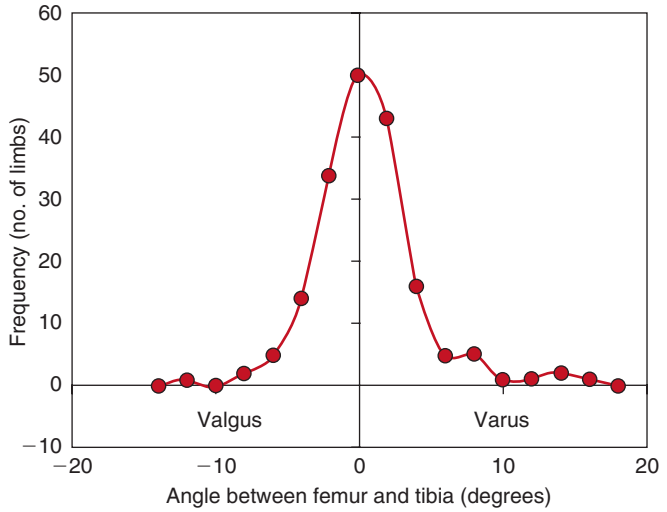


FIG 26-4 Histogram of the data illustrating the relative deviation of limb alignment from a straight line in the normal population of 180 limbs. Of the 90 individuals, 37 had bilateral valgus, 22 had bilateral varus, and 31 had varus alignment of one limb and valgus of the other limb or varus or valgus alignment of one limb and neutral alignment of the other limb. (From Eckhoff DG, Bach JM, Spitzer VM, et al. Three-dimensional mechanics, kinematics, and morphology of the knee viewed in virtual reality. *J Bone Joint Surg Am.* 2005;87:71-80.)

GAIT ANALYSIS

Although a high adduction moment may be anticipated as a result of varus malalignment, the moments and loads on the knee joint cannot be reliably predicted from the static measurement of lower limb alignment on radiographs.[98,168] Many factors in patients with ACL-deficiency, varus malalignment, and posterolateral deficiency can be assessed by gait analysis. Abnormal limb alignment, either varus or valgus in the coronal plane or hyperextension in the sagittal plane, produces substantial alterations in the moments and forces about the knee joint (Fig. 26-5).[28,55,72,118,168,181,198] The analysis of external moments about the knee during gait allows the clinician to understand the effect of the altered gait dynamics on the knee joint. Abnormally high knee adduction moments increase the risk for progression of medial tibiofemoral arthritis owing to excessive loading.[16,139,180,182] The success of HTO has been related to lowering these moments to below normal values.[28,180,217] In addition, gait analysis allows calculation of abnormally high tensile forces in the lateral soft tissue restraints that increase the risk of elongating these tissues from lateral condylar lift-off with activity. Abnormal tensile loads on posterolateral soft tissues preclude successful FCL and PMTL reconstruction. Markholf and associates[123] reported that lateral tibiofemoral compartment condylar lift-off had a marked effect on producing joint instability.

Many studies have documented that the external moments about the knee joint and the corresponding tibiofemoral compartment loads are markedly influenced by individual gait characteristics and adaptations that occur after injury.[11,14,15,17,18,26,42,107,180,217] ACL deficiency may produce marked abnormalities in moments about the knee joint in the sagittal plane, which is further affected by lower limb varus

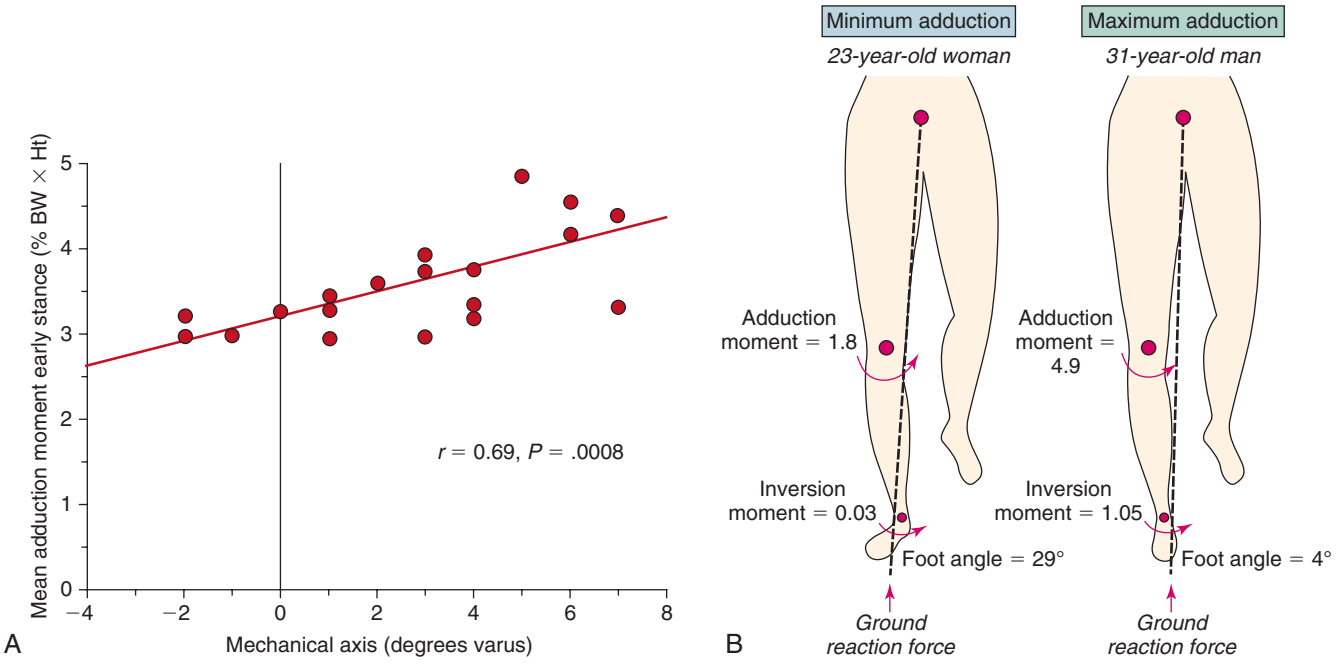


FIG 26-5 The knee adduction moment that produces medial tibiofemoral compartment loading and lateral joint tensile loads is dependent on both the mechanical axis (**A**) and patient gait characteristics such as the rotation of the lower limb and the foot angle at stance phase (**B**). *BW,* Body weight; *Ht,* height. (From Andrews M, Noyes FR, Hewett TE, Andriacchi TP. Lower limb alignment and foot angle are related to stance phase knee adduction in normal subjects: a critical analysis of the reliability of gait analysis data. *J Orthop Res.* 1996;14:289-295.)

CRITICAL POINTS Gait Analysis

Moments and loads on knee joint cannot be reliably predicted from static measurement of lower limb alignment on radiographs. Abnormally high knee adduction moments increase the risk for progression of medial tibiofemoral arthrosis. Success of HTO is related to lowering abnormal moments to normal or below-normal values.

Our study conclusions:

- Majority ACL-deficient varus-angulated knees have abnormally high adduction moments on walking.
- One third of patients have normal or low adduction moments, normal to low medial tibiofemoral compartment loads. Gait characteristics/adaptations lowered medial tibiofemoral loads despite varus angulation.
- Significant correlation between high adduction moments and high medial tibiofemoral compartment loads, high lateral soft tissue forces.
- In knees with high lateral ligament tensile forces, separation of the lateral tibiofemoral joint may occur with "condylar lift-off" during weight bearing.
- Large tensile loads on posterolateral tissues cause stretching, deficiency (double and triple varus knees), and failure of posterolateral reconstructive procedures.

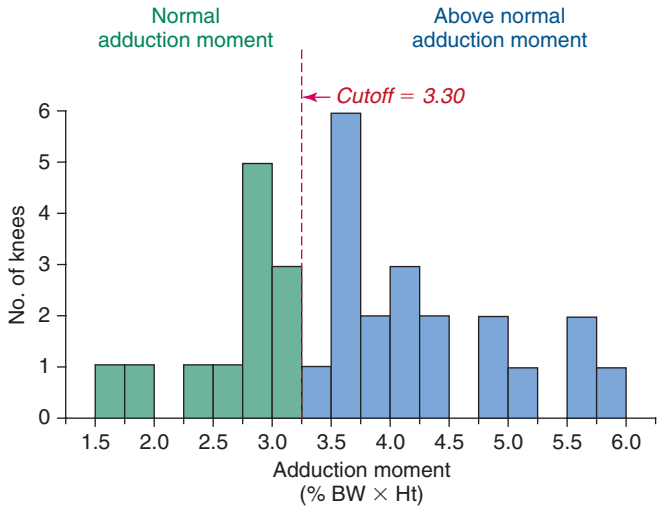


FIG 26-6 The distribution of the adduction moments during walking in the anterior cruciate ligament–deficient knees. The cutoff value (3.30, % body weight [BW] × height [Ht]) represents the control mean minus 1 standard deviation. (From Noyes FR, Schipplein OD, Andriacchi TP, et al. The anterior cruciate ligament-deficient knee with varus alignment. An analysis of gait adaptations and dynamic joint loadings. *Am J Sports Med.* 1992;20:707-716.)

malalignment. Patients with ACL deficiency may show a decrease in the magnitude of the external flexion moment (quadriceps-reduced gait) or an increase in the external extension moment (hamstrings-protective muscle force).[12,13] These effects are discussed in Chapter 6. The alignment of the foot markedly influences the knee adduction moment. Patients with toe-in, or less than normal external axial rotation of the foot during stance phase, tend to have a higher knee adduction moment as the WBL passes farther medial to the knee joint.[10,98]

Gait analyses were conducted in a study at our institution[168] involving 32 patients with ACL deficiency and varus angulation. A force plate and optoelectronic system were used to measure forces and moments of the lower limb and knee joint. Knee joint loads and ligament tensile forces were calculated using a previously described mathematical model.[189] Sixty-two percent of the patients had an abnormally high magnitude of the moment, tending to adduct the affected knee (Fig. 26-6). The calculated medial tibiofemoral loads were excessively high in 66% of the patients ($P < .01$). Forty-seven percent of the patients had predicted abnormally high lateral ligament tensile forces ($P < .05$). The adduction moment showed a statistically significant ($P < .05$) correlation to predicted high medial tibiofemoral compartment loads and high lateral ligament tensile forces ($P < .01$). A shift had occurred in the center of maximal joint pressure to the medial tibiofemoral compartment, with a corresponding increase in the lateral ligament tensile forces to achieve frontal plane stability (Figs. 26-7 and 26-8). If muscle forces are not sufficient to maintain lateral tibiofemoral compressive loads, tensile forces develop in the lateral ligament tissues. The data indicate that in knees with high lateral ligament tensile forces, separation of the lateral tibiofemoral joint occurs with condylar lift-off during weight bearing.

The magnitude of the flexion moment (which is related to quadriceps muscle force) was significantly lower in 47% of the patients ($P < .05$), and the extension moment (related to hamstring muscle force) was significantly higher in 50% ($P < .05$). These findings indicated that a gait adaptation occurred that diminished quadriceps muscle activity and enhanced hamstring muscle activity hypothesized to provide anteroposterior (AP) stability in these ACL-deficient knees.[26]

Equally important in the results was the finding that approximately one third of the patients had normal or low adduction moments and corresponding normal to low medial tibiofemoral compartment loads. These patients had gait characteristics or adaptations that lowered medial tibiofemoral loads despite the varus lower limb alignment. Gait analysis allowed identification of patients with a potentially better overall prognosis; the adduction moment and medial tibiofemoral loads were not excessively high, and an HTO would result in a substantial lowering of the loads placed on the medial tibiofemoral joint.

We[158] studied patients with varus-angulated knees with insufficient posterolateral structures in whom prior posterolateral reconstructive procedures failed and an HTO was required before further soft tissue reconstructive procedures could be done. One explanation for these clinical findings is that these knees had a varus or hyperextension thrust during the stance phase of gait, which placed undue tensile forces on the deficient posterolateral structures (Fig. 26-9). Untreated varus malalignment has also been identified as a predisposing cause of failure of ACL reconstructions[153,160] and posterior cruciate ligament (PCL) reconstructions[155] as well.

CLINICAL EVALUATION

Subjective and Functional Outcome

Patients complete questionnaires and are interviewed for the assessment of symptoms, functional limitations, sports and occupational activity levels, and patient perception of the overall knee condition according to the Cincinnati Knee Rating System (CKRS; see Chapter 41).[22]

Symptoms of pain, swelling, and giving way are well recognized consequences of ACL deficiency.[167] However, in a knee with combined varus malalignment and ACL deficiency, several different knee subluxations may produce symptoms of instability. These include anterior subluxation of the tibia, separation of the lateral tibiofemoral compartment on walking (varus thrust), posterior subluxation of the lateral tibial plateau (with knee flexion and external tibial rotation), and excessive hyperextension or varus recurvatum with a back-knee or feeling of the knee joint going into hyperextension. By history and asking the patient to demonstrate the knee instability, the surgeon must carefully determine the subluxations present.

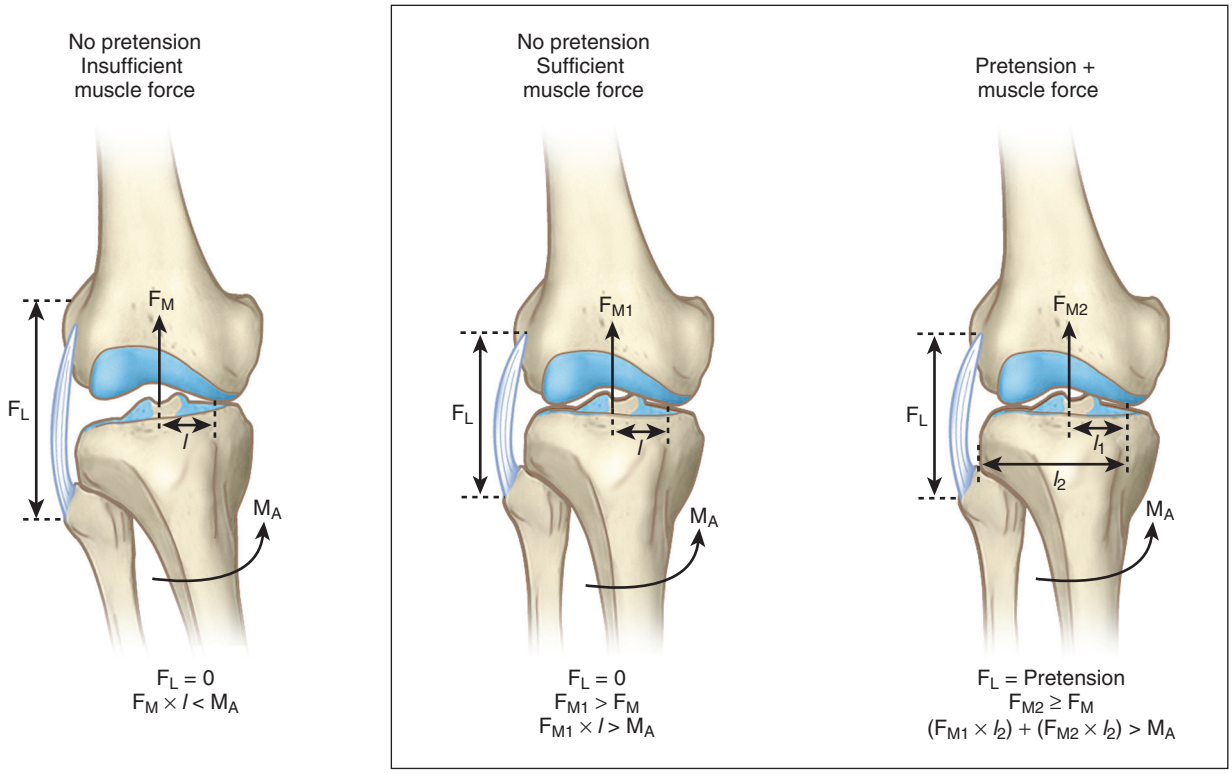


FIG 26-7 A critical interaction between the dynamic muscle forces and the forces in the passive soft tissues is needed to stabilize the knee joint during walking. The knee joint remains closed laterally if either pretension in the lateral soft tissues or increased muscle force resulting from antagonistic muscle groups is present. Distances l and l_1 = 20 mm; l_2 = 60 mm. F_l, Soft tissue force; F_M, F_{M1}, F_{M2}, muscle forces; M_A, adducting moment.

CRITICAL POINTS Clinical Evaluation

Assessment of Symptoms and Functional Limitations With Activity: Cincinnati Knee Rating System

Physical Examination

- Knee flexion and extension
- Joint effusion
- Patellofemoral: extensor mechanism malalignment
- Tibiofemoral crepitus, joint line pain, compression pain, inflammation
- Gait abnormalities
- Abnormal knee motion limits and subluxations

Diagnostic Clinical Tests

- Posterior drawer, 90 degrees of knee flexion
- KT-2000, 20 degrees of knee flexion, 189-N force
- Pivot shift, Lachman
- Lateral and medial tibiofemoral joint opening at 0 and 25 degrees of knee flexion
- Varus recurvatum: supine

Tibiofemoral Rotation (Dial Test)

- 30 and 90 degrees of knee flexion
- An increase in external tibial rotation represents either a posterior subluxation of the lateral tibial plateau (injury to the posterolateral structures) or anterior subluxation of the medial tibial plateau (injury to the medial collateral ligament and posteromedial structures)
- Supine position preferred; difficult to palpate the medial and lateral tibiofemoral position in the prone position

Radiographic Assessment

- Double-stance, hip-knee-ankle to measure mechanical axis, WBL, lateral compartment separation
- Lateral, 30 degrees of knee flexion (patellar height measurement)
- PA, weight bearing, 45 degrees of knee flexion
- Patellofemoral axial
- Lateral stress, neutral tibial rotation, tibia unconstrained, 67-N varus force

Physical Examination

A complaint of medial joint line pain may or may not correlate with the degree of medial compartment articular cartilage damage.[89,101] In the early stages, the patient usually complains of medial pain occurring with sports activities but not with daily activities. When pain occurs with daily activities, there is a high likelihood that extensive damage exists to the joint articular cartilage. Loss of the medial meniscus is the major risk factor for the progression of arthritis in the medial compartment.[64]

The physical examination of the knee joint to detect all of the abnormalities in a varus-angulated knee is comprehensive (Table 26-2) and includes assessment of (1) the patellofemoral joint, especially possible extensor mechanism malalignment caused by increased external tibial rotation and posterolateral tibial subluxation; (2) medial tibiofemoral crepitus on varus loading, indicative of articular cartilage

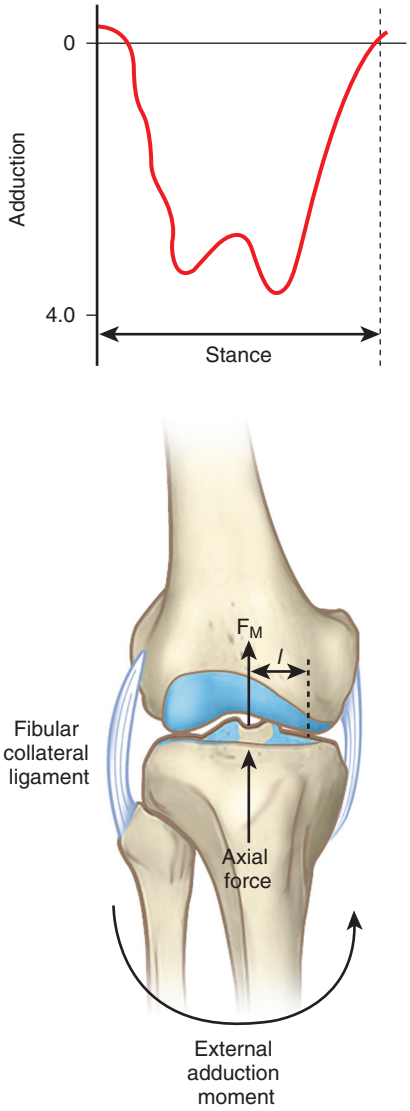


FIG 26-8 The external adducting moment is resisted by the minimum sagittal plane muscle force (F_m) and axial load acting over *l*. Pretension in the lateral soft tissues would maintain equilibrium if the muscle force were insufficient.

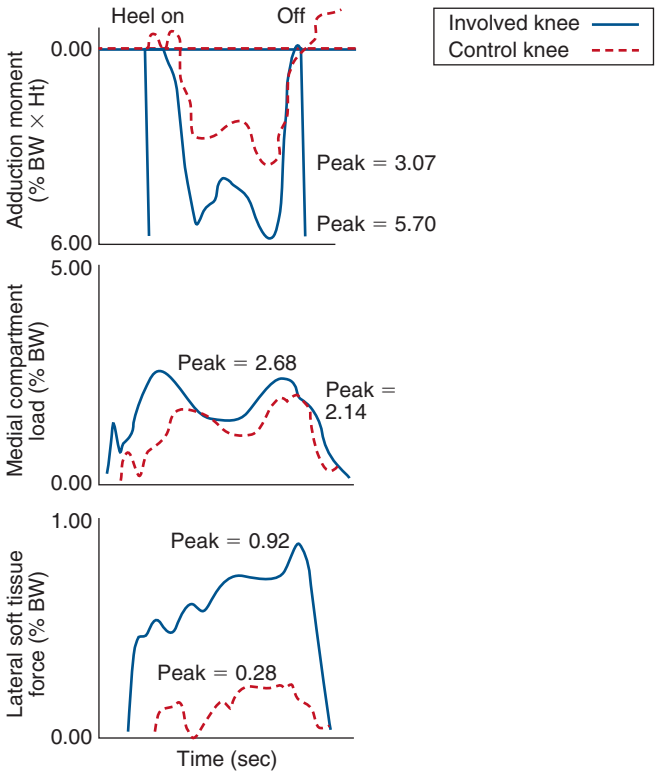


FIG 26-9 The increased adduction moment, medial compartment load, and lateral soft tissue force in an involved knee compared with a control knee. *BW*, Body weight; *Ht*, height. (From Noyes FR, Schipplein OD, Andriacchi TP, et al. The anterior cruciate ligament-deficient knee with varus alignment. An analysis of gait adaptations and dynamic joint loadings. *Am J Sports Med.* 1992;20:707-716.)

damage even if not visible on radiographs; (3) pain and inflammation of the lateral soft tissues caused by tensile overloading; (4) gait abnormalities (excessive hyperextension or varus thrust) during walking and jogging[163]; and (5) abnormal knee motion limits and subluxations compared with the contralateral knee.[165]

Diagnostic Clinical Tests

The medial posterior tibiofemoral step-off on the posterior drawer test is done at 90 degrees of flexion (Fig. 26-10). This test is performed first to identify that the tibia is not posteriorly subluxated, indicating a partial or complete PCL tear. A KT-2000 (MEDmetric) arthrometer test may be done at 20 degrees of flexion (134-N force) to quantify total AP displacement. The Lachman test is performed at 20 degrees of knee flexion. The pivot shift test is done and the result recorded on a scale of 0 to III, with a grade of 0 indicating no pivot shift; grade I, a slip or glide; grade II, a jerk with gross subluxation or clunk; and grade III, gross subluxation with impingement of the posterior aspect of the lateral side of the tibial plateau against the femoral condyle.

FCL insufficiency is determined by the varus stress test at 0 and 30 degrees of knee flexion (see Fig. 26-10). The surgeon estimates the amount of joint opening (in millimeters) between the initial closed contact position of each tibiofemoral compartment, performed in a constrained manner avoiding internal or external tibial rotation, to the maximal opened position. The result is recorded according to the increase in the tibiofemoral compartment of the affected knee compared with that of the opposite normal knee. This comparison is crucial, and it is important to avoid measuring only the degrees of varus or valgus rotation in the involved knee.

An increase in medial joint opening may occur compared with the opposite knee that represents a pseudolaxity because the increase is actually caused by medial tibiofemoral joint narrowing. When the test is conducted under a varus stress, the medial joint opening returns the limb to a more normal alignment, and there is no true medial ligamentous damage. The true amount of medial and lateral tibiofemoral compartment opening is later confirmed during the arthroscopic examination with gap tests. The primary and secondary restraints that resist lateral joint opening have been described previously.[78] The abnormal medial joint opening depends on the knee flexion angle at which the test is conducted and the integrity of the secondary restraints.

Tibiofemoral Rotation Test (Dial Test)

The tibiofemoral rotation test was first described by the senior author (F.R.N.)[162] and is used to estimate the amount of posterior tibial

TABLE 26-2 Diagnosis of Abnormalities

Abnormality	Diagnostic Test
Tibiofemoral alignment	Full-length standing radiograph: double support (closure of lateral tibiofemoral joint required)
Narrowing of medial tibiofemoral joint	Change in millimeters from opposite side on 45-degree PA weight-bearing x-ray or stress radiograph
FCL insufficiency	Increase in lateral joint opening at 30 degrees of flexion
FCL, PMTL, PL capsule insufficiency	Further increase in lateral joint opening at 30 degrees of flexion; increase in external tibial rotation at 30 degrees of flexion; varus recurvatum in extension
Lateral tibiofemoral joint separation	Standing radiograph shows increased joint width compared with opposite side; amount of increase on stress radiograph compared with opposite side
Varus recurvatum	Defined by degrees of hyperextension and varus angulation; elicited on supine varus recurvatum test. Standing tests with patient assuming maximal knee hyperextension position provides greatest subluxation. Estimate degrees of increase in varus and hyperextension.

From Noyes FR, Simon R. The role of high tibial osteotomy in the anterior cruciate ligament–deficient knee with varus alignment. DeLee JC, Drez D, editors: *Orthopaedic Sports Medicine: Principles and Practice*. Philadelphia: WB Saunders; 1994;1401-1443.
FCL, Fibular collateral ligament; *PA,* posteroanterior; *PL*, posterolateral; *PMTL*, popliteal muscle-tendon-ligament unit.

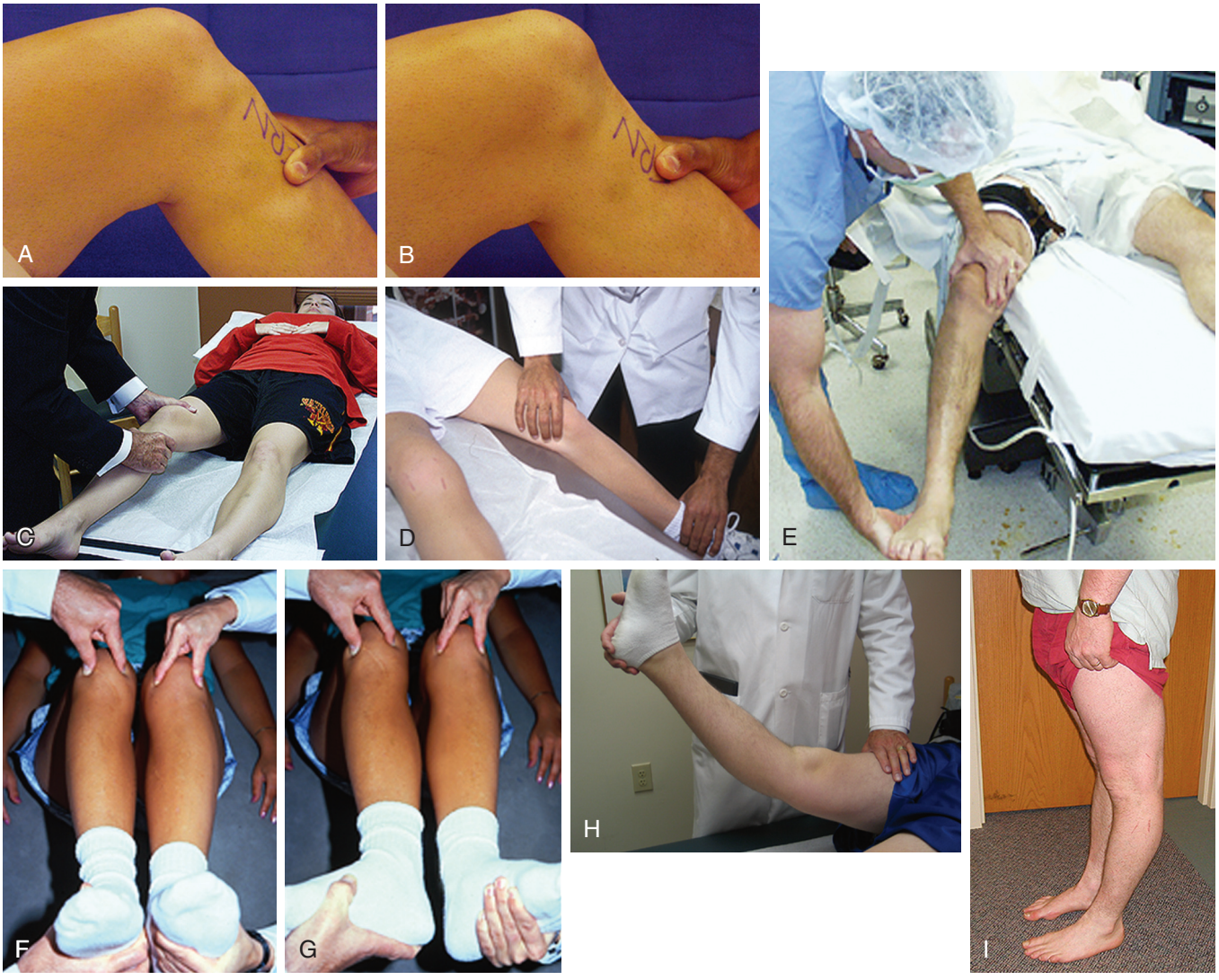


FIG 26-10 Manual knee tests. **A** and **B,** Posterior drawer test at 90 degrees of knee flexion. **C,** Lachman test. **D,** Valgus manual test for medial joint opening. **E,** Varus manual test for lateral joint opening. Dial test at 90 degrees of knee flexion in neutral tibial rotation (**F**) maximum external tibial rotation (**G**). Varus recurvatum in the supine (**H**) and standing (**I**) positions.

subluxation (see Fig. 26-10). The test is conducted in the following manner: (1) the tibia is positioned at 30 degrees of knee flexion, in neutral rotation; (2) the position of the anterior aspect of the medial and lateral tibial plateaus are determined in reference to the femoral condyles by palpation; (3) the tibia is externally rotated to its maximum position; (4) the positions of the medial and lateral tibial plateaus are palpated to determine an abnormal posterior subluxation of the lateral compartment or anterior subluxation of the medial compartment; (5) the examiner observes the location of the tibial tubercle to determine any increase in external tibial rotation compared with the opposite normal knee; and (6) the test is repeated at 90 degrees of knee flexion and may also be conducted by starting at the neutral tibial rotation position, progressing to internal tibial rotation.

If an increase in external tibial rotation is present, it represents either a posterior subluxation of the lateral tibial plateau (indicating injury to the FCL and PMTL) or anterior subluxation of the medial tibial plateau (indicating injury to the superficial medial collateral ligament [SMCL] and posteromedial structures). In some knees, both anteromedial and posterolateral subluxations are present.

The tibiofemoral rotation test involves close observation of the location of the internal and external tibial rotation axis and comparison of the location of this axis with that in the normal knee. With posterior subluxation of the lateral tibial plateau during external tibial rotation, the examiner may detect a shift in the axis of tibial rotation to the medial tibiofemoral compartment. Alternatively, with an anterior subluxation of the medial tibial plateau, the center of tibial rotation shifts to the lateral tibiofemoral compartment as the maximal external tibial rotation position is reached.

The advantages of the tibiofemoral rotation test over the traditional posterolateral drawer test[96] are (1) the knee may be positioned at varying flexion positions (30 and 90 degrees); (2) the tibia is less constrained because the foot is not held fixed to the examining table; and (3) the axis of tibial rotation can be observed as the tibia is rotated externally and internally. More information is gained when the tibiofemoral rotation tests are performed in a supine position. In the prone position, it is difficult to palpate the medial and lateral tibiofemoral position required to diagnose the abnormal compartment subluxations. The only indication for the prone dial test is a PCL-deficient knee in which the tibia can be gently displaced to a reduced anterior position during the rotation tests. In the supine position, the tibia can also be displaced anteriorly to prevent posterior subluxation, which makes the interpretation of the dial test more difficult.

A varus recurvatum test in both the supine and standing positions and the reversed pivot shift test are included in the assessment of posterolateral tibial subluxation. However, these represent qualitative tests that are difficult to measure in objective terms. Still, they provide useful information regarding the magnitude of the overall subluxation of the knee joint when two or more abnormal motion limits are present.

Radiographic Assessment

Radiographic assessment of lower limb alignment is based on full-length radiographs of the extremity with the patient in the standing position.[60,198] Separation of the lateral tibiofemoral compartment may occur, preventing a correct assessment of true tibiofemoral osseous alignment. Double-stance, full-length AP radiographs showing both lower extremities from the femoral heads to the ankle joints are obtained. The knee is flexed 3 to 5 degrees to avoid a hyperextension position, and the foot angle is set to approximately 10 to 12 degrees. If separation of the lateral tibiofemoral joint is observed on radiographs, it is necessary to subtract the lateral compartment opening so that the true tibiofemoral osseous alignment is determined and a valgus overcorrection at surgery is avoided as is discussed under Preoperative Planning.



FIG 26-11 Lateral stress radiographs used to quantify the increase in lateral tibiofemoral joint opening between knees. Approximately 67 N of varus force is applied, and a comparison is made of the millimeters of lateral tibiofemoral compartment opening between knees.

During varus-valgus testing at 30 degrees of flexion, the clinician should assess for a possible teeter-totter effect, in which simultaneous contact of the medial and lateral tibiofemoral compartments is not possible owing to advanced tibial obliquity and bone loss of the medial tibiofemoral joint.

Additional radiographs taken during the initial examination include a lateral at 30 degrees of knee flexion, weight-bearing PA at 45 degrees of knee flexion, and patellofemoral axial views. Telos medial or lateral stress radiographs may be required in select knees (Fig. 26-11).

The height of both patellas is measured on lateral radiographs (Fig. 26-12) to determine whether or not an abnormal patella infera or alta position exists that may be a factor in selecting an opening or closing wedge osteotomy, which would further decrease or elevate the patella position.[170,171]

The clinical algorithm for the preoperative clinical and radiographic assessment to determine candidates for either a medial opening wedge or lateral closing wedge osteotomy is shown in Figure 26-13.

PREOPERATIVE PLANNING

Calculations to Determine Angular Correction

The preoperative calculations for HTO involve measurements to determine the amount of angular correction desired to redistribute tibiofemoral forces while not altering tibial slope and tibiofemoral joint obliquity in the frontal plane.[60,166] The radiographic measurement and correction may require alteration at surgery with fluoroscopic analysis, as described. The normal tibiofemoral coronal alignment is shown in

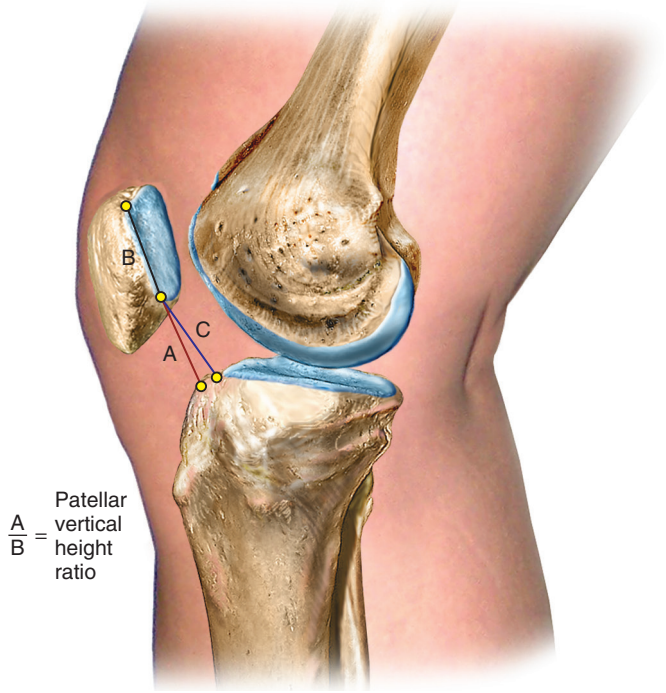


FIG 26-12 Method used to determine patellar vertical height ratio on lateral radiograph. The numerator, *line segment A*, is the distance between the most ventral (anterosuperior) rim of the tibial plateau and the lowest end of the patellar articular surface. The denominator, *line segment B*, is the maximum length of the patellar articular surface. An alternative numerator, *line segment C*, locates the tibial reference point on the middle of the tibial plateau. The patellar vertical-height ratio equals A/B or C/B.

Figure 26-14. In varus angulated knees, there is a slight increase in obliquity caused by medial tibiofemoral joint arthrosis principally involving the medial condyle.

An undercorrection or overcorrection in the coronal plane may result if the surgeon fails to recognize the effect of lateral tibiofemoral separation on increasing varus angulation from slack or deficient lateral soft tissues. Inaccurate calculations may also arise from failure to use the WBL from double-stance, full-length, standing radiographs of both lower extremities. A single-stance radiograph of the affected limb will show the maximum varus angulation caused by lateral condylar lift off; however, this should not be used for osteotomy calculations. A double-stance radiograph helps close the lateral tibiofemoral compartment so the osseous alignment is calculated, which is required for surgical correction.

Sabharwal and Zhao[187] compared lower limb coronal alignment on full-length, standing radiographs to supine intraoperative hip-knee-ankle fluoroscopy measurements in 102 limbs. There was a statistically significant mean difference between the two techniques (mean, 13.4 mm deviation in the WBL, measured from the center of the joint). This difference in the two techniques is of concern in the preoperative planning and the final intraoperative osteotomy correction in the coronal plane. There was no description of the effect of abnormal lateral joint opening on the standing radiographs that may account for errors in preoperative measurements. Furthermore, during surgery there was no description of the fluoroscopy technique. The surgeon must verify medial and lateral tibiofemoral joint contact to account for possible opening of the medial or lateral tibiofemoral joint during the WBL measurement.

CRITICAL POINTS Preoperative Planning

- Determine angular correction to achieve redistribution of tibiofemoral forces without altering tibial slope.
- Take into account abnormal lateral tibiofemoral separation from deficient posterolateral structures.
- Measure WBL on bilateral standing hip-knee-ankle radiographs. WBL is dependent on femoral and tibial lengths and angular deformity.
- Measure tibial slope on lateral radiographs.
- Increasing tibial slope increases anterior tibial translation and potentially tensile loads on the ACL.
- Decreasing tibial slope increases posterior tibial translation and potentially tensile loads on PCL.
- Do not alter normal tibial slope unless it is abnormal (>2 standard deviations above normal).
- Do not alter a normal tibial slope in ACL- or PCL-deficient knees.
- Maintain normal tibial slope: anterior gap at medial opening wedge should be half the posteromedial gap. Every millimeter of anterior gap change = 2 degrees change in tibial slope.

Timing of HTO in Knees with Ligament Deficiencies

Primary Varus Knees

- Cruciate reconstruction with HTO or later (no abnormal lateral joint opening present)

Double Varus Knees

- HTO first
- Posterolateral structures may shorten with valgus alignment
- Perform cruciate, posterolateral reconstructions later if required

Triple Varus Knees

- HTO first; cruciate and posterolateral reconstruction later

Opening Wedge Advantages

- Avoids lateral dissection, fibular osteotomy
- Large correction >12 degrees, avoids tibial shortening
- Distal advancement or reconstruction of the MCL in chronic MCL ruptures
- In subsequent posterolateral reconstructions, avoids proximal fibular osteotomy, allows FCL grafts to be fixated securely to proximal fibula

Closing Wedge Advantages

- Faster healing
- Earlier resumption of weight bearing
- Superior strength initial osteotomy fixation
- Decreased risk early loss of correction, nonunion
- More difficult to achieve correction at surgery
- Large closing wedge may elevate patellar height and decrease lower limb length; reverse applies with opening wedge

Opening Wedge HTO: Maintenance of Tibial Slope

- Opening wedge angle is dependent on the angle of coronal valgus correction and the angle of obliquity of the anteromedial tibial cortex.
- Every millimeter of alteration in anterior gap height results in a change of 2 degrees in tibial slope.

The fluoroscopy technique during HTO involves the surgeon placing an axial load against the foot to overcome medial or lateral joint opening, which is verified by the fluoroscopic image. The lower extremity should be held in 10 degrees of knee flexion and approximately 10 to 12 degrees of external rotation (hip to ankle axial

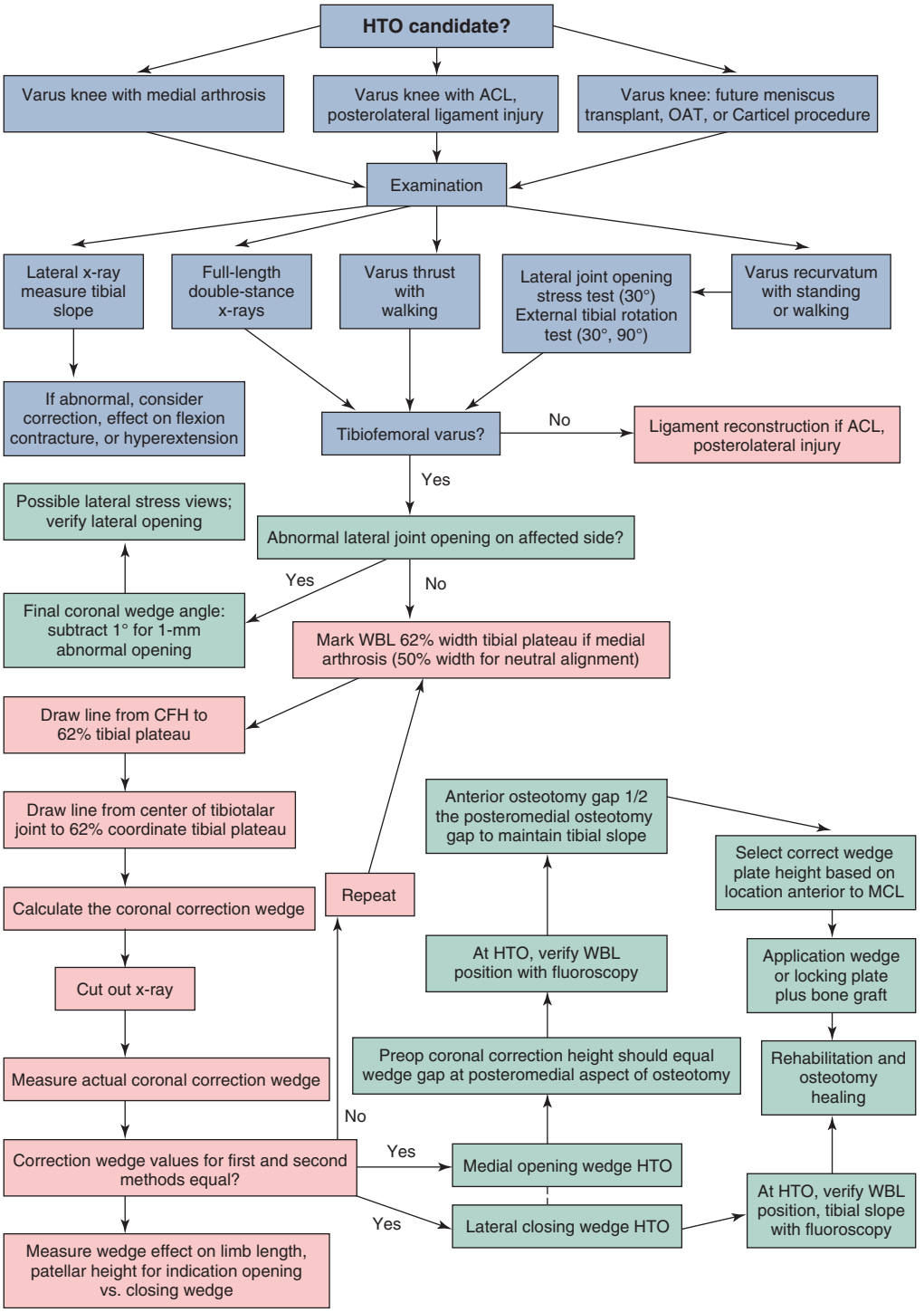


FIG 26-13 The clinical algorithm for the preoperative clinical and radiographic assessment to determine candidates for medial opening wedge or lateral closing wedge osteotomy. *ACL*, Anterior cruciate ligament; *CFH*, center femoral head; *HTO*, high tibial osteotomy; *MCL*, medial collateral ligament; *OAT*, osteochondral autograft transfer; *WBL*, weight-bearing line.

alignment simulating foot progression angle). The limb alignment rod at the knee joint can be observed to move medial to lateral with internal to external limb rotation, which is another source of error in measuring the WBL intersection at the tibia. This is because the alignment rod is placed anterior to the true center of axial rotation at the ankle joint, and therefore lower limb rotation induces this error. One advantage of the computerized navigation technique is that the WBL is centered through the hip-knee-ankle joints, and an alignment rod or cord used at surgery is placed anterior to these respective joints.

An example of the potential effect of the failure to account for increased lateral joint opening is shown in Figure 26-15. The case represents a 38-year-old man whose full-length, standing radiograph shows a varus angular deformity (mechanical axis) of 7 degrees and a 4-mm increase in lateral joint opening. The width of the tibial plateau

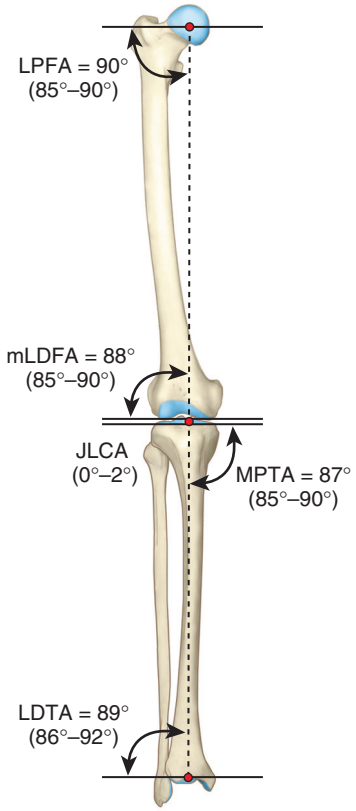


FIG 26-14 The normal tibiofemoral coronal alignment.

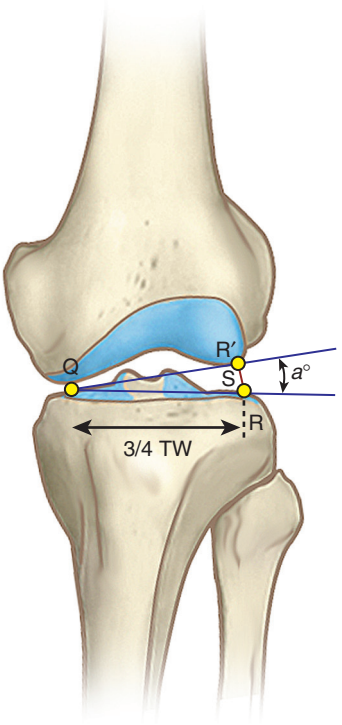


FIG 26-16 The effect of abnormal lateral joint opening on varus angular deformity. With a varus moment applied through a fulcrum, or center of rotation (Q), lateral joint space opening (S) occurs in the presence of slack lateral soft tissues resulting in an additional α degrees of varus angular deformity. *TW,* Total width tibial plateau.

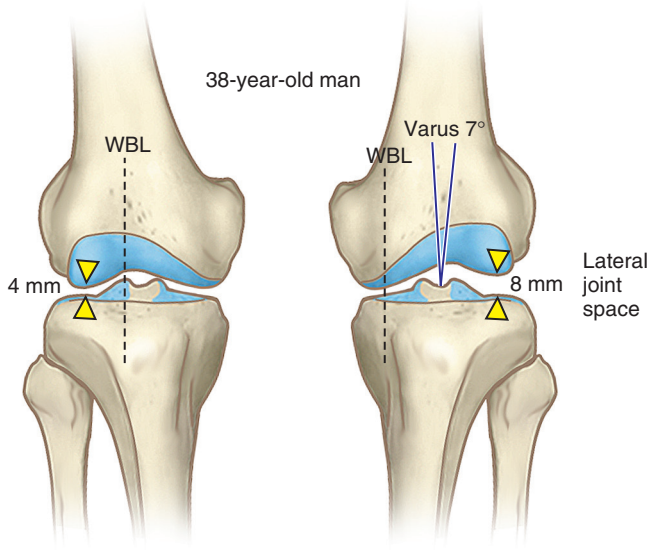


FIG 26-15 Sketch of standing anteroposterior radiograph. The lateral joint space is 8 mm on the left side and 4 mm on the right side. The calculated angular deformity resulting from the 4-mm joint opening is 3.7 degrees of the total 7 degrees of deformity. *WBL,* Weight-bearing line.

is 81 mm. The equation to determine the angular deformity resulting from the lateral tibiofemoral separation distance is:

$$\alpha = 76.4S/TW$$

Therefore, in this patient, the calculated amount of varus angular deformity caused by the lateral joint opening increase of 4 mm is 76.4 (4 mm)/81 mm = 3.7 degrees, or approximately 1 degree/mm increased lateral joint separation. Failure to account for the lateral joint opening would result in approximately 4 degrees of valgus overcorrection after HTO, assuming closure of the lateral tibiofemoral joint (Fig. 26-16). A WBL crossing the knee lateral to the 75% coordinate has the potential for a lift off of the medial femoral condyle and a cosmetic abnormal valgus alignment. Unicondylar weight bearing resulting from distraction of the medial compartment is undesirable and could result in subsequent arthritis of the lateral compartment, MCL laxity, and a progressive valgus deformity (Fig. 26-17). The WBL–tibial intersection depends on the coronal mechanical axis angle and the femoral and tibial lengths of the patient; the senior author's published study[60] showed the WBL axis to be more accurate than the anatomic axis for osteotomy correction.

Two methods are used to determine the correction wedge on preoperative radiographs.[60] First, the centers of the femoral head and tibiotalar joint (center of the talus) are marked on the full-length radiograph (Fig. 26-18). The desired correction in the WBL coordinate of the tibial plateau is identified and marked. This is usually placed at 62% of the tibial width (just at the down slope of the lateral tibial spine), which allows the WBL to pass through the lateral tibiofemoral compartment, providing a 2 to 3 degrees of angular valgus overcorrection. The 62% WBL coordinate is used if there is medial tibiofemoral articular cartilage damage, and the intention is to transfer major loads to the lateral compartment. A 50% to 54% WBL coordinate is chosen if there is no medial tibiofemoral joint damage and the surgeon wishes to correct to a neutral axial alignment (e.g., before posterolateral reconstruction). One line is drawn from the center of the femoral head to the selected percent WBL intersection at the tibia, and a second line is drawn from the center of the tibiotalar joint to the same tibial



FIG 26-17 A 32-year-old woman with abnormal lateral joint opening underwent high tibial osteotomy elsewhere. The preoperative planning failed to account for the abnormal lateral joint opening, which resulted in a severe valgus overcorrection and need for revision osteotomy.

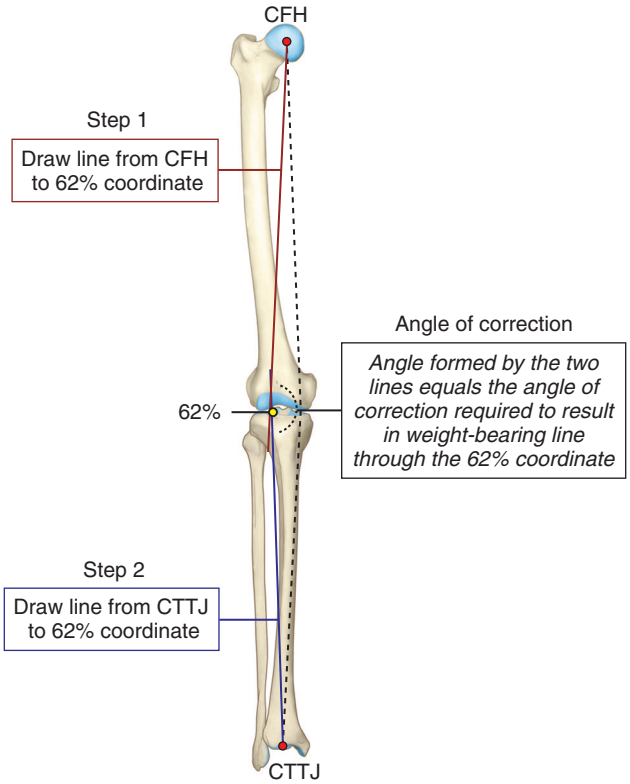


FIG 26-18 The method used to calculate the correction angle of a high tibial osteotomy using a full-length anteroposterior radiograph of the lower extremity. The lines from the centers of the femoral head (CFH) and tibiotalar joint (CTTJ) converge in this example at the 62% coordinate.

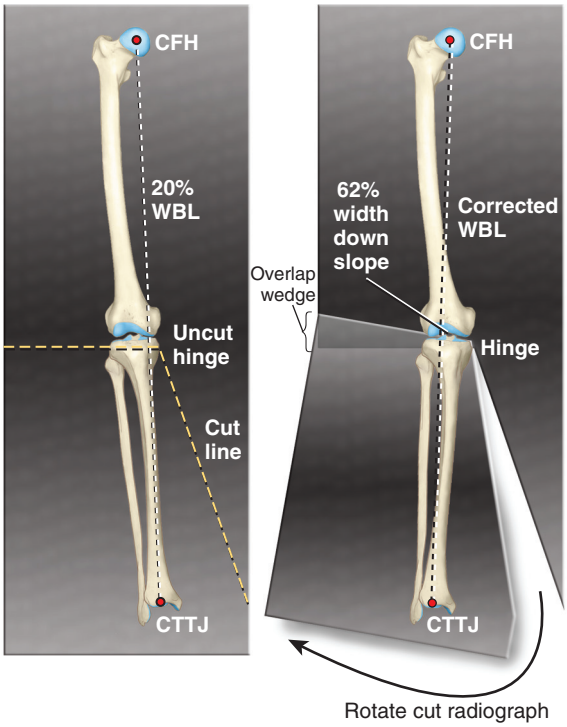


FIG 26-19 An alternative method used to calculate the correction angle of a high tibial osteotomy using a full-length anteroposterior radiograph of the lower extremity. The radiograph is cut to allow the center of the femoral head (CFH), the 62% coordinate, and the center of the tibiotalar joint (CTTJ) to become collinear. The angle of the resulting wedge of radiograph overlap equals the desired angle of correction. The example is provided for a closing wedge osteotomy. The same technique is used for an opening wedge osteotomy in which the medial tibial opening wedge is made to obtain the desired correction. *WBL,* Weight-bearing line.

coordinate position. The angle formed by the two lines intersecting at the tibia represents the angular correction required to realign the WBL through this coordinate. An alternative method was published[60] in which the previously discussed femoral and tibial axis lines intersect at the hinge point of the tibial osteotomy. This technique ends up with a similar measurement for the angular correction. However, the surgeon does not have the measured WBL tibial intersection required for intraoperative fluoroscopy verification.

The second method of determining the correction wedge involves cutting the full-standing radiograph horizontally through the line of the superior osteotomy cut (Fig. 26-19). A vertical cut of the lower tibial segment (opening or closing wedge) is made to converge with the first cut. The distal portion of the radiograph is aligned until the center of the femoral head, the selected WBL coordinate point on the tibial plateau, and the center of the tibiotalar joint are all collinear. With the radiograph taped in this position, the angle of the wedge formed by the overlap of the two radiographic segments is measured and compared with the value obtained using the first method. The mechanical axis is measured to determine the angular correction. If there is a discrepancy between the two correction wedge angles, the procedures should be repeated.

Calculations to Determine Tibial Slope and Clinical Indications to Change Tibial Slope

Lateral radiographs are examined and measurements made of the tibial slope. Abnormal posterior sloping of the tibia in the sagittal plane may

TABLE 26-3 Literature Review of Radiographic Medial and Lateral Tibial Plateau Slope Measurements

			MEDIAL SLOPE (DEGREES)		LATERAL SLOPE (DEGREES)	
Study	**Gender/Group**	**Measurement**	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**
Stijak et al[203] (2008)	ACL deficient, men and women	PTAA	5.24 ± 3.60	NA	7.52 ± 3.39	NA
	Patellofemoral pain, men and women		6.58 ± 3.21	NA	4.36 ± 2.26	NA
Meister et al[135] (1998)	ACL deficient	PTAA	9.7 ± 1.8	NA	NA	NA
	Patellofemoral pain		9.9 ± 2.1	NA	NA	NA
Hohmann et al[92] (2010)	ACL deficient, men and women	PTC	6.10 ± 3.57	0-17	NA	NA
	ACL reconstructed, men and women		7.20 ± 4.49	0-17	NA	NA
Hohmann et al[93] (2011)	ACL deficient, men	PTC	5.5 ± 3.4	0-16	NA	NA
	ACL deficient, women		6.7 ± 3.7	0-17	NA	NA
	Control, men		5.8 ± 3.1	1-14	NA	NA
	Control, women		5.0 ± 3.4	1-15	NA	NA
Jiang et al[106] (1994)	Men and women	PTAA	10 ± 4	0-20	NA	NA
Matsuda et al[129] (1999)	Varus-angulated knees, men and women	PTAA	9.9	1.5-19	6	1-13
	Normal-angulated knees, men and women		10.7	5-15.5	7.2	0-14.5
Billings et al[27] (2000)	Varus-angulated knees, men and women	TSA	8.7 ± 4.31	NA	NA	NA
Yoshioka et al[229] (1989)	Men	Mechanical axis*	7 ± 2.2	NA	8 ± 3.8	NA
	Women		7 ± 3	NA	7 ± 3.9	NA
Julliard et al[108] (1993)	Men and women	Mechanical axis*	7.03 ± 3.17	–2 to +19	NA	NA
Genin et al[70] (1993)	Men and women	Mechanical axis*	7.03 ± 3.17	–1 to +18	NA	NA
		ATC	7.9 ± 3.2	–1 to +18	NA	NA
Chiu et al[43] (2000)	Chinese cadaver tibia	ATC	14.7 ± 3.7	5-22	NA	NA
		TSA	11.5 ± 3.6	2-18.5	NA	NA
Brazier et al[36] (1996)	Men and women	ATC	11.41 ± 3.61	3.47-20.29	NA	NA
		PTAA	9.16 ± 3.37	2.54-17.91	NA	NA
		TSA	10.39 ± 3.72	2.82-19.29	NA	NA
		PTC	6.96 ± 3.28	0-15.44	NA	NA
		PFAA	9.54 ± 3.62	0-17.34	NA	NA
		FSA	8.23 ± 3.51	1.59-16.59	NA	NA

*Mechanical axis: measurement from center of ankle to center of knee (distal femur) in full extension.
ACL, Anterior cruciate ligament; *ATC*, anterior tibial cortex; *FSA*, fibula shaft axis; *NA*, not available; *PFAA*, proximal fibular anatomic axis; *PTAA*, proximal tibial anatomic axis; *PTC*, posterior tibial cortex; *SD*, standard deviation; *TSA*, tibial shaft axis.

occur after tibial osteotomy, tibial fractures, growth abnormalities, or rarely, as a congenital abnormality.

Several methods have been reported to measure the medial and lateral tibial slope based on lateral tibial radiographs (Table 26-3).[44,50,83,86,120,172,178] Each method results in different slope values for the same tibia (Fig. 26-20), and all studies show high standard deviations and ranges, indicating that tibial slope may show variation among individual patients. Brazier and colleagues[36] measured 83 lateral knee radiographs and concluded that the methods of slope measurement of proximal tibial anatomic axis (PTAA) and posterior tibial cortex were more reliable than other methods. Genin and coworkers[70] and Julliard and associates[108] recommended using the tibial mechanical axis to represent the true tibial slope. The PTAA is our preferred method for HTO, and the anterior tibial cortex measurement is used when cutting the proximal tibia during total knee arthroplasty (TKA).

Most authors have measured the medial tibial slope; only a few have measured and provided data on the lateral tibial slope.[129,203,229] The lateral tibial slope is less angled than the medial tibial slope. Few investigators have distinguished between the tibial plateau osseous slope and the change that would occur in slope if the articular cartilage and meniscus were added to the calculations. The osseous tibial slope is most commonly noted in the literature and is measured from sagittal radiographs. The true tibial slope, which includes the articular cartilage and meniscus, was noted to be 6 degrees less than the osseous tibial slope according to Jenny and colleagues.[104]

Increasing the tibial slope increases anterior tibial translation and, potentially, tensile loads on the ACL or an ACL reconstruction (Fig. 26-21).[51] Conversely, decreasing the tibial slope theoretically would increase tensile loads on the PCL and shift the tibia to a more anterior position. Shelburne and colleagues[191] studied how changes in posterior tibial slope affected tibial shear force, anterior tibial translation, and knee ligament loading during standing, squatting, and stance-phase walking activities. These authors used a validated computer modeling of the lower extremity and altered the posterior tibial slope in 1-degree increments up to a maximum of 10 degrees of change in slope. The results showed that anterior tibial translation increased as posterior tibial slope increased, and ACL force increased (for standing and walking) as tibial slope increased. It is important to note that the increased ACL force values were in the modest range because ACL force increased by 16 N for each degree of increase in posterior tibial slope. The model predicted a 6-N decrease in PCL force and a 15-N decrease in posterolateral ligament force for each degree increase in posterior tibial slope. Similar results were reported by Marouane and associates[124] who used two finite element models of the knee joint to

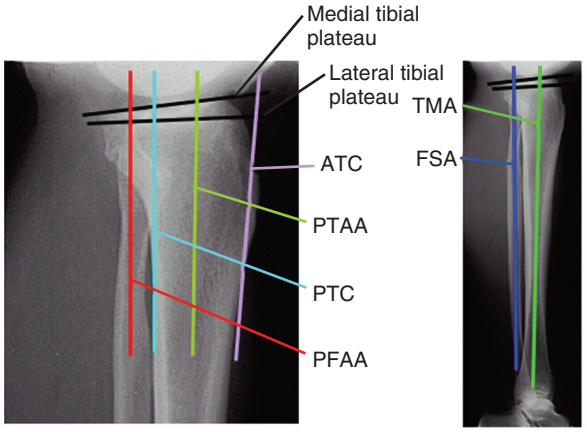


FIG 26-20 Some reported radiographic techniques to measure the tibial slope. The values obtained depend on the anatomic site selected on the tibia. Selected literature references for reported values are shown in Table 26-3. *ATC*, Anterior tibial cortex; *FSA*, fibular shaft axis; *PFAA*, proximal fibular anatomic axis; *PTAA*, proximal tibial anatomic axis; *PTC*, posterior tibial cortex; *TMA*, tibial mechanical axis. (From Noyes FR, Goebel SX, West J. Opening wedge tibial osteotomy: the 3-triangle method to correct axial alignment and tibial slope. *Am J Sports Med.* 2005;33:378-387.)

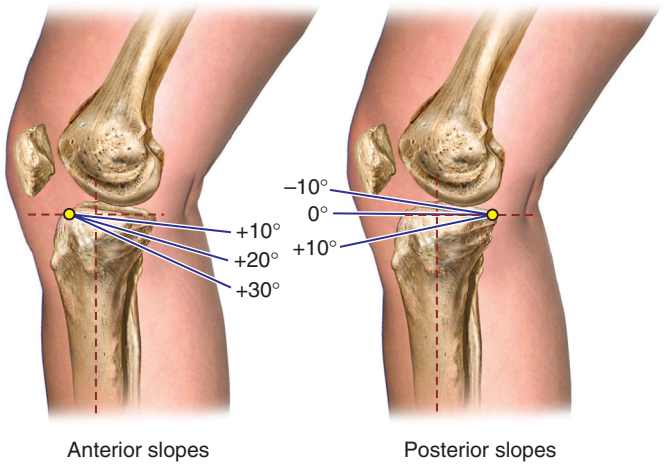


FIG 26-21 The effect of an increase in the tibial slope is shown. The degree of tibial slope is based on proximal tibial anatomic axis.

model the effect of changes in posterior tibial slope on ligament loads and tibial translation and to predict contact pressures of the lateral and medial plateau (under 100-N axial load). The data showed that, at mid stance in the gait model, a change in posterior tibial slope from –5 to +5 degrees resulted in a change in ACL force from –79 to +136 N from the 0 neutral reference point. This corresponded to a change in AP position from –1.2 to +1.2 mm from the 0 neutral position. In comparison, the study by Shelburne and colleagues[191] showed an alteration in posterior tibial slope of –5 to +5 degrees in walking resulted in a change from –75 to +80 N in ACL force, as well as a change from –2.3 to +2.4 mm in anterior tibial translation relative to reference values. Accordingly, these studies show that there is the potential for higher ACL forces on a healing ACL graft substitute with an abnormal tibial slope; however, the increase in forces is in the modest range and well below predicted ACL graft rupture. It would thus be prudent to measure the tibial slope in patients undergoing ACL surgery and determine those outliers (±2 standard deviations) in whom a more conservative rehabilitation program should be used to protect the healing graft in the early to mid postoperative period. This suggestion may even have increased relevance with low-strength ACL grafts that have decreased healing potential, as shown with allografts. Marouane and associates[124] reported in their second finite element model that a 1400-N axial load at 45 degrees of knee flexion at posterior tibial slopes of –5 degrees, neutral 0 degree, and 5 degrees produced calculated ACL forces of 102 N, 181 N, and 317 N, respectively.

Giffin and coworkers[75] reported in cadaveric knees that an increase of 5 degrees in the tibial slope produced an anterior shift in the resting position of the tibia (maximum, 3.6 mm ± 1.4 mm at full extension). However, under a 200-N axial load, there was only a 2-mm anterior shift in the tibiofemoral contact position (30 and 90 degrees) and no increase in ACL forces. The authors concluded that small changes in tibial slope under simulated weight-bearing conditions would have little effect on tibiofemoral position; however, the 200-N axial load does not simulate larger weight-bearing loads with activity.

In a second study conducted by Giffin and associates,[74] a 5-mm anterior opening wedge osteotomy in PCL-sectioned cadaveric knees was performed, and an anterior shift in the tibia resting position of approximately 4 mm was measured. The beneficial effect of an increase in tibial slope in a PCL-deficient knee should be viewed in terms of functional loading conditions, and it is questionable whether the resting no-load position data are applicable to in vivo loading conditions. In this study, under a combined 134-N tibial translation load and 200-N axial compressive load, there was no statistical difference in the amount of posterior tibial subluxation between the PCL-deficient and PCL-deficient osteotomy knees. The data show that the tibia reached a similar abnormal posterior tibial position (mean, 90 degrees AP translation: intact knee, 10 mm; PCL deficient, 20.6 mm; PCL deficient osteotomy, 20.3 mm). The authors concluded that "increasing the tibial slope would improve stability in the PCL-deficient knee"; however, this would be true only for conditions of no posterior tibial loading not expected in functional activities. The data in this study may be viewed from an opposite standpoint to indicate that PCL graft reconstruction is warranted in symptomatic knees because the opening wedge osteotomy is not effective in preventing posterior tibial subluxation under posterior tibial loading conditions.

In cadaveric knees, Agneskirchner and colleagues[4] studied the effect of an opening wedge osteotomy combined with a flexion osteotomy (to change the tibial slope) on tibiofemoral contact pressures and the resultant tibiofemoral position. The study reported that the flexion osteotomy shifted the tibiofemoral contact to a more anterior position (15 degrees of flexion osteotomy, ~5 mm, 30 degrees of knee flexion) that neutralized the effect of sectioning the PCL and reduced pressures of the posterior half of the tibial plateau. The authors suggested in varus-angulated, PCL-deficient knees with associated posterolateral knee ligament injury and knee hyperextension that an associated change in tibial slope would have a beneficial effect. Only quadriceps-induced leg extension loading was used without weight-bearing loads or posterior translational loads that are required to determine the resultant tibiofemoral position under more physiologic loading conditions. The quadriceps loading (to resist the applied external flexion moment) changed with the quadriceps extension force, nearly doubling with the flexion osteotomy (without osteotomy, ~550 N, with 15 degrees of flexion; with osteotomy, ~1100 N quadriceps applied load). In fact, the increased quadriceps loading increased joint contact pressures.

In contrast to the study just discussed, Rodner and coworkers[183] reported in cadaveric knees that an increase in tibial slope in the ACL-deficient knee at the time of an HTO has the potential to redistribute

tibiofemoral contact pressures to a more posterior position on the tibial plateau. From a theoretical standpoint, a redistribution of pressures posterior on the tibial plateau would be detrimental to the long-term success of an HTO in ACL-deficient knees with meniscectomy and posterior tibial plateau articular damage. The cadaver knee studies involved uniaxial loading knee joint loads instead of the quadriceps loading in the study by Agneskirchner and colleagues,[4] thereby demonstrating the marked effect that in vitro experimental loading conditions have on joint contact pressures and study conclusions.

Brandon and associates[35] measured the tibial slope in 100 ACL-deficient patients and 100 controls and reported that female and male patients had similar tibial slope measurements. ACL-deficient female and male patients had increases in tibial slope (mean values increased 3.6 degrees and 2.4 degrees, respectively), and the high-grade pivot shift patient group had an increase in tibial slope (mean value increased ~2 degrees). The measurements show high standard deviations (~35% of the mean values), and it is probable that the few degrees difference among patient groups are not clinically significant or would result in increased ACL load and anterior tibial displacement.

Dejour and colleagues[53] evaluated chronic ACL-deficient knees with monopodal lateral weight-bearing films (knee flexed 20 to 30 degrees with the quadriceps contracted) and compared the anterior tibial translation with the tibial slope. The tibial slope was defined as the angle between the medial tibial plateau and the long axis of the tibia, which had an average value of 6 degrees. The anterior tibial translation was defined as the distance between a parallel line at the posterior medial tibial plateau and a posterior point on the medial femoral condyle. The authors reported a statistically significant relationship between the standing anterior tibial translation and the tibial slope in both normal and chronic ACL-deficient knees. The regression line showed a 6 mm increase in anterior tibial translation for every 10-degree increase in tibial slope. However, it should be noted that a wide variation was present in the data between knees. For example, in chronic ACL-deficient knees with a tibial slope of 10 degrees, anterior tibial translation varied from approximately –2 to 12 degrees.

Griffin and Shannon[73] summarized the clinical role of HTO with knee ligament instability, showing the benefit of an anterior opening wedge HTO for severe recurvatum and correcting an abnormal increased tibial slope in select patients who had failed multiple ligament reconstructions.

Marti and coworkers[125] recommended that knees with ACL insufficiency and associated medial arthritis with a tibial slope of 10 degrees or more undergo correction at the time of a varus-producing osteotomy. However, no clinical data were provided to demonstrate whether a change in slope decreased instability symptoms. Other authors[54] have discussed increases in ACL tensile loads when tibial slope exceeded 10 degrees and postulated the need for correction, again without clinical data.

Griffin and Shannon[73] noted that the anterior tibial subluxation with ACL insufficiency results in a "copula" owing to increased damage of the medial plateau; however, the effect of a medial meniscectomy on producing the same effect should be considered.

We agree with recommendations to correct tibial slope when a distinct abnormality is present (Figs. 26-22 and 26-23). The published literature does not provide objective data regarding the degrees of abnormal increase or decrease in tibial slope when corrective osteotomy is indicated where there is an associated ACL or PCL insufficiency.

It is probable that a change in AP shear forces, cruciate tensile loads, and tibiofemoral contact under dynamic conditions would not have clinical significance after a 5-degree change in the tibial slope when the preoperative tibial slope is in the normal range. Therefore changing

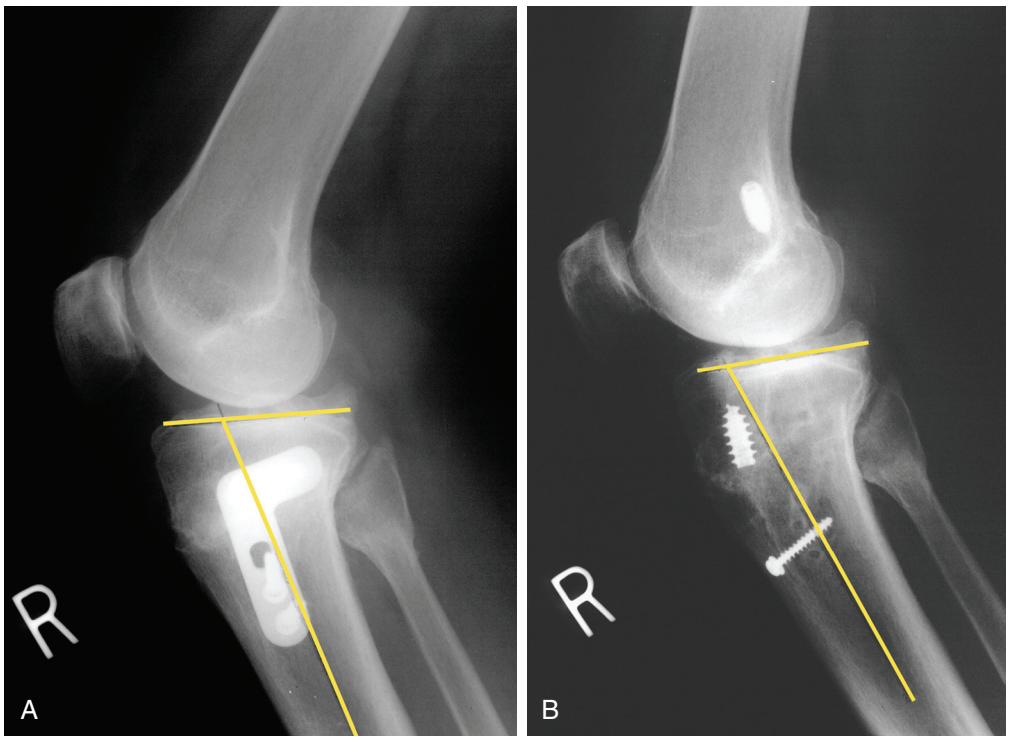


FIG 26-22 Radiographs of a 52-year-old physician referred for treatment after a closing wedge osteotomy (**A**) and subsequent anterior cruciate ligament (ACL) bone-patellar tendon-bone autograft (**B**) that failed. It would have been desirable to correct the abnormal tibial slope, which may have been a factor in the ACL graft failure.

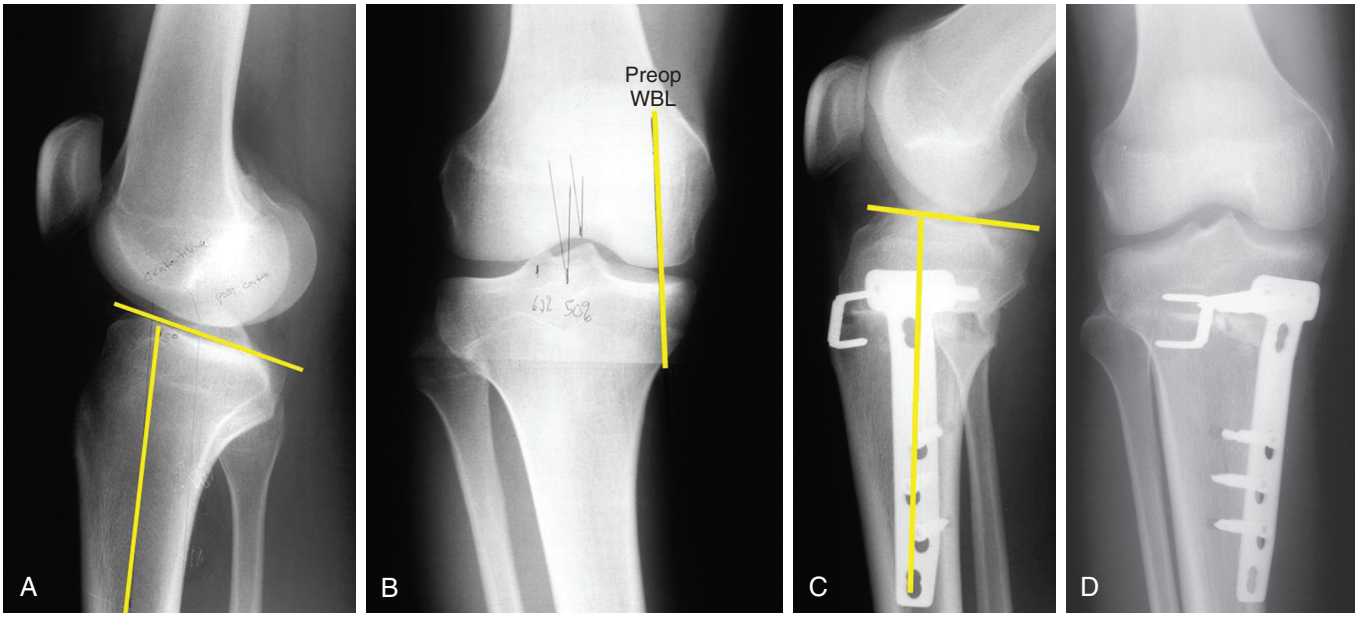


FIG 26-23 **A** and **B,** Preoperative radiographs of a 24-year-old man with bilateral severe varus angulation with medial joint line pain. **C** and **D,** Postoperative radiographs after a biplanar opening wedge osteotomy that was done to correct the abnormal tibial slope. *WBL,* Weight-bearing line.

the tibial slope to alter the tibiofemoral contact position by a few millimeters to produce an anterior or posterior shift in tibia position (to an area of less cartilage damage) has theoretical benefits but has not been proven in clinical studies to be adopted as a treatment recommendation.

There are patients who have a distinctly abnormal tibial slope from a prior osteotomy, tibial fracture, or growth abnormality or an underlying genetic variability in which correction of the tibial slope is required before cruciate ligament surgery or other conditions discussed. Occasionally, ACL revision patients have an abnormally increased slope that should be corrected before ACL revision surgery. Empirically, a tibial slope 2 standard deviations above normal or more (based on the method) may be considered for correction. In these knees, at the time of HTO, it is possible to decrease the tibial slope to normal or below normal in ACL-deficient knees, or to increase the slope in PCL-deficient knees to alter loads on the respective cruciate ligament and possibly change the abnormal resting tibiofemoral weight-bearing position.

A normal tibial slope should not be altered in ACL-deficient knees or PCL-deficient knees undergoing a varus-producing opening wedge osteotomy. The rule is described elsewhere in this chapter (Opening Wedge Osteotomy: Preservation of Tibial Slope) that the anterior gap at the medial opening wedge should be one half of the posteromedial gap to maintain a normal tibial slope.[164] For every 1 mm of anterior gap change, an approximate 2-degree change in tibial slope would be produced. This is based on the angle of the anteromedial tibial cortex, the tibial width, and the AP distance where the gap measurement is made (see Table 26-5). It is common in opening wedge osteotomies to incorrectly produce a symmetrical anterior and posterior gap at the osteotomy site, which results in a considerable increase in the tibial slope, potentially leading to a decrease in knee extension and increase in ACL tensile loads. For example, a change in the tibial slope by 10 degrees would result if an anterior gap measurement error of only 5 mm occurred. The final tibial slope is verified at surgery by lateral fluoroscopic views.

If the surgeon elects to decrease the tibial slope, a staple may be placed at the tibial tubercle after the osteotomy is carefully closed anteriorly to the desired amount. In the senior author's experience, biplanar corrections require the use of a secure locking plate design to maintain the correction because it is necessary to extend the osteotomy through the lateral tibial cortex to close the anterior osteotomy gap (Fig. 26-24). Caution is required when closing the anterior osteotomy gap to apply only gentle hyperextension pressure on the tibia. If any resistance is obtained, it is necessary to be sure the posterolateral tibial cortex has been osteotomized to prevent a lateral tibial plateau fracture from occurring just anterior to the remaining posterolateral cortex.

Song and associates[194] reported that the normal tibial slope would be maintained if the gap or millimeters of opening along the anteromedial cortex of the anterior plate was two thirds the gap at the location of the posterior plate. The reader should note that the authors are referring to the location of two plates placed along the anteromedial tibial cortex and not the most posterior and anterior gap of the tibial opening wedge discussed in a Noyes and colleagues study (anterior gap 50% of posterior gap).[164] The data of Noyes and colleagues' study allow the gap to be computed along the entire anteromedial cortex. The Song et al[194] study does not specify where the two plates are placed, whereas data of the Noyes and colleagues' study[164] show the actual gap distance where one or two plates would be placed.

Hohmann and coworkers[91] retrospectively reviewed the radiographs of 67 patients who had a closing wedge HTO and reported a mean decrease of 4.9 degrees in the tibial slope. They suggested that this occurred because of the triangular geometry of the tibia, with a larger width of bone removed from the anterolateral portion of the lateral tibia.

Timing of Procedures

The timing of HTO and ligament reconstructive procedures is based on several factors (Table 26-4 and Fig. 26-25). In primary varus knees that do not demonstrate abnormal lateral joint opening and external

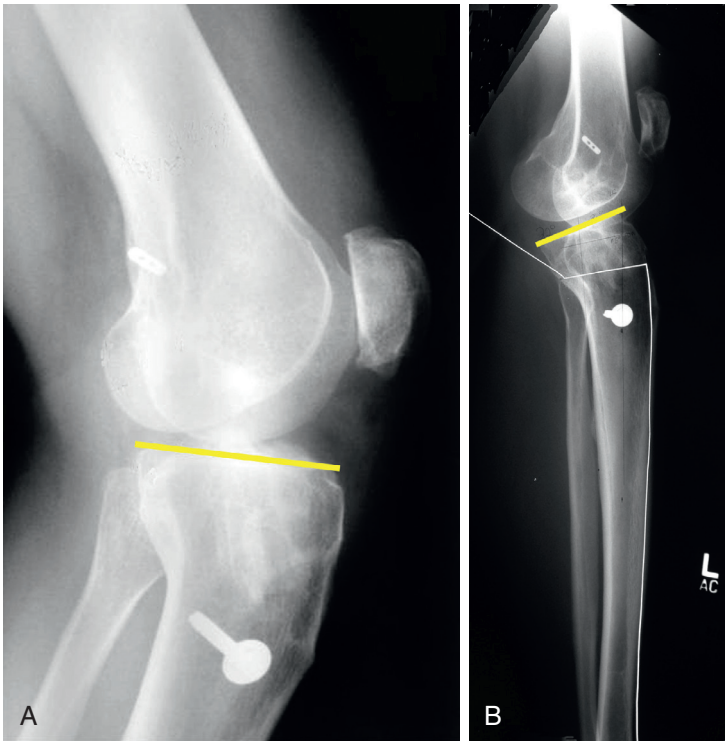


FIG 26-24 A 42-year-old athletic woman sustained an anterior cruciate ligament (ACL) rupture and subsequently underwent an ACL reconstruction that failed for unknown reasons. Two ACL revision reconstructions also failed. She became disabled and had severe giving way with walking and all daily activities. **A,** Lateral radiograph in which the abnormal posterior tibial slope was not recognized. **B,** The posterior tibial slope measured on this long-leg radiograph was 22 degrees. The opposite leg had a similar congenital abnormal tibial slope. The patient required a biplanar osteotomy and ACL revision reconstruction.

TABLE 26-4 Indications and Timing of Knee Ligament Reconstructive Procedures

Ligament Deficiency	Surgical Procedure	Timing Related to HTO	Indications/Comments
ACL	**Autograft***: 1. Central third B-PT-B 2. Semitendinosus-gracilis four-strand 3. QT-PB **Allograft:** 1. B-PT-B 2. Achilles tendon 3. Others†	With HTO only in primary varus knees that do not have abnormal lateral joint opening. Stage HTO double, triple varus knees.	Any patient who had instability before HTO and who should not risk a further trial of function and possible reinjury Consider when secondary ligamentous restraints are lost (pivot shift III + impingement, >10 mm increased anterior displacement involved knee) and with associated medial or FCL, PL deficiency. When meniscus repair is performed; athletically active patient desiring best knee possible for return to sports
FCL, PMTL (PL structures partial injury, increase 5-mm lateral joint opening, 5-10 degrees external rotation)	Usually not required after HTO. Confirm negative gap test for abnormal lateral joint opening if ACL reconstruction required (primary vs. double varus knee).	Avoid FCL reconstruction	Expect adaptive shortening of FCL, lateral tissues in majority after valgus producing osteotomy. Prefer opening wedge HTO. If closing wedge HTO, avoid disrupting tibiofibular joint, with proximal migration and laxity of PL structures.
FCL, PMTL, PL capsule complete deficiency	1. Proximal advancement PL structures (interstitial stretching). 2. FCL, PMTL anatomic reconstruction with autograft or allograft.	Staged procedure: HTO first, followed by combined ACL, FCL/PMTL anatomic reconstruction	Usually have increased lateral joint opening of 8 mm at the intercondylar notch (≥12 mm at periphery), increased external tibial rotation of 15 degrees, varus recurvatum, requiring PL reconstruction. PL and ACL reconstructions always performed together.

*Ipsilateral or contralateral autogenous grafts preferred over allografts.
†We prefer allografts with bone compared with anterior tibialis.
ACL, Anterior cruciate ligament; *B-PT-B*, bone-patellar tendon-bone; *FCL*, fibular collateral ligament; *HTO*, high tibial osteotomy; *PL*, posterolateral; *PMTL*, popliteal muscle-tendon-ligament; *QT-PB*, quadriceps tendon-patellar bone.

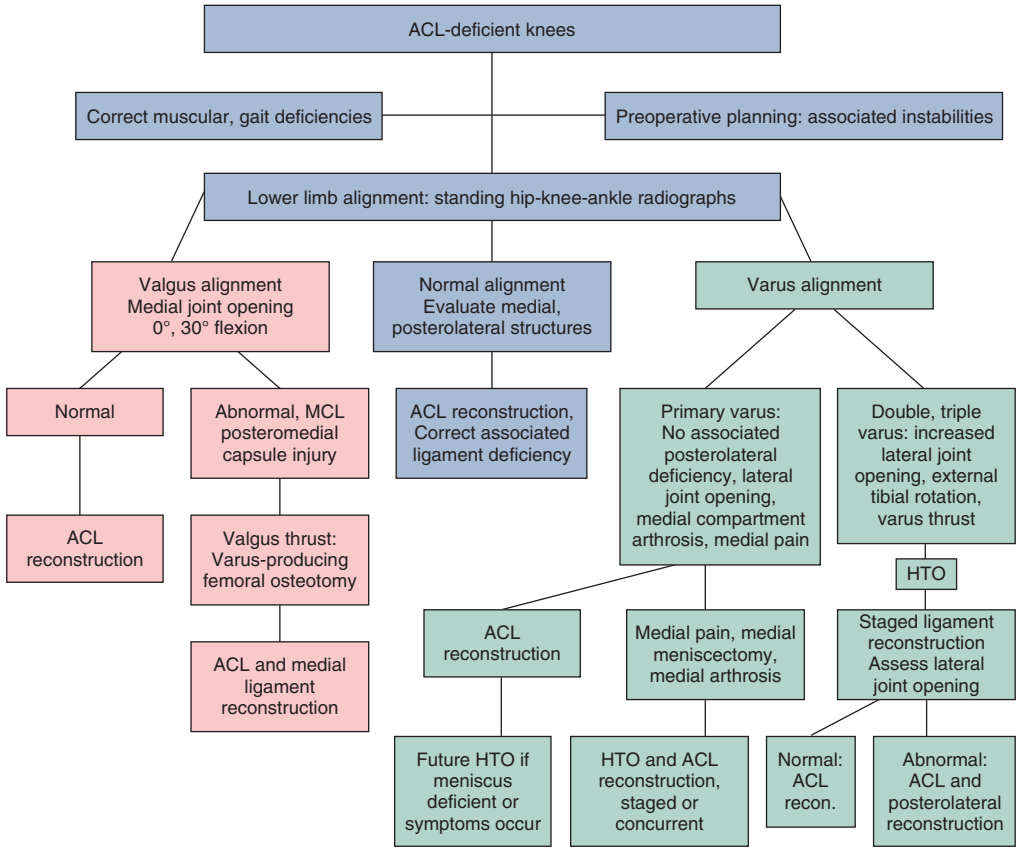


FIG 26-25 Timing of a high tibial osteotomy (HTO) and knee ligament reconstructive procedures. *ACL,* Anterior cruciate ligament; *MCL,* medial collateral ligament. (From Noyes FR, Barber-Westin SD. Revision anterior cruciate ligament surgery with use of bone-patellar tendon-bone autogenous grafts. *J Bone Joint Surg Am.* 2001;83:1131-1143.)

tibial rotation, the HTO and cruciate reconstruction may be performed at the same setting.[152] In double and triple varus knees, the ligament reconstructive procedures are performed after the HTO to reduce the risk of complications.[159] Prolonged rehabilitation and an increased risk of knee arthrofibrosis and motion problems have been described after HTO and ligament reconstructive procedures are performed simultaneously.[34,117,208]

We prefer to perform the HTO first and, after adequate healing of the osteotomy, the required ligament reconstructive procedures are performed. In ACL-deficient double varus knees, an increase in the lateral tibiofemoral joint gap test contraindicates ACL reconstruction. HTO is effective in decreasing abnormal loads in the lateral and posterolateral tissues, allowing physiologic remodeling and shortening to occur, particularly when the deficiency of the posterolateral structures is only moderate (5 to 8 mm of increased lateral joint opening, 10 degrees of increased external tibial rotation).[152,159] In a study conducted by us,[152] described later in this chapter, 22 of 41 double varus knees (54%) had abnormally increased lateral joint opening on varus stress testing before osteotomy. Of these, only five (12%) had this abnormal joint opening at follow up. An FCL and posterolateral reconstruction was avoided in many patients. A subgroup of 11 patients (27%) did not require ACL reconstruction because instability symptoms did not exist after the HTO.[152]

In triple varus knees, the ACL and posterolateral structures are reconstructed after the HTO to allow all ligament structures to function together to resist anterior subluxation, abnormal lateral tibiofemoral joint opening, and varus recurvatum. These represent major surgical procedures that are always staged and not combined with the HTO.

Cruciate Graft Options

A four-strand semitendinosus-gracilis (STG) autograft may be harvested from the involved side with little morbidity. Most patients undergoing HTO will not be involved in strenuous athletics, and a STG autograft provides suitable stability for light recreational activities. In revision knees, a STG graft may be used if there are no enlarged femoral or tibial tunnels.

A bone-patellar tendon-bone (B-PT-B) autograft is preferred if there is gross anterior subluxation (grade III pivot shift). In knees undergoing revision ACL reconstruction in which the ipsilateral patellar tendon was previously harvested, the contralateral B-PT-B graft or the ipsilateral quadriceps tendon-patellar bone (QT-PB) graft are preferred substitutes.[153,157] However, care must be taken when harvesting these autografts from the same knee at the time of the osteotomy. The opposite knee may be used for graft harvest.

The use of allografts for ACL reconstruction is controversial owing to the higher graft stretch-out and failure rates compared with bone-patellar tendon-bone autografts as discussed in detail in Chapters 7 and 8.[149-151,160] If an allograft is required, the B-PT-B has an advantage of more secure bone fixation.

Graft preferences for PCL reconstruction are a two-strand QT-PB autograft or allografts, further described in Chapter 16.[154,156] The options for surgical restoration of deficient posterolateral structures are described in Chapter 17.

Opening Versus Closing Wedge Osteotomy

The two most common operative techniques for correcting a varus deformity are the opening and the closing wedge tibial osteotomies. An opening wedge avoids the lateral dissection and fibular osteotomy. Knees that require a large angular correction of greater than 12 degrees are candidates for the opening wedge procedure because it avoids excessive tibial shortening.

Opening wedge osteotomy is advantageous in knees that have chronic medial ligamentous deficiency (MCL, posteromedial capsule), in which a distal advancement or reconstruction of the MCL is required. Knees with rupture of the posterolateral structures requiring posterolateral reconstruction are candidates for opening wedge osteotomy to avoid a proximal fibular osteotomy because an FCL graft will be anchored to the proximal fibula. Opening wedge osteotomy is advantageous in cases of patella alta or decreased lower limb length which would be made worse by a closing wedge osteotomy. A significant patella infera is a relative contraindication for an opening wedge osteotomy. A significant patella alta is a relative contraindication for a closing wedge osteotomy.

The major disadvantage of an opening wedge osteotomy is that an appropriate structural corticancellous autograft or allograft is required to restore the anteromedial and posteromedial cortex, add fixation strength, and promote osseous union (with major corrections). Autogenous bone grafting of the open defect aids in promoting prompt union with reduced risk of varus collapse caused by a delayed union.

Several opening wedge plate designs are available. We prefer a tibial plate with locking screws to achieve secure osseous fixation.[200] The reader is referred to the appropriate literature by the respective manufacturer, because each locking plate design is different and the recommended technique must be followed. There are rules that must be followed to avoid changing the tibial slope with the use of any fixation plate. A greater chance of increasing the posterior tibial slope exists if an opening wedge buttress plate is placed in an anterior position.[39] With attention to this problem during surgery, the normal tibial slope in the sagittal plane can be preserved with any of the available plate designs.[164]

A disadvantage of an opening wedge osteotomy is that transection of the superficial distal attachment of the MCL is required. In an opening wedge osteotomy of 5 mm, the MCL fibers may be incompletely transected at several different levels (pie-crust approach) to lengthen the ligament. However, osteotomies entailing a correction greater than 5 mm require distal MCL sectioning, careful reflection from the osteotomy site, and reattachment.

The closing wedge osteotomy has the advantage of faster healing and early resumption of weight bearing because contact of two large cancellous surfaces of the proximal tibia is achieved. The initial interval fixation of the osteotomy is more secure than an opening wedge procedure, and there is less chance for a change in osteotomy position and loss of correction. It is more difficult (compared with the opening wedge technique) to achieve or change the desired amount of bone resection to obtain accurate angular alignment correction at surgery.

The closing wedge osteotomy involves more soft tissue dissection. Osteotomy of the fibula is preferred at the proximal fibular neck region. The lateral dissection must be meticulous to avoid the peroneal nerve. It is more tedious to resect more bone and alter the lower limb valgus correction if it is necessary to achieve additional angular correction. The triangular bone wedge is removed and saved in case it is necessary to reinsert bone during the procedure if an overcorrection occurs.

Brouwer and associates[40] conducted a prospective clinical trial in 92 patients randomized to either an opening wedge (Puddu plate) or a closing wedge osteotomy. At 1 year postoperatively, a valgus alignment (defined as 0 to 6 degrees valgus) was noted in 79% of the closing wedge osteotomies compared with 56% of the opening wedge osteotomies. The authors concluded that the Puddu plate had insufficient strength to maintain the operative correction. The investigation had several flaws because it involved four surgeons, and hip-knee-ankle radiographs were not obtained in the initial postoperative period. The number of opening wedge osteotomies that received autogenous bone grafting was not provided. The results emphasize the importance of determining that the appropriate valgus correction is achieved during surgery and maintained in the early postoperative period until union has occurred. The failure to achieve the desired valgus alignment would be expected to decrease long-term success rates. Full-standing weight-bearing hip-knee-ankle radiographs may be obtained by 3 to 4 weeks postoperative after either opening or closing wedge osteotomy to verify that correction has been achieved. In a small percentage of cases in which the correction is found not to be ideal on early postoperative radiographs, a revision angular correction may then be performed.

The use of an external fixator has been advocated with tibial osteotomy, with the advantage of allowing adjustments in lower limb alignment that is helpful in difficult or biplanar corrections.[201,219] Disadvantages of an external fixator are the risk of pin tract infection[2,19,71,201,219] and the 12-week period that the fixator is typically used. The use of an external fixator is ideal when both coronal lower limb alignment and tibial rotation need to be corrected.

Opening Wedge Osteotomy: Preservation of Tibial Slope

On cross-section, the proximal anteromedial tibial cortex has an oblique or triangular shape, whereas the lateral tibial cortex is more perpendicular at the posterior margin of the tibia. Because of this relationship, a medial opening wedge osteotomy that has an anterior tibial tubercle width equal to the width at the posteromedial margin would increase tibial slope, decrease knee extension, and possibly increase ACL tensile loads. A lateral closing wedge osteotomy with an equal anterior-to-posterior width or gap along the lateral tibial cortex tends to decrease the tibial slope by a few degrees, as is described next.

A study was conducted using 3-dimensional analysis of the proximal tibia to determine how the angle of the opening wedge along the anteromedial tibial cortex influences the tibial slope (sagittal plane) and valgus correction (coronal plane) when performing a medial opening wedge osteotomy.[164]

The data in this study on the obliquity of the anteromedial cortex of the proximal tibia relative to the posterior tibial cortex (Fig. 26-26) are presented from 35 magnetic resonance imaging (MRI) films in healthy young individuals (mean age, 32.7 years). Serial CT images of a cadaveric tibia were made in 1.25-mm slices and digitized using a computer-aided design package to create a solid model of the proximal tibia.

A medial opening wedge osteotomy was created along the AP axis to include a hinge axis on the lateral margin of the tibia. The open wedge osteotomy was just proximal to the tibial tubercle, ending 20 mm below the cortical margin of the lateral tibial plateau. The distal portion of the tibia was rotated on the virtual model about the hinge axis through the lateral point of the osteotomy maintaining the anatomic tibial slope (sagittal plane). Measurements of the width of the wedge angle and gap angle (Fig. 26-27) along the anteromedial tibial cortex were made from the resulting computerized model. Standard algebraic calculations were made using the law of triangles to determine the effect of different degrees of opening wedge osteotomy on coronal (valgus) and sagittal (tibial slope) alignment.

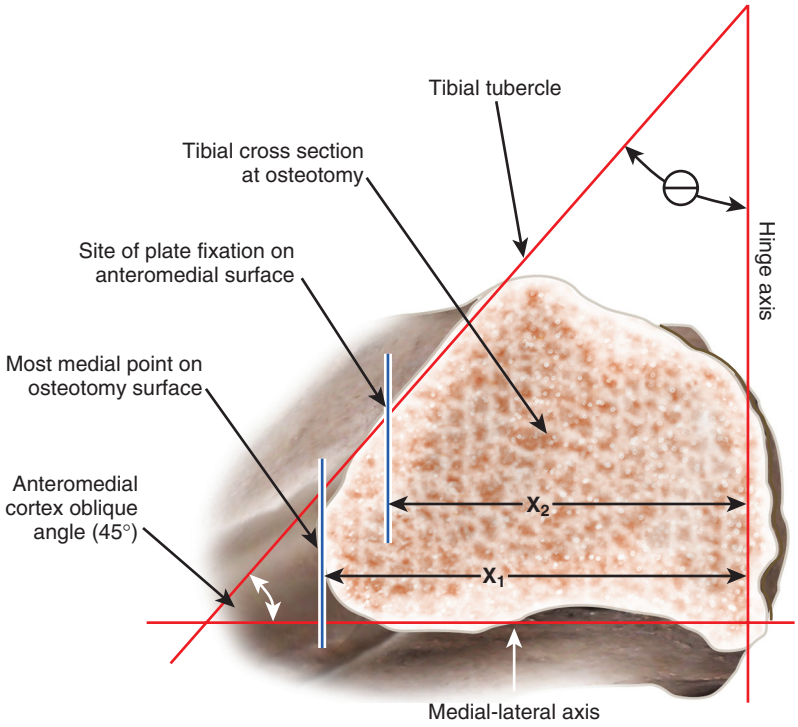


FIG 26-26 An axial cut of the proximal tibia at the diaphyseal-metaphyseal junction. The angle formed by the intersection of the mediolateral axis along the posterior tibia and the axis along the anteromedial tibial cortex is called the *anteromedial cortex oblique angle* (⊖). This angle measures approximately 45 degrees to the coronal plane.

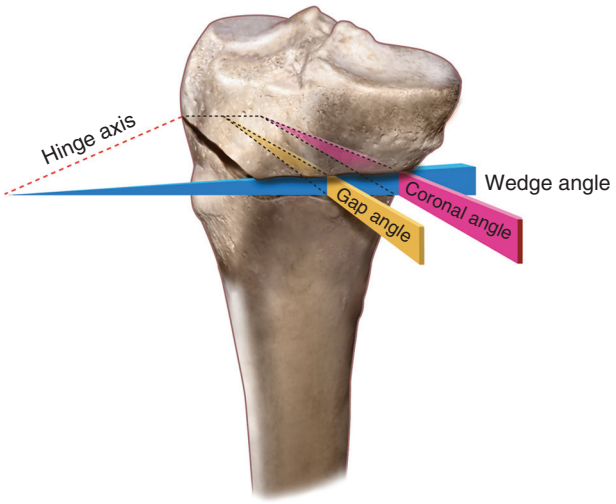


FIG 26-27 The distal portion of the tibia was rotated about an anteroposterior axis, which ran through the hinge point of the osteotomy to maintain the posterior tibial slope. A solid model of a high tibial osteotomy plate was placed at a series of positions around the medial aspect of the tibia, just anterior to the medial collateral ligament. The anteromedial cortex wedge angle is that angle formed along the oblique anteromedial tibial cortex during a prescribed opening wedge osteotomy (coronal plane). The gap angle is formed by planes that are perpendicular to the wedge angle along the anteromedial tibial surface.

The MRI measurement of the anteromedial tibial cortex oblique angle at the site of the opening wedge osteotomy was 45 ± 6 degrees (range, 34-56 degrees). The opening wedge angle, along the anteromedial tibial cortex to maintain the tibial slope, was found to be dependent on the angle of coronal valgus correction (HTO coronal angle) and the angle of obliquity of the anteromedial tibial cortex. In Figure 26-28, the results are shown for the calculation of the opening wedge angle (along the anteromedial tibial cortex) for five different osteotomy corrections in the coronal valgus plane (2.5-12.5 degrees).

The gap angle is perpendicular to the anteromedial oblique surface of the tibia with a vertex on the hinge axis posterior to the tibia. This is shown in Figure 26-29, in which the gap angle in degrees is shown for five different osteotomy corrections as a function of the obliquity of the anteromedial tibial cortex.

As an example, a 10-degree coronal valgus correction (assuming a normal 45-degree obliquity of the anteromedial tibial cortex) would result in a 7-degree gap angle at the osteotomy site. An error in the anteromedial tibial cortex opening wedge angle would result in an error in the tibial slope. An example of this is shown in Figure 26-30, which represents the desired wedge angle for a 10-degree coronal correction. An equal anterior and posterior opening or gap at the osteotomy site would result in an increased tibial slope and loss of normal knee extension.

These variables are shown in Table 26-5. For example, an error of 5 mm in the Y_2 gap (Fig. 26-31) at the tibial tubercle, assuming the length of the anteromedial cortex (L) is 45 mm, would result in an unexpected change in the tibial slope of 10 degrees. As a general rule in this example, every millimeter of alteration in the gap height induces a change of 2 degrees in the tibial slope.

The opening wedge angle can be set at surgery by measuring and altering the vertical gap (width) at two points along the osteotomy site,

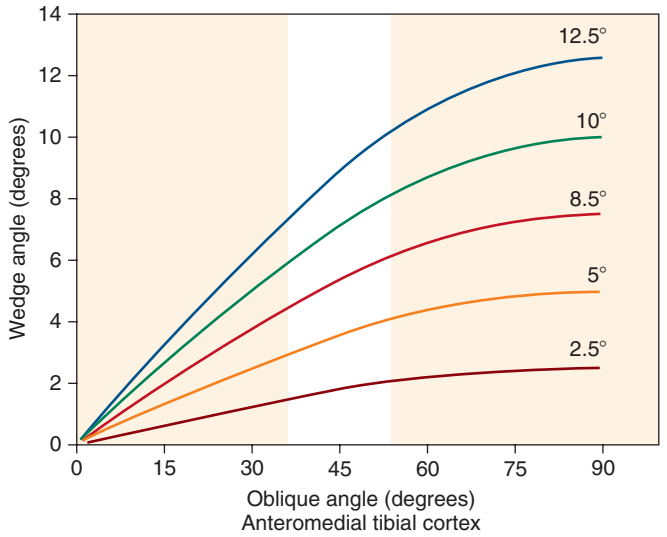


FIG 26-28 The anteromedial cortex opening wedge angle depends on the oblique angle of the tibial cortex with respect to the hinge axis. Each line represents the desired calculated degrees of correction for the opening wedge osteotomy in the true coronal (90-degree) plane. (From Noyes FR, Goebel SX, West J. Opening wedge tibial osteotomy: the 3-triangle method to correct axial alignment and tibial slope. *Am J Sports Med.* 2005;33:378-387.)

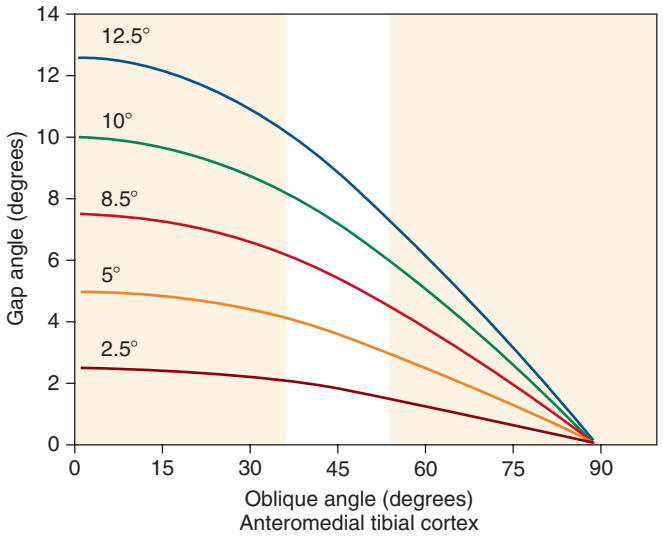


FIG 26-29 The magnitude of the gap angle changes with the obliquity of the anteromedial tibial cortex angle. Each line represents the calculated degrees of correction for the opening wedge osteotomy in the coronal plane. (From Noyes FR, Goebel SX, West J. Opening wedge tibial osteotomy: the 3-triangle method to correct axial alignment and tibial slope. *Am J Sports Med.* 2005;33:378-387.)

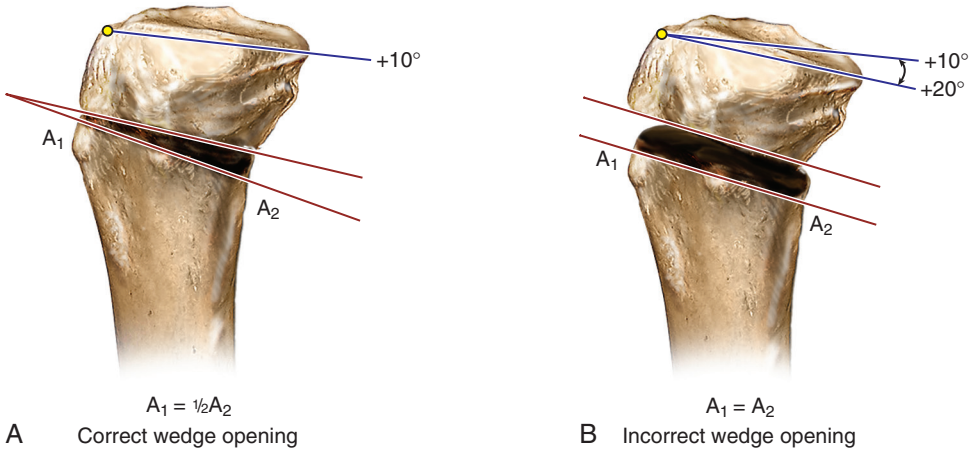


FIG 26-30 **A,** Appropriate choice of the wedge angle to maintain the sagittal tibial slope. **B,** Inappropriate wedge angle results in increased tibial slope.

Y_1 and Y_2 (Fig. 26-32). This has importance in determining that the correct wedge angle is obtained before internal fixation at the osteotomy site. The site at which the vertical gap measurement is taken depends on the coronal distance from the hinge axis, the obliquity of the anteromedial tibial cortex, and the distance along the osteotomy site on the anteromedial surface (Tables 26-6 and 26-7).

In Table 26-6, the millimeters of opening at the osteotomy site are based on the width of the tibia and the angle of correction. In Table 26-7, an average 45-degree oblique angle of the anteromedial cortex and a tibial width of 60 mm are assumed. This allows the surgeon to calculate at the time of surgery the desired gap height at two points along the osteotomy to maintain the tibial slope.

For example, the measurement of the posterior tibial width is made at the osteotomy site (X_1). The opening height at the most posteromedial point (Y_1) and the distance between the two measurement points (Y_1-Y_2) are used in Table 26-7 to determine the second opening height at a defined distance (L) along the osteotomy site to maintain tibial slope.

If the tibial plate is placed just anterior to the superficial MCL on the anteromedial tibial cortex, approximately 20 mm anterior to the most posteromedial point of the osteotomy, the osteotomy gap at this site can be determined in Table 26-7, with a 10-mm posteromedial opening (Y_1), the correct width at the tibial plate would be 7.6 mm (tibial width, 60 mm).

For a 12-mm posteromedial opening, the correct width of the gap at the tibial plate would be 9.2 mm. A wider gap at the tibial plate would result in excessive valgus alignment and altered tibial slope. The change in the oblique angle of the anteromedial cortex, within the standard deviations reported, would have only a small and negligible effect on the width measurements of the opening wedge (see

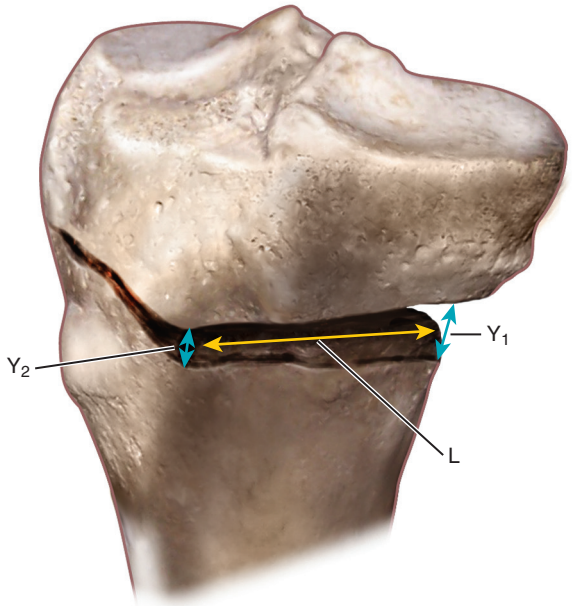
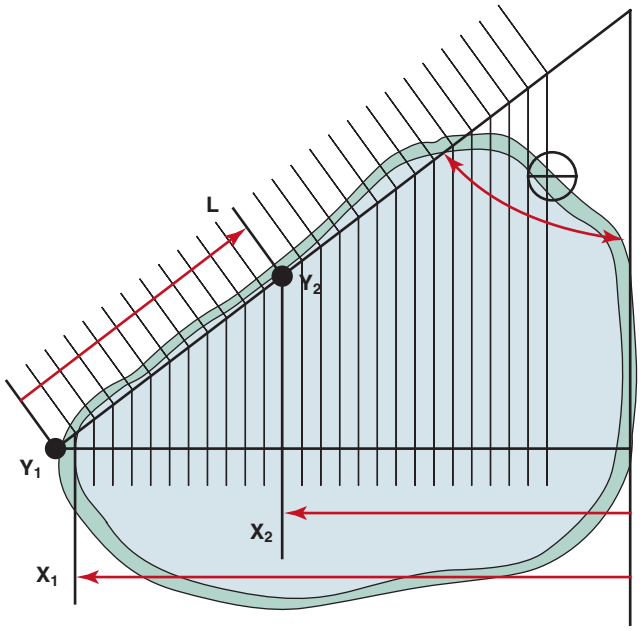


FIG 26-31 The opening wedge angle along the anteromedial tibial cortex can be calculated using the three linear measurements along the osteotomy opening wedge. *Y*$_1$, Gap anterior to Y_2; *Y*$_2$, posterior gap; *L*, length between Y_1 and Y_2.



$$L = \frac{X_1 \, 2 \, X_2}{\text{Sin}\,(\theta)} \qquad Y_2 = \frac{(X_2)\ 2(Y_1)}{X_1}$$

FIG 26-32 Vertical gap measurements of the opening wedge osteotomy are a function of distance from the hinge axis of the lateral tibial cortex for the opening wedge (X_1, X_2), oblique angle of the anteromedial tibial cortex (Θ), and distance along the osteotomy site L. (From Noyes FR, Goebel SX, West J. Opening wedge tibial osteotomy: the 3-triangle method to correct axial alignment and tibial slope. *Am J Sports Med.* 2005;33:378-387.)

TABLE 26-5 Errors in the Tibial Slope Caused by Errors in Vertical Gap Height (Y_2)

Error at Y_2 (mm)	LENGTH OF ANTEROMEDIAL CORTEX (mm)							
	25	30	35	40	45	50	55	60
1	4	3.2	2.7	2.3	2	1.8	1.6	1.5
2	8.1	6.5	5.4	4.6	4	3.6	3.2	2.9
3	12	9.6	8.1	6.9	6.1	5.4	4.9	4.4
4	15.8	12.8	10.7	9.2	8.1	7.2	6.5	5.9
5	19.5	15.8	13.3	11.4	10	8.9	8.1	7.3
6	23	18.8	15.8	13.6	12	10.7	9.6	8.8
7	26.3	21.6	18.3	15.8	13.9	12.4	11.2	10.2
8	29.5	24.4	20.7	17.9	15.8	14.4	12.8	11.6
9	32.5	27	23	20	17.7	15.8	14.3	13
10	35.3	29.5	25.2	22	19.5	17.4	15.8	14.4

Values are in degrees.

Table 26-7). To maintain the proper anterior and posterior gaps at the osteotomy site, appropriate distraction instruments at surgery are required to maintain the desired coronal and sagittal angular correction.

Final Recommendations to Obtain Correct Coronal and Slope Alignment

1. Determine the coronal valgus angular correction in degrees based on preoperative full-standing radiographs for the desired placement of the WBL at the tibial plateau and measure the tibial slope based on a lateral radiograph.
2. Determine the millimeters of opening at the posteromedial osteotomy site at surgery (Y_1 gap) using the width of the tibia (X_1 distance) for the coronal valgus correction based on the law of triangles (first triangle; see Table 26-6).
3. Determine the proper gap width of the osteotomy opening wedge along the anteromedial cortex to maintain tibial slope and the proper width beneath the tibial plate based on its location along the anteromedial cortex (see Table 26-7). The opening wedge gap will always be 3 to 4 mm less where the plate is located. If the tibial slope is to be increased or decreased, the effect on the degrees of tibial slope is shown in Table 26-5.
4. Confirm final coronal and sagittal angular correction based on intraoperative fluoroscopy and early postoperative full standing and lateral radiographs.

INTRAOPERATIVE EVALUATION

An operative "time-out" and identification of the operative limb by the surgeon and patient are performed as described in detail in Chapter 7. All knee ligament subluxation tests should be performed after the induction of anesthesia in both the injured and contralateral limbs. The amount of increased anterior tibial translation, posterior tibial translation, lateral joint opening, and external tibial rotation should be documented as previously described.

A thorough arthroscopic examination should be conducted, documenting articular cartilage surface abnormalities[169] and the condition of the menisci. The gap test is done during the arthroscopic examination.[159] The knee is flexed to 30 degrees, and a varus load of approximately 89 N is applied. A calibrated nerve hook is used to measure the amount of lateral tibiofemoral compartment opening (Fig. 26-33). Knees that have 12 mm or more of joint opening at the periphery of

TABLE 26-6 Opening at the Osteotomy Site Based on Width of Tibia and Angle of Correction

	ANGULAR CORRECTION (DEGREES)								
TW	5	6	7	8	9	10	11	12	13
50	4.37	5.25	6.15	7	8	8.8	9.7	10.85	11.55
55	4.81	5.78	6.77	7.7	8.8	9.68	10.67	11.94	12.71
60	5.25	6.3	7.38	8.4	9.6	10.56	11.64	13.02	13.86
65	5.69	6.83	8	9.1	10.4	11.44	12.61	14.11	15.02
70	6.12	7.35	8.61	9.8	11.2	12.32	13.58	15.19	16.17
75	6.56	7.88	9.23	10.5	12	13.2	14.55	16.28	17.33
80	7	8.4	9.84	11.2	12.8	14.08	15.52	17.36	18.48
85	7.44	8.93	10.46	11.9	13.6	14.96	16.49	18.45	19.64
90	7.87	9.45	11.07	12.6	14.4	15.84	17.46	19.53	20.79
95	8.31	9.98	11.69	13.3	15.2	16.72	18.43	20.62	21.95
100	8.75	10.5	12.3	14	16	17.6	19.4	21.7	23.1

Values are in millimeters.
TW, Coronal tibial width at osteotomy site.

TABLE 26-7 Opening Wedge Height of Y_2 Gap Based on Tibial Width (X_1)

Opening at Osteotomy (Y_1)	L	TIBIAL WIDTH 50	55	60	65	70
8	0	8	8	8	8	8.0
	20	5.7	5.9	6.1	6.3	6.4
	25	5.2	5.4	5.6	5.8	6
	30	4.6	4.9	5.2	5.4	5.6
	35	4	4.4	4.7	5	5.2
	40	3.5	3.9	4.2	4.5	4.8
	45	2.9	3.4	3.8	4.1	4.4
10	0	10	10	10	10	10
	20	7.2	7.4	7.6	7.8	8
	25	6.5	6.8	7.1	7.3	7.5
	30	5.8	6.1	6.5	6.7	7
	35	5.1	5.5	5.9	6.2	6.5
	40	4.3	4.9	5.3	5.6	6
	45	3.6	4.2	4.7	5.1	5.5
12	0	12	12	12	12	12
	20	8.6	8.9	9.2	9.4	9.6
	25	7.8	8.1	8.5	8.7	9
	30	6.9	7.4	7.8	8.1	8.4
	35	6.1	6.6	7.1	7.4	7.8
	40	5.2	5.8	6.3	6.8	7.2
	45	4.4	5.1	5.6	6.1	6.5

All values are in millimeters.
By measuring the width of the tibia, the opening wedge height at the most medial point (Y_1), and the distance between vertical measurement points (L), the vertical height at the second measurement point (Y_2) at which the plate implant can be found on the table. Calculations are based on a 45-degree angle of the anteromedial tibial cortex at the osteotomy site.

the lateral tibiofemoral compartment will usually require a staged posterolateral reconstructive procedure.

A medial gap test is performed with a valgus load to measure the opening of the medial tibiofemoral compartment. There may be an increased medial opening because of medial joint damage and loss of cartilage and flattening of the femoral and tibial condyles. In rare cases, there is increased opening caused by a chronic MCL rupture. In most knees with varus malalignment, adaptive shortening of the medial ligamentous tissues occurs, and MCL advancement and posteromedial plication procedures are not indicated.

CRITICAL POINTS Intraoperative Evaluation

Repeat all knee ligament subluxation tests under anesthesia on both injured and contralateral limbs.

Rate All Articular Cartilage Surfaces for Abnormalities and Millimeters of Involvement

- Normal
- Grade 1, softening
- Grade 2A, fissuring and fragmentation < half the depth of the articular surface
- Grade 2B, fissuring and fragmentation > half the depth of the articular surface
- Grade 3, subchondral bone exposed

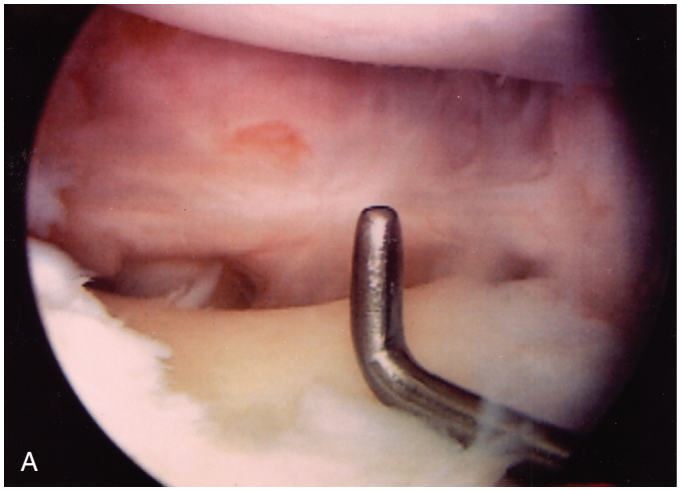
Gap Test during Arthroscopy

- Knee 30 degrees of flexion
- Varus load, valgus load
- Measure millimeters lateral and medial tibiofemoral compartment opening with calibrated nerve hook

OPERATIVE TECHNIQUE: OPENING WEDGE TIBIAL OSTEOTOMY

Step 1: Initial Operating Room Preparations

Preoperative calculations are made as previously described. The entire lower extremity is prepped and draped free with the tourniquet placed high on the proximal thigh to assist visual observation of lower limb alignment. If an autogenous iliac crest autograft is to be performed, the ipsilateral anterior iliac crest is prepped and draped for the limited iliac crest bone harvest of the outer cortex. The patient is positioned to allow fluoroscopic views of the hip-knee-ankle WBL to verify the angular correction at surgery, and lateral views are obtained for tibial slope analysis.



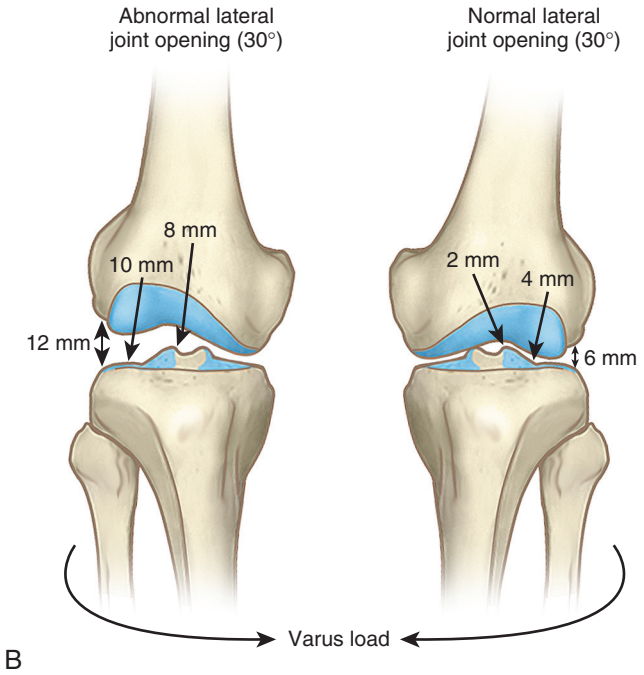


FIG 26-33 **A** and **B,** Arthroscopic gap test for determining the amount of lateral joint opening.

Step 2: Knee Arthroscopy

Arthroscopy is performed at the time of the HTO to evaluate articular surfaces of the medial and lateral tibiofemoral compartments and patellofemoral joint to confirm that the patient is an appropriate candidate for the osteotomy. ACL-deficient knees may have associated meniscus tears that require repair[185] or partial removal. Appropriate debridement of tissues, inflamed synovium, and notch osteophytes limiting knee extension is performed. In particular, there is a secondary weight-bearing area established in varus-angulated knees in which the lateral tibial spine produces a bone erosion over the inner margin of the lateral femoral condyle. The femoral condylar bone erosion may be debrided to remove the painful weight-bearing site.

Step 3: Anterior Iliac Crest Bone Graft Harvest (Opening Wedge ≥15 mm)

Large osteotomies that require 15 mm or more of correction are empirically treated with an iliac crest bone graft. Mid range corrections of 10 to 12 mm are treated with freeze-dried allograft bone wedges plus a locking plate and screws.

A 4-cm incision is made over the anterior iliac crest with care to avoid the ilioinguinal nerve. The incision is deepened to the periosteum (Fig. 26-34), which is sharply incised and reflected medially only to the inner cortex. Laterally, meticulous subperiosteal dissection is

CRITICAL POINTS Operative Technique for Opening Wedge Osteotomy

- Arthroscopy before HTO to assess all knee compartments, confirm HTO indicated, and treat meniscus tears and notch osteophytes blocking knee extension.
- Anterior iliac crest meticulous dissection; remove outer cortex; do not disturb inner cortex or muscle attachments.
- Harvest graft 40 mm in length, 10 mm in width, 30 mm in depth to produce three triangular bone grafts.
- HTO incision: 5-cm vertical medial tibia midway between tibial tubercle and posteromedial tibial cortex, starting 1 cm inferior to joint line.
- Partially detach gracilis and semitendinosus tendons at their tibial insertion; retract posteriorly exposing SMCL and posterior border of the tibia.
- Sharp periosteal incision just anterior to SMCL; meticulous subperiosteal dissection beneath the SMCL fibers. Protect inferior medial geniculate artery beneath the SMCL.
- Posterior tibial subperiosteal dissection to protect neurovascular structures. Wide dissection not necessary. Surgeon's headlight always used.
- Small osteotomies ≤5 mm: "pie-crust" procedure using multiple transverse incisions may effectively lengthen SMCL.
- Osteotomies >5 mm: transect distal SMCL attachment, carefully elevated to the tibial border, protected and reattached after osteotomy.
- Keith needle placed in anteromedial joint above tibia; distance marked for desired point of osteotomy. Second Keith needle placed posteromedial tibial joint space, distance marked. Two marks connected.
- Anterior and posterior guide pins placed at 15 degrees obliquity to tibial shaft; verify position with fluoroscopy.
- Ensure guide pins are at least 20 mm distal to the lateral joint line to prevent lateral tibial plateau fracture.
- Begin osteotomy with oscillating saw for medial and anterior cortices. Follow by nonflexible thin ¾-inch osteotome placed anterior, directly above the guide pin, verified by fluoroscopy.
- Use ½-inch osteotomy for posterior cortex, with osteotome edge visualized and palpated posterior to the tibia as the osteotomy is advanced.
- Carry osteotomy to within 10 mm of the posterolateral cortex; confirm by fluoroscopy.
- Place thin spreader bars across osteotomy. Initial distraction requires several minutes to prevent fracture of the lateral cortex; if major resistance, place holes in lateral cortex with guide pin.
- Anterior gap of osteotomy should be half that of the posterior gap to maintain tibial slope. Maintain osteotomy gap; use anterior tibial staple, if necessary and posterior wedge; confirm alignment by fluoroscopy.
- Apply and fixate locking plate with fluoroscopy verification; confirm final coronal and sagittal (slope) alignment.
- Suture SMCL fibers distally and secure to either plate screws or suture anchors to maintain tension. Reapproximate pes anserine tendons and sartorius fascia.
- Knees with chronic SMCL deficiency require distal advancement if the ligament appears normal without scar replacement.
- Semitendinosus augmentation of SMCL is required in knees with scar replacement.
- When the SMCL is advanced distally or reconstructed, repair medial meniscus attachments.

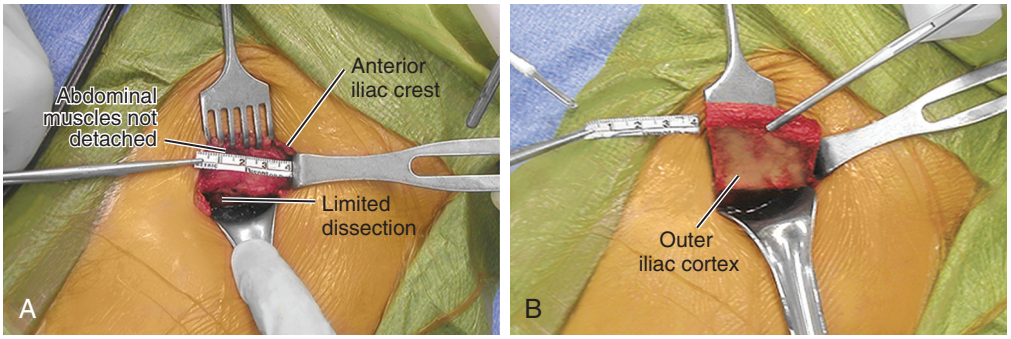


FIG 26-34 **A,** A 4-cm incision over the anterior iliac crest is made to harvest the iliac crest bone graft. The graft is composed of the anterior crest and outer iliac cortex; the inner table is not removed. **B,** The usual iliac crest bone graft dimensions are 40 mm in length, 10 to 12 mm in width, and 30 mm in depth. (From Noyes FR, Mayfield W, Barber-Westin SD et al. Opening wedge high tibial osteotomy. An operative technique and rehabilitation program to decrease complications and promote early union and function. *Am J Sports Med.* 2006;34:1262-1273.)

carried along the outer table of the pelvis, avoiding the lateral muscles. The graft size is defined on the outer cortex using electrocautery. In most patients, the graft will be 40 mm in length, 10 mm in width, and 30 mm in depth. However, in smaller patients, the graft may be smaller in width and approximately 8 mm in depth. Patients undergoing large osteotomies may require a longer graft of approximately 45 to 50 mm.

The inner iliac cortex is not dissected; the muscle attachments are not disturbed, which reduces postoperative pain; and a spacer of the iliac crest defect is not required. Additional cancellous bone is removed from the inner graft site. A drain is not required at the iliac crest harvest site. The wound is closed in layers with deep sutures to close the dead space. The graft is later fashioned into three carefully sized triangles: one triangle is placed posterior to the tibial plate to close the gap at the posterior tibial cortex, one triangle is placed in the midportion of the osteotomy deep to the plate, and one smaller-width triangle is placed in the gap in the anterior tibial cortex. In large osteotomy corrections (>10 mm gap), autogenous bone is always used, and any remaining defect filled with corticocancellous freeze-dried tibial or iliac crest allografts.

Step 4: Initial Anteromedial Tibial Approach

The operative technique is shown in Figure 26-35. A 5-cm vertical skin incision is made medially midway between the tibial tubercle and posteromedial tibial cortex, starting 1 cm inferior to the joint line. A vertical incision is preferred over an oblique or transverse incision because vertical incisions are subsequently used in knees progressing to partial or complete TKA. The sartorius fascia is incised in line with its fibers, proximal to the gracilis tendon, exposing the distal SMCL attachment.

The gracilis and semitendinosus tendons are partially detached at their tibial insertion in an L-shaped manner and retracted posteriorly to further expose the SMCL and posterior border of the tibia. The SMCL is transected at its most distal tibial attachment. Anteriorly, the retropatellar bursa is entered by incising the medial patellar retinaculum, allowing the patellar tendon to be lifted to expose the anterior tibia.

A sharp periosteal incision is just anterior to the SMCL to allow the SMCL to be dissected subperiosteally in a proximal direction and to allow meticulous posterior tibial subperiosteal dissection by a Cobb elevator. Care is taken to identify the inferior medial geniculate artery, which lies just beneath the SMCL. Only sufficient posterior tibial subperiosteal dissection is used to protect the neurovascular structures; wide dissection is not necessary. A malleable retractor is placed in the subperiosteal posterior tibial space.

Step 5: Proximal Osteotomy and Placement of Tibial Guide Pins

The patellar tendon and retropatellar bursa are exposed medially. The superior attachment of the tendon is recessed 5 mm using a scalpel to provide adequate exposure for the osteotomy. Retractors are placed anteriorly and posteriorly to complete the exposure. A Keith needle is placed in the anteromedial joint just above the tibia, and the distance is marked on the desired point of the osteotomy at the tibial tubercle patellar tendon attachment. A second Keith needle is placed at the posteromedial tibial joint space, and the same millimeters are marked. The two marks are connected to provide the osteotomy line perpendicular to the tibial slope.

A 2-mm guide pin is placed at the posteromedial cortex at the marked line and advanced across the tibia at an oblique angle (Fig. 26-36). The anterior and posterior guide pins are placed at 15 degrees of obliquity to the tibial shaft and verified by intraoperative fluoroscopy. An alternative technique is to place the site of the osteotomy directly at the posterior guide pin, maintaining the oblique angle of the pin across the osteotomy site without using the osteotomy guide system.

To prevent a fracture extending into the joint at the lateral tibial plateau, it is important for the guide pins to be at least 20 mm distal to the lateral joint line. An error that may occur is to have too much obliquity to the guide pin.

A this point, it is imperative to ensure that the medial osteotomy line (from anterior to posterior) is in line with the tibial slope based on the radiographs and prior anteromedial cortex joint line measurements by the Keith needles. A measurement of the perpendicular cut from the joint line confirms the distance of each guide pin from the articular surface of the tibia. The length of the posterior pin (medial to lateral cortex) is measured and used following the law of triangles[164] to determine tibial width and the millimeters of osteotomy opening to obtain the desired angular correction (Table 26-6).

The osteotomy is initially performed using an oscillating saw for the medial and anterior cortices, followed by a nonflexible thin ¾-inch and ½-inch osteotome, placed in the same orientation and anterior to



FIG 26-35 **A,** Initial draping of varus-aligned lower extremity. **B,** Incision location, anterior third of medial tibia. **C,** Initial exposure beneath patella tendon under retraction. **D,** Initial subperiosteal dissection of superficial medial collateral ligament. The distal attachment has been incised. **E,** Posterior subperiosteal exposure to protect neurovascular structures. **F,** Placement of navigation femoral and tibial markers; used only in special cases. **G,** A Keith needle placed at the anterior, and later the posterior, aspect of the joint line is used to outline the planned osteotomy.

Continued

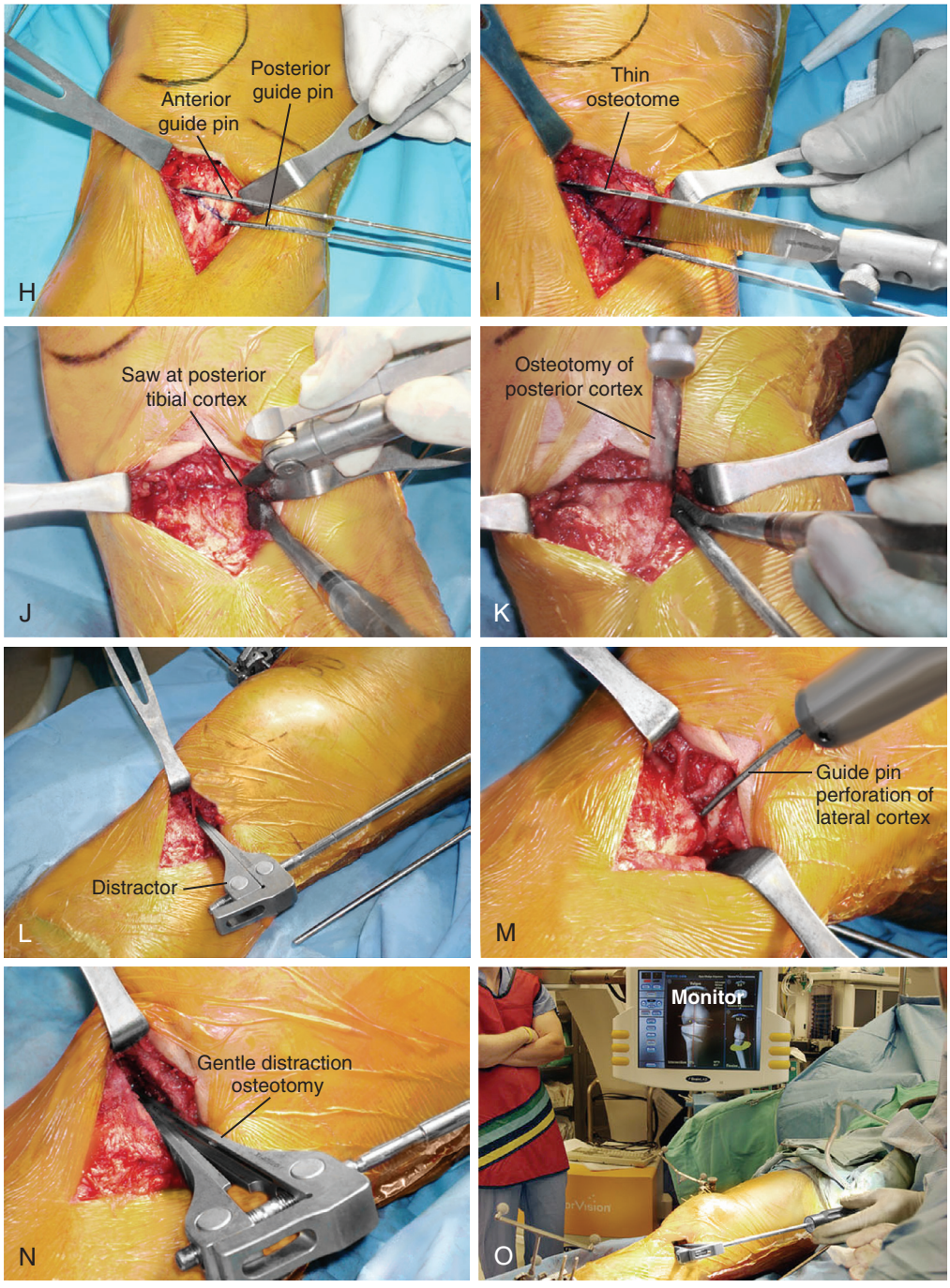


FIG 26-35, cont'd **H,** Two guide pins are placed under fluoroscopic control. **I,** A thin osteotomy blade is placed under fluoroscopic control. Different width blades are used to complete the osteotomy within 5 mm of the lateral cortex. **J,** Initial posterior cortex osteotomy using thin power saw under direct visualization. **K,** Completion of the posterior cortex osteotomy to within 5 mm of posterolateral cortex. **L,** Initial gentle opening of osteotomy. **M,** Guide pin perforation of dense posterolateral tibial cortex to weaken bone owing to failure of the osteotomy gap to increase under gentle dislocation. **N,** Further opening of osteotomy site. **O,** Use of computerized navigation to monitor valgus alignment, or use fluoroscopy with rigid rod from center of hip to ankle for corrected weight-bearing line. Compression at foot closes both tibiofemoral compartments.

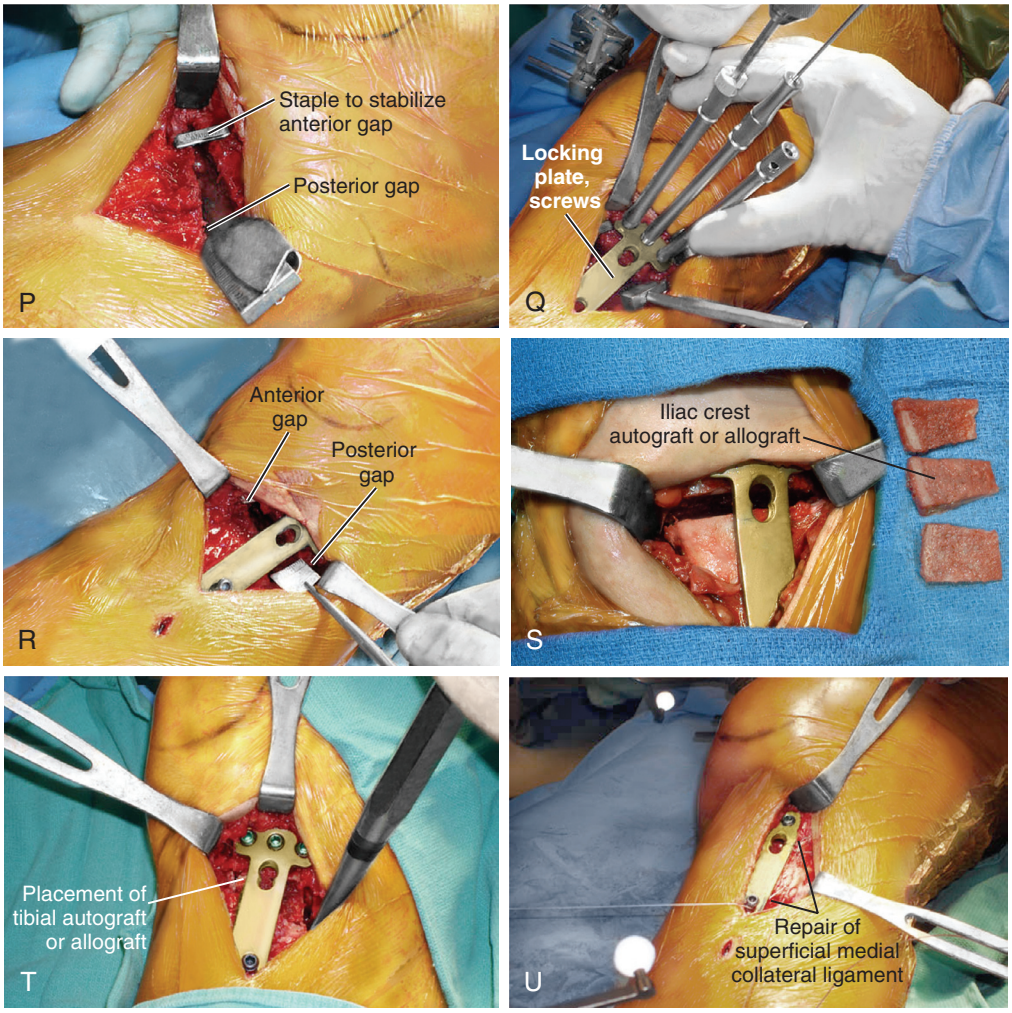


FIG 26-35, cont'd **P,** Staple is placed anterior to the tibial gap to control tibial slope. **Q,** Initial fixation of osteotomy, maintaining the measured osteotomy correction. **R,** Confirmation of the anterior and posterior osteotomy gap measurement. **S,** Bicortical iliac crest autograft or freeze-dried allograft bone is selected. **T,** Placement of the anterior, central, and posterior bone grafts. **U,** Fixation of the anterior border of the superficial medial collateral ligament to the tibial plate.

the guide pin and verified by fluoroscopy (Fig. 26-36). The lateral cortex is osteotomized to Gerdy's tubercle, leaving the posterolateral tibial cortex hinge. A ½-inch osteotome is used for the posterior cortex, with the osteotome exposed 2 to 3 mm and viewed posterior to the tibia as the osteotomy is advanced. The osteotomy is carried to within 10 mm of the posterolateral cortex. It is imperative that the lateral cortex not be fractured because this would produce loss of the lateral cortex buttress and potential collapse and loss of the angular correction. If a fracture of the lateral cortex does occur, with gross instability to the osteotomy site, the lateral tibial cortex may be secured with a two-hole small plate through a limited lateral incision to achieve stability.

Step 6: Opening Wedge Technique and Measurement of Gaps to Confirm Tibial Slope

Commercially available calibrated opening wedges are gently inserted into the osteotomy site to achieve the desired angular correction with the opening medial gap hinging on the intact posterolateral cortex. This step requires several minutes to prevent fracture of the lateral tibial pillar. The spreader bars are inserted entirely across the osteotomy site to prevent a fracture extending into the lateral tibial plateau. If there is a rigid nonyielding response to the spreader bars, the lateral cortex is weakened with three to four guide pin perforations.

The anterior gap of the osteotomy site should be one half of the posterior gap, following rules previously described to maintain the tibial slope.[164] The width of the tibial plate along the anteromedial cortex and just anterior to the SMCL is measured and is always less than the millimeters at the posterior medial gap owing to the angular inclination of the anteromedial tibial cortex.

In select cases as previously described, the tibial slope may be purposefully increased in PCL-deficient knees, decreased in ACL-deficient knees, or altered with abnormal knee hyperextension or flexion contracture. The method to complete the desired change in tibial slope and corresponding width of the anterior and posterior osteotomy sites has been presented in an earlier section of this chapter. A locking plate design is always used in single and biplanar corrections.

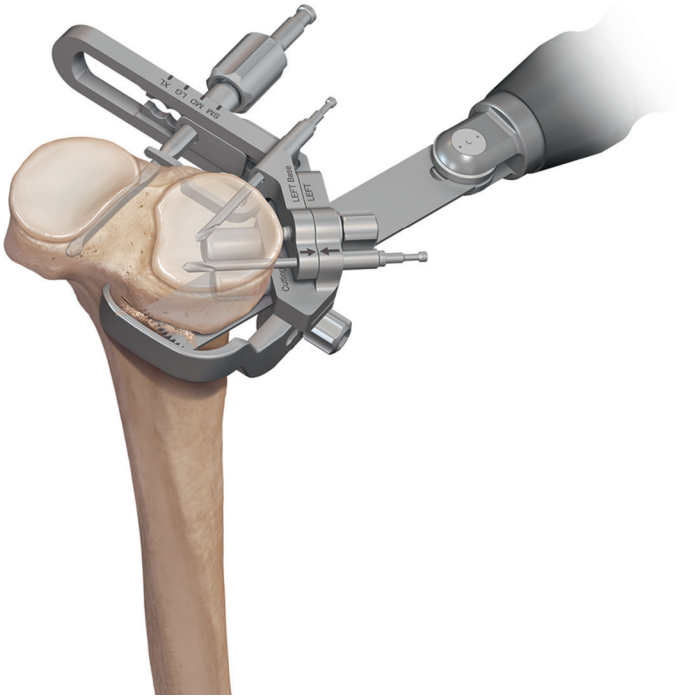


FIG 26-36 A commercial osteotomy wedge system (Arthrex iBalance Opening Wedge Osteotomy System, Arthrex, Inc.) provides protection of neurovascular structures and allows precise guidance of the osteotomy blade. (Courtesy Arthrex.)

Step 7: Intraoperative Verification of Desired Limb Alignment Correction

In addition to preoperative measurements of axial alignment (obtained from double-stance hip-knee-ankle radiographs) and calculations to correct for increased lateral joint opening as previously described, the surgeon must verify intraoperatively that the desired limb alignment has been achieved. After the selected wedge correction (which is maintained using one of the commercial wedge-shaped instruments), a small pad is positioned behind the knee to avoid hyperextension, and the knee is placed in 5 degrees of flexion. With the lower limb lying on the table, the surgeon gently determines that there is closure of both the medial and lateral tibiofemoral compartments viewed by fluoroscopy. An axial load is placed across the bottom of the foot to compress the knee joint to maintain the correct axial alignment. The lower limb is positioned in 10 to 12 degrees of external rotation to simulate the normal lower limb position during gait. A rigid rod is placed at the center of the hip to the center of the ankle, verified by fluoroscopy, and the WBL at the tibia is determined. Adjustment in the millimeters of gap at the osteotomy site is made to obtain the preoperatively selected WBL. The procedure is repeated after internal plate fixation to verify the final alignment correction. The fluoroscopic technique for lower limb positioning to obtain accurate WBL measurements and verify the operative correction does take time and may require repeated steps. The lateral fluoroscopic view determines the final position of the tibial slope. The role of computer navigation is discussed later in this chapter (see "Role of Computerized Navigation for High Tibial Osteotomy").

Obtaining an alignment correction in which the WBL is transferred to the lateral tibiofemoral compartment within the desired 50% to 62% range is the key to achieving short- and long-term decreases in pain in the medial tibiofemoral compartment. The surgeon cannot simply rely on the preoperative calculations because the intraoperative hip-knee-ankle fluoroscopic measurements may indicate that the desired correction of the tibial WBL has not been achieved. This problem was demonstrated in a report by Marti and coworkers,[125] who described the accuracy of obtaining the desired alignment correction using preoperative and postoperative double-stance radiographs following opening wedge osteotomy in 32 knees. In their series, only 50% of the limbs demonstrated the desired correction on postoperative radiographs (±5 degrees of calculated correction). An undercorrection was found in 31% and an overcorrection in 19%. These authors did not report on the use of intraoperative fluoroscopy to verify the lower limb correction. Many authors have described problems in obtaining the desired angular correction at surgery, with a substantial percentage of limbs remaining in varus or overcorrected into excessive valgus. Either fluoroscopy or computerized navigation techniques require defining accurate anatomic landmarks and precision to obtain accurate measurements.

Step 8: Placement of Bone Graft and Internal Fixation

An appropriate plate is selected and secured. The senior author uses only a locking plate design. If the surgeon elects to use allograft bone, the added fixation strength of a locking plate and screws is strongly recommended to prevent varus collapse at the osteotomy site. Various commercial locking plates and screw systems are available that provide added stability at the operative site.

The senior author recommends structural corticocancellous wedge bone grafts (autograft or allograft) and avoids the use of synthetic grafts or cancellous grafts. The clinical studies using these grafts have shown an unacceptable nonunion rate, as is discussed later in this chapter. The senior author prefers autograft iliac crest grafts or freeze-dried tibia corticocancellous allografts.

The three corticocancellous bone graft triangular segments are fashioned based on direct measurements of the anterior and posterior widths at the osteotomy site. The three grafts are impacted tightly into the posterior, middle, and anterior portions of the osteotomy site to obliterate the space and provide added stability, particularly in the sagittal plane. Fluoroscopy is used to confirm the final alignment and tibial slope.

The SMCL fibers are sutured distally and secured to either the plate screws or to suture anchors to maintain tension. The pes anserine tendons and sartorius fascia are reapproximated. The tourniquet is deflated and hemostasis obtained. A drain is not required. The wound is closed in layers in the usual manner. The lower limb is wrapped with cotton, and additional padding is placed posteriorly and over the peroneal nerve. A commercial ice delivery system with the bladder incorporated a few cotton layers from the wound is always used. A postoperative hinged brace and bilateral sequential compression devices are applied.

The neurovascular status is immediately checked in the operating room and over the initial postoperative period. The importance of limb elevation for the first postoperative week and use of a venous compressive system is emphasized. Close observation for lower limb soft tissue swelling is mandatory. There is a high suspicion for a venous thrombosis, and therefore aspirin is prescribed. There is also a low threshold for venous ultrasound of both lower extremities, which is obtained in the majority of patients in the first 3 to 7 postoperative days. The postoperative protocol is covered extensively in Chapter 28.

Management of the Superficial Medial Collateral Ligament

There are three surgical approaches for management of the SMCL. In a small opening wedge osteotomy of 5 to 7 mm, a "pie-crusting" procedure using multiple transverse incisions at different places may effectively lengthen the SMCL. In larger opening wedge osteotomies, it is

necessary to transect the distal attachment and perform a distal elevation of the attachment in a subperiosteal plane. This allows for the SMCL to be reattached distally after the opening wedge osteotomy with the SMCL bridging the osteotomy site. Transecting the SMCL at the most distal attachment site preserves its length, allows excellent exposure and bone grafting, and allows the tibial fixation plate to be placed in a correct midline position. The tibial slope is not altered, and function of the SMCL is retained.

A third approach is used when distal advancement of the SMCL is required as a reconstructive procedure owing to SMCL insufficiency and abnormal medial joint opening. At the conclusion of the osteotomy and plate fixation, the SMCL is dissected to the medial joint, including the deep medial fibers. A posterior incision is made at the junction of the SMCL and posteromedial capsule (posterior oblique ligament). The anterior incision extends only to the joint and preserves the attachment of the medial patellofemoral ligament. The medial meniscus position is carefully examined when a distal advancement of the SMCL is performed. It may be necessary to incise the medial meniscus capsular attachment (deep meniscotibial ligament) and then resuture the attachment to preserve the correct anatomic location of the meniscus when the SMCL is advanced distally.

The SMCL should appear relatively normal without scar replacement because advancement of only scar tissue would not provide medial stability. In select cases, a STG augmentation of the SMCL may be necessary, as described in Chapter 19. The need to surgically reconstruct the SMCL is infrequent; however, the surgical techniques presented allow for restoration of function when required.

OPERATIVE TECHNIQUE: CLOSING WEDGE TIBIAL OSTEOTOMY

Step 1: Initial Operating Room Preparation and Arthroscopy

The entire lower extremity is prepped and draped free with the tourniquet placed high on the proximal thigh to assist visual observation of lower limb alignment. The patient is positioned to allow fluoroscopic views of the hip-knee-ankle WBL to verify the angular correction at surgery, and arthroscopy is performed as already described.

Step 2: Initial Anterolateral Tibial Approach

A sterile tourniquet is inflated, and an oblique incision is made 1 cm distal to the head of the fibula in a line directed to the center the tibial tubercle (Fig. 26-37). The subcutaneous tissues are incised down to the fascia of the anterolateral tibial musculature. A fascial incision is made from the lateral aspect of the tibial tubercle sloping up proximally to the distal aspect of Gerdy's tubercle and is extended posteriorly and laterally to the anterior bare area of the fibula. The anterior bare area of the fibula is an important and safe anatomic landmark. The FCL and peroneal nerve are safely avoided when one identifies this area, which is used to initiate the limited subperiosteal exposure of the fibular neck for the fibular osteotomy.

Subperiosteal dissection on the tibia is initiated just distal to Gerdy's tubercle, using a scalpel followed by a Cobb elevator. The dissection is continued just lateral to the patellar tendon and should be done cleanly, with a relatively bloodless field and without damage to muscle tissue. The retinaculum adjacent to the patellar tendon is incised and the retropatellar space entered. The patellar tendon is retracted anteriorly.

The dissection is continued posteriorly on the tibia. It is important to remain in a subperiosteal plane because of the proximity of neurovascular structures. The safe zone is just distal to Gerdy's tubercle to avoid the peroneal nerve. Posteriorly, the dissection is completed across the width of the tibia in one location and is then carefully extended proximally and distally in this safe posterior tibial subperiosteal plane.

CRITICAL POINTS Operative Technique for Closing Wedge Osteotomy

- Arthroscopy first to assess all compartments, confirm HTO indicated, treat meniscus tears and notch osteophytes blocking knee extension.
- Oblique incision from fibular head to tibial tubercle.
- Subperiosteal dissection on tibia begun just distal to Gerdy's tubercle. Clean dissection; relatively bloodless field without damage to muscle tissue.
- Identify anteromedial bare area of fibula when initiating limited subperiosteal exposure of the fibular neck. Be aware of anatomic variability of the superficial peroneal nerve.
- Complete subperiosteal dissection posteriorly across width of tibia; extend proximally and distally in posterior tibial subperiosteal plane as required.
- Proximal fibular osteotomy through fibular neck region recommended.
- Fibular bone section removed is 2-3 mm less than the computed tibial wedge to allow compaction at the osteotomy site. Avoid bone step-off adjacent to peroneal nerve.
- Pass a smooth guide pin transversely at the posterolateral tibia to the medial cortex, 25-30 mm distal to joint line. Use fluoroscopy to ensure proper placement. Measure tibial width; compute desired bone width to obtain WBL correction. Place second guide pin anterior to first guide pin.
- Leave at least 25 mm of proximal tibia to avoid tibial plateau fracture.
- Make initial osteotomy cuts with a micro-oscillating saw to only cut outer cortex. Complete osteotomy with thin osteotomes.
- Place a malleable retractor in the subperiosteal plane posteriorly to protect the neurovascular structures with knee flexed 10 degrees.
- Surgeon seated with a headlamp. Osteotomy plane is maintained in a coronal triangular plane. The midpoint of the tibia width is half of the lateral wedge.
- Posteromedial cortex preserved to provide stability and prevent medial or lateral tibial translation or varus recurrence.
- Close osteotomy gap with gentle valgus force applied over a few minutes to gradually deform remaining medial cortex.
- Sagittal plane of osteotomy should be perpendicular to the long axis of the tibia. Equal width of cortex removed both anteriorly and posteriorly to preserve normal posterior tibial slope.
- Under fluoroscopy, position alignment guide rod over center of femoral head and center of tibiotalar joint to determine corrected WBL intersection at tibial plateau. Axially load the lower limb at the foot to maintain closure of medial and lateral tibiofemoral compartments at 5 degrees of flexion to avoid hyperextension.
- Further bone may be resected if necessary to adjust WBL.
- Internal fixation: locking plate and screws.
- Tourniquet released; hemostasis obtained.
- Reattach fascia of the anterior compartment musculature to anterolateral aspect of the tibial border with absorbable sutures.
- Generous cotton Ace compression bandage, multiple layers. Commercial ice delivery system and bilateral venous foot pumps applied.

Close observation of limb swelling, maintain frequent limb elevation, deep venous thrombosis protocol, ultrasound within first postoperative week in majority of patients.

Step 3: Fibular Osteotomy

There are three options for the fibula when performing an HTO: proximal slide, proximal fibular osteotomy, and distal fibular

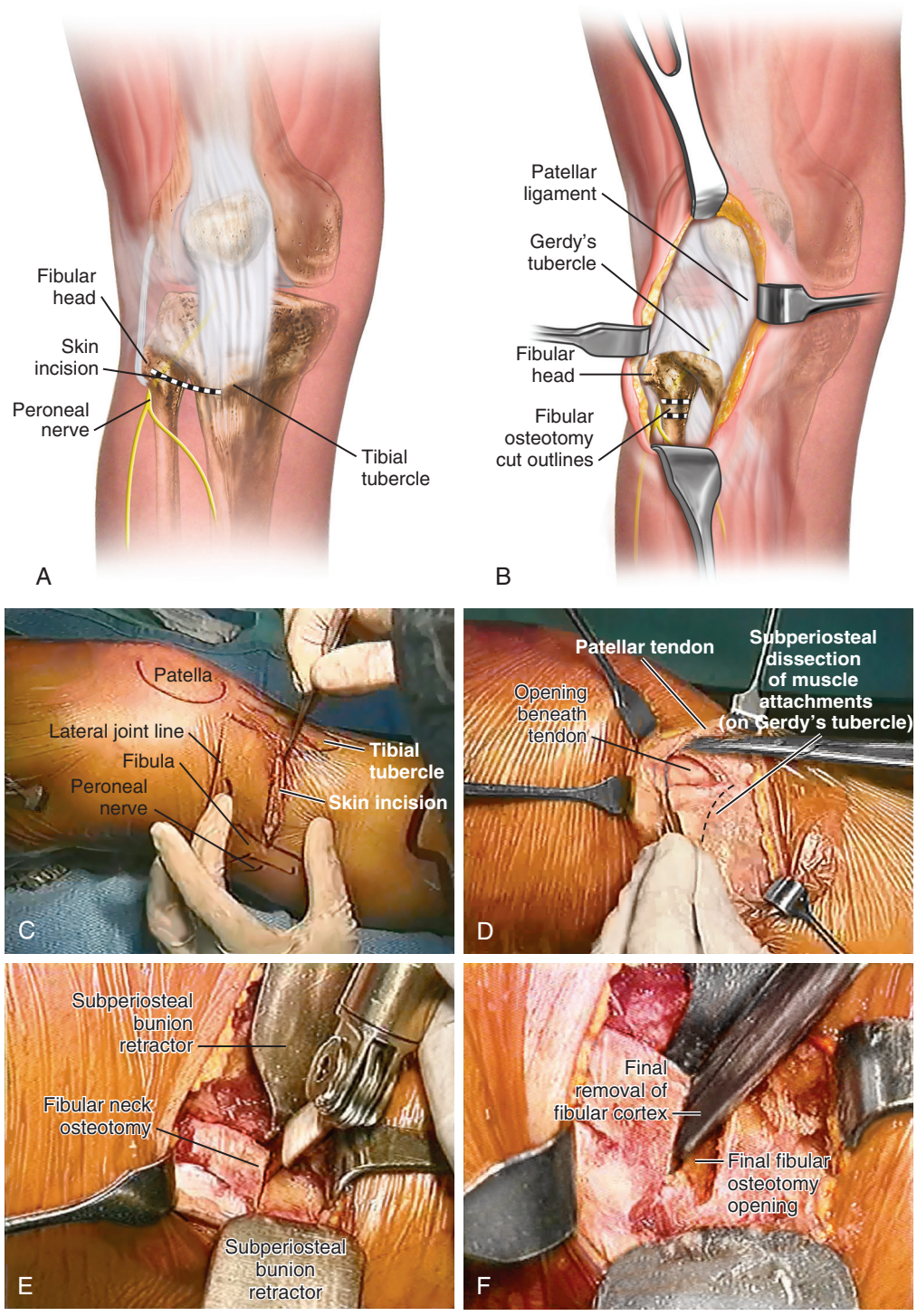


FIG 26-37 Closing wedge osteotomy technique. **A,** Skin incision. **B,** Exposure for the lateral tibial and fibular osteotomy. **C,** Landmarks for the skin incision. **D,** Subperiosteal dissection of the muscles to expose the lateral tibia and proximal fibula. **E,** Osteotomy of the fibula at head-neck junction. **F,** Removal of the fibular bone.

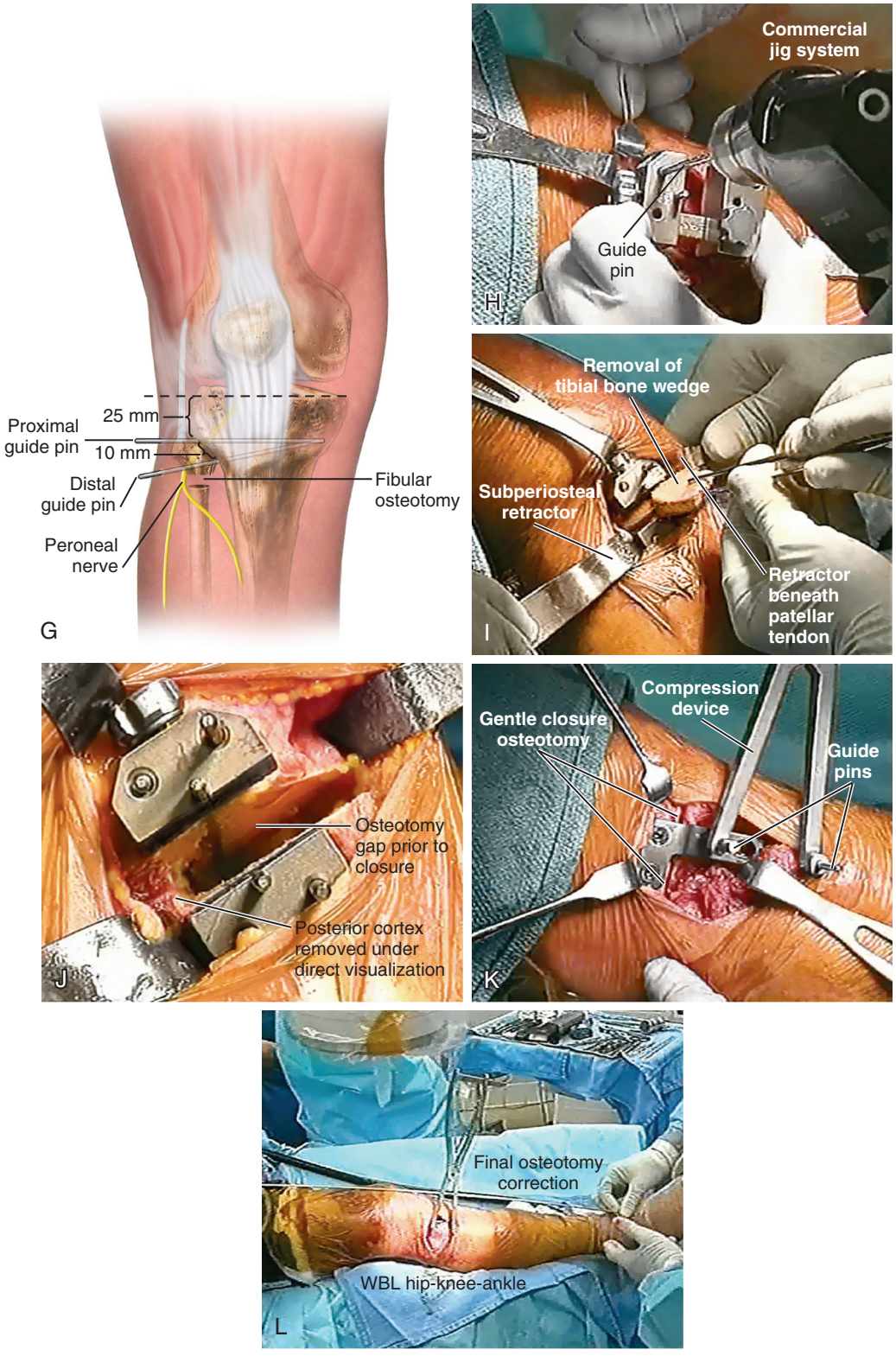


FIG 26-37, cont'd **G,** Placement of two guide pins at predetermined measured angles and depth for correction. **H,** Alternative use of a commercial guide system for guide pin placement. **I,** Removal of the bone wedge. **J,** Lateral gap is equal except for the anterior triangular portion where the gap narrows to prevent alteration of the tibial slope. **K,** Gentle closure of the osteotomy to protect the medial cortex. **L,** Determination of the weight-bearing line correction by fluoroscopy and computerized navigation, which is recommended.

osteotomy. A proximal slide (disruption of tibiofibular joint) is strongly contraindicated because this shortens the FCL and posterolateral structures and may lead to a severe posterolateral instability in an already unstable knee.

The preferred procedure is a proximal fibular osteotomy through the fibular neck region (see Fig. 26-37). Meticulous surgical technique with protection and palpation of the peroneal nerve is essential. To protect the peroneal nerve, the lateral and posterior periosteal sleeve about the fibular neck is carefully preserved and not retracted under tension. If there is any question as to the position of the nerve or chance of nerve damage, exposure of the entire nerve is indicated with direct visualization and protection.

The fibular bone section removed is 2 to 3 mm less than the computed tibial wedge to allow compaction at the fibular osteotomy site. Excellent bony apposition is achieved when the osteotomy is closed, and it is not necessary to add internal fixation. Careful inspection of the fibular osteotomy is done to remove any rough osteotomy edges which would be adjacent to the peroneal nerve.

An alternative choice for a fibular osteotomy is at the junction of the middle and distal thirds of the fibula through a 3-cm posterolateral incision. The peroneal muscles are retracted anteriorly and two bunion retractors can be used for exposure after subperiosteal exposure. A lateral section of the fibula is removed. The medial cortex of the proximal fibula is osteotomized at one site and allowed to slide to maintain bone contact and promote union. A bone graft from the tibial site is added. With this technique, it is not necessary to add internal fixation.

The surgeon should be well aware of the anatomic variability of the superficial peroneal nerve (SPN) in the middle third of the leg. Barrett and colleagues[23] reported on this factor in 35 nonpaired and 40 paired cadaver lower extremities. The SPN was identified in the lateral compartment adjacent to the fascial septum in 72%, in the anterior compartment in 23%, or with a branch in both the anterior and lateral compartments in 5% of the specimens. Ducic and coworkers,[59] in a study of 111 cadaver and clinical specimens, described a similar variability of the location of the SPN in the middle third of the leg. The SPN traveled to the lateral compartment in 70% of the specimens or split with branches in both the lateral and anterior compartments in 16%. In 6% of the specimens, the SPN was found within the intermuscular septum, and in 8%, it traveled only within the anterior compartment.

Step 4: Proximal Osteotomy: Removal of Tibial Wedge

The proximal tibial closing wedge osteotomy technique may be performed using commercially available calibrated osteotomy guide systems, or the bone cuts may be determined using a free-hand method. A smooth guide pin is placed transversely at the proximal tibia to the medial cortex, 25 mm distal to the joint line with fluoroscopy used to ensure proper placement. It is critical to leave at least 25 mm of proximal tibia to avoid a tibial plateau fracture. The transverse length of the guide pin determines the proximal tibia width.

Following the preoperative measurements and based on tibial width (see Table 26-6), the entry point of the second guide pin distally is marked with proper positioning of the guide pins confirmed with fluoroscopy. These guide pins determine the osteotomy triangular bone wedge that is removed to achieve the desired correction. It is important to determine whether or not the lateral cortex is entirely perpendicular at the osteotomy site. In some knees, there will be a slight triangular anterior slope where it is necessary to downsize the osteotomy gap anteriorly not to decrease the tibial slope. The width of the tibia anteriorly is measured and the anterior gap determined (see Table 26-6).

The initial osteotomy cuts are made using a micro-oscillating saw. Initially, only the outer cortex is cut and then the osteotomy is completed with thin osteotomies. An oscillating saw in the cancellous bone may wander and potentially change the correction angle.

A malleable retractor is placed in the subperiosteal plane posteriorly to protect the neurovascular structures at all times with the knee flexed 10 degrees. The lateral half of the wedge is removed as a single piece. Portions of this bone wedge may rarely need to be replaced if an inadvertent overcorrection is obtained at surgery. The remaining triangular wedge of bone is removed under direct visualization.

The surgeon is seated, and a headlamp is always used to view the depth of the osteotomy. The osteotomy plane is maintained in a triangular plane, noting that at the midpoint of the tibia, the tibial width is one half that at the lateral cortex.

The 7 to 10 mm of the wedge adjacent to the posteromedial cortex is left intact to provide stability and prevent medial or lateral tibial translation or varus angulation postoperatively. The posterior tibial cortex of the wedge is removed under direct visualization. The patellar tendon is carefully protected.

Two to three perforations of the posteromedial cortex with a guidewire are often required before the osteotomy gap can be closed with a gentle valgus force that is applied over a few minutes to gradually deform the remaining medial cortex. An option is to use a commercially available compression device to close the osteotomy. Apposition of the bony surfaces of the tibia and fibula should be visualized and inspected.

It is important that the HTO does not increase or decrease the normal posterior tibial slope. The sagittal plane of the osteotomy should be perpendicular to the long axis of the tibia with the width of posterolateral cortex removed based on the coronal angular corrections required (see Table 26-6). In select cases, a biplanar osteotomy for correction of an abnormal tibial slope may be required, as already described. An opening or closing gap in the sagittal plane is performed to the necessary degrees of slope correction.

Step 5: Fluoroscopic Verification of the Weight-Bearing Line for Corrected Alignment

Using fluoroscopy, an alignment guide rod (rigid 3- to 4-mm rod, 1 m in length) is positioned over the center of the femoral head and the center of the tibiotalar joint to determine the corrected WBL intersection at the tibial plateau. A large single staple may be placed across the lateral tibial osteotomy site for provisional fixation. During fluoroscopy, the lower limb is axially loaded at the foot to maintain closure of both the medial and lateral tibiofemoral compartments at 5 to 10 degrees of flexion to avoid hyperextension. It is important to view by fluoroscopy that there is no abnormal opening of the medial or lateral compartment. The knee is taken through a gentle varus-valgus loading to palpate the respective compartments and confirm closure of both because significant errors in the final axial alignment occur if great care is not taken at this junction. A second source of error in the WBL tibial intersection occurs if the lower limb is positioned incorrectly with excessive hip internal or external rotation. The lower limb and foot are positioned with a normal 10 to 12 degrees of external rotation, representing the normal gait foot progression alignment. The alignment guide rod represents a new WBL, which should agree with preoperative calculations. If necessary, further bone may be removed or added to the osteotomy to adjust the WBL. The tibial slope is also verified with fluoroscopy.

Internal fixation of the osteotomy is achieved using a locking plate and screws (Fig. 26-38). Rarely, a 6.5-mm cancellous screw is placed in a lag fashion across the osteotomy site into the medial aspect of the proximal tibial bone for additional fixation. Newer locking plates and

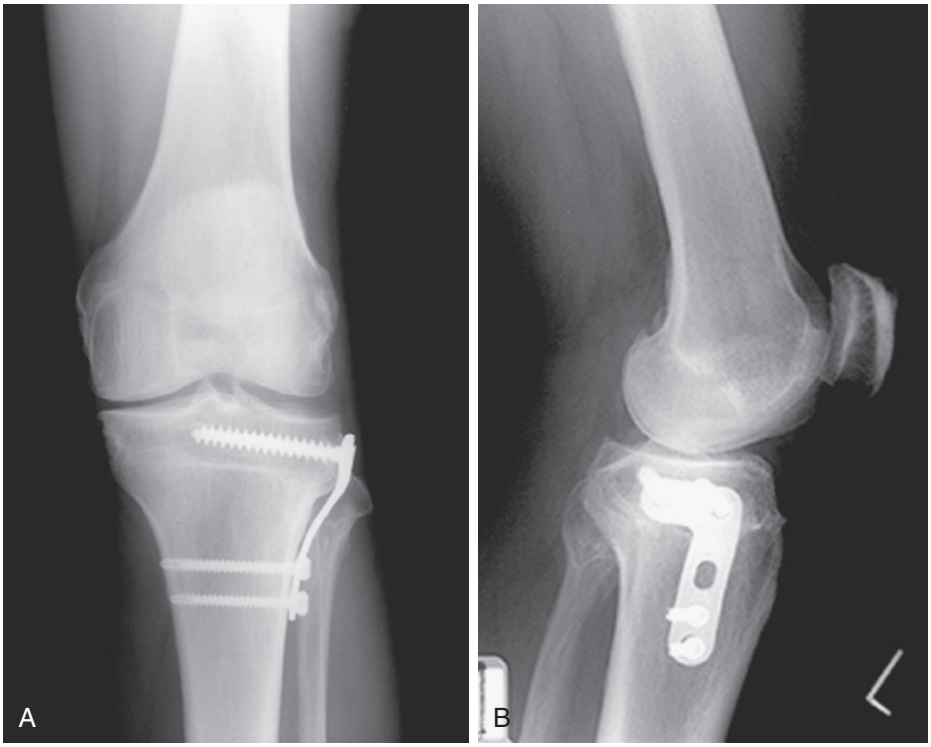


FIG 26-38 Anteroposterior (**A**) and lateral radiographs (**B**) show the postoperative appearance after proximal tibial osteotomy, fibular osteotomy, and internal fixation. (From Noyes FR, Barber-Westin SD, Hewett TE. High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. *Am J Sports Med.* 2000;28:282-296.)

screws provide the advantage of more secure fixation. The final WBL is determined after fixation.

The tourniquet is released and hemostasis obtained. The fascia of the anterior compartment musculature is reattached to the anterolateral aspect of the tibial border with absorbable sutures. It is important to reattach the muscles with adequate suture fixation because muscle tension postoperatively may disrupt the muscle attachment site. A drain is not used.

The lower limb is wrapped with cotton, and additional padding is placed posteriorly and over the peroneal nerve, followed by an Ace bandage, postoperative hinged brace, and bilateral ankle-foot compression boots. A commercial ice delivery system with the bladder incorporated over the initial cotton wrapping, a few layers from the wound, is always used. The neurovascular status is checked immediately in the operating room and carefully monitored in the initial postoperative period. A calf or foot compression system is used for the first 24 hours to promote venous blood flow. Aspirin is prescribed and, rarely in high-risk patients, low-molecular-weight heparin (LMWH) or warfarin sodium (Coumadin). Early rehabilitation emphasizes early quadriceps isometrics, range of knee motion, ankle pumping, and ambulation (see Chapter 28). The surgeon should have a high suspicion for venous thrombosis and a low threshold for ordering ultrasound evaluation in the postoperative period, which is obtained in the majority of patients in the first few days after surgery.

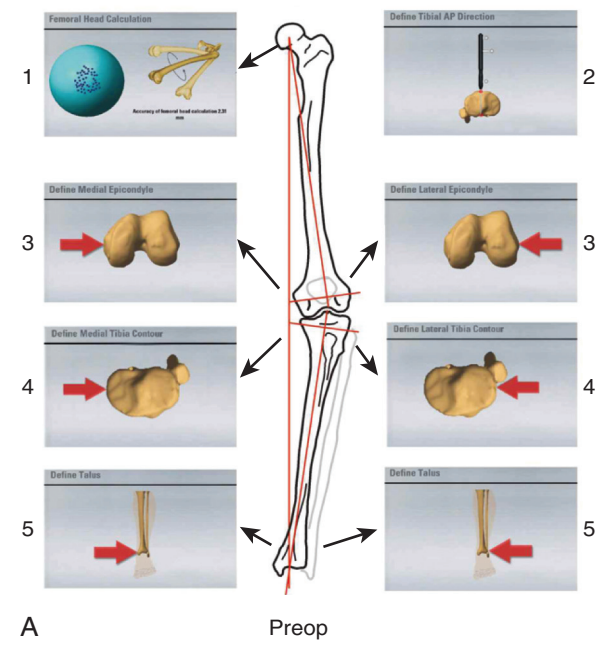
With the meticulous dissection technique described, a postoperative compartment syndrome should be an exceedingly rare occurrence, if at all. The operative limb is always elevated for the first postoperative week, except for periods of ambulation with crutches. The maximum swelling of limb tissues after HTO is usually present 48 to 96 hours postoperatively. The postoperative rehabilitation program is discussed in Chapter 28.

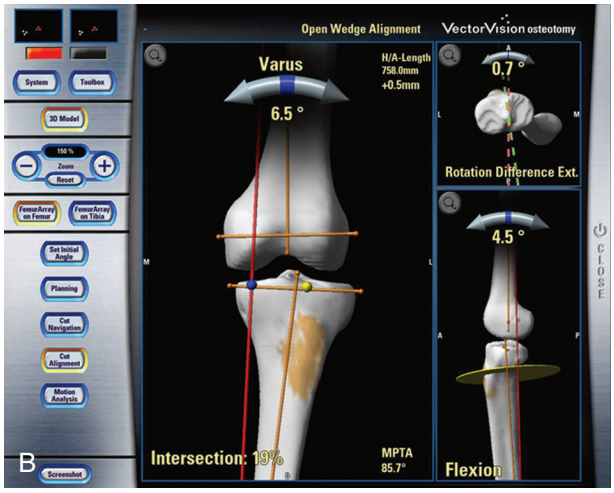
ROLE OF COMPUTERIZED NAVIGATION FOR HIGH TIBIAL OSTEOTOMY

For surgeons who are trained on computerized navigation for total knee joint replacement, the addition of the same techniques for HTO in select cases offers an advantage in determining the final WBL and overall limb alignment. The registration process is easier with fewer points required than total knee replacement (Fig. 26-39, *A*). The software allows for the preoperative and postoperative varus-valgus position and WBL to be determined (Fig. 26-39, *B*). We recommend that the lower limb be held with the knee in 5 degrees of flexion for the measurement of the WBL and degrees of valgus overcorrection. This compares with the full-standing hip-knee-ankle radiographs in 5 degrees of flexion to avoid a hyperextension position in which different WBL measurements would be erroneously obtained. The operating room setup combining the computerized navigation system with fluoroscopy is shown in Figure 26-39, *C*.

Keppler and associates[109] reported on the use of a computer-aided surgical navigation system of opening wedge tibial osteotomy in a plastic bone model and cadaveric lower limbs. These authors found high consistency among operators in registering anatomic landmarks and concluded that improved accuracy and reliability of correcting the mechanical axis would be the benefits of this approach. A number of studies have shown that full-standing radiographic measurements may have errors induced in the coronal plane (affecting WBL measurements) owing to the rotation of the lower limb during the radiographic procedure.[105,140,224] Song and associates[194] reported that a navigation-assisted opening wedge HTO procedure improved the surgeon's ability to obtain a more accurate postoperative alignment correction.

Clinical studies are still required to determine in a large patient series the increased accuracy obtained with computerized navigation









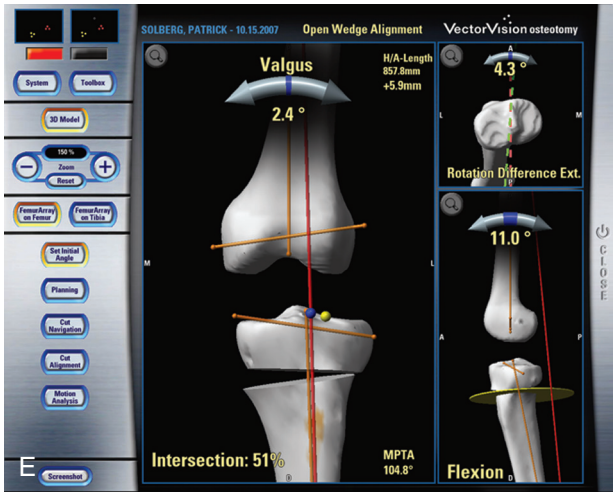


FIG 26-39 **A,** The registration points for the computerized navigation procedure (BrainLAB). **B,** Preoperative measurement shows the angular malalignment of 6.5 degrees varus and a 19% weight-bearing line (WBL) intersection. **C,** Operating room setup. The fluoroscopy and computer navigation instruments are on the operative side. The surgeon is able to perform the medial opening wedge procedure from the medial aspect, usually in a seated position. The photographs shows the ability of the surgeon to determine the lower limb alignment from the foot of the table. **D,** Demonstration of the navigation instrumentation that may be used to determine the osteotomy plane (see text). **E,** Final operative correction obtained, with a 2.4 degrees valgus alignment and a 51% WBL intersection.

CRITICAL POINTS Role of Computerized Navigation for High Tibial Osteotomy

- Offers advantage in determining final overall limb alignment in select cases
- Hold lower limb with the knee in 5 degrees of flexion to measure WBL, degrees of valgus overcorrection.
- Full standing radiographic measurements may have errors induced in the coronal plane (affecting WBL measurements) caused by the rotation of the lower limb during the radiographic procedure.
- Fluoroscopy still required on pin placement and to determine depth of osteotomy during surgery.
- Fluoroscopy confirms final WBL coronal correction and tibial slope.

techniques. However, in our experience, the following points are important. It is still necessary to determine the tibial slope (using the Keith needle technique previously described in the "Operative Techniques" sections) for each knee, although an arbitrary tibial slope may be selected for the navigation technique (Fig. 26-39, *D*). The navigation of the actual osteotomy cut can be performed as easily as with the placement of guide pins and fluoroscopy. In essence, fluoroscopy is still required on pin placement and to determine the depth of the osteotomes during surgery to maintain integrity of the opposite cortex. Increased accuracy of determining the final WBL, compared with hip-knee-ankle fluoroscopy, is expected because the variable of internal-external limb rotation and its effect on the WBL is nearly eliminated (Fig. 26-39, *E*). An error may occur in determining the WBL intersection at the tibia with the standard hip-knee-flexion fluoroscopy method because the measurement line or rigid rod is placed on the limb and does not correspond to the central measurement line in the hip-knee-ankle joints based on navigation.

OPENING WEDGE DISTAL FEMORAL OSTEOTOMY

A femoral closing or opening wedge osteotomy is an accepted treatment for the correction of an abnormal valgus lower limb alignment. Details of the operative indications and procedures are also covered in Chapter 27 and are therefore only summarized here.

The indications and contraindications for surgical treatment are similar to those for an HTO except that the osteotomy is designed to decrease weight-bearing forces on the lateral tibiofemoral compartment. The most common presentation is a younger patient who has undergone lateral meniscectomy and shows progressive valgus alignment and narrowing of the lateral tibiofemoral compartment and has lateral joint symptoms. The procedure is often performed before a lateral meniscus transplantation or other articular cartilage restorative procedures to the lateral compartment (see Illustrative Cases 10, 11, and 12). Similar to a corrective procedure for varus malalignment already discussed, the goal of the procedure is to buy time. It is important not to correct the lower limb to an excessive varus alignment, as is discussed next. If there has been a prior medial meniscectomy or if medial tibiofemoral joint damage is present, a relative contraindication to the varus-producing femoral osteotomy may exist, or the correction should only obtain a neutral alignment. The goal is to correct an abnormal abduction moment at the knee joint but not to produce an abnormal adduction moment that would overload the medial compartment (see Fig. 26-5).

Contraindications to a varus-producing osteotomy are similar to those previously discussed for HTO and include the absence of remaining lateral tibiofemoral articular cartilage and lateral joint tibial concavity, indicating advanced lateral joint arthritis.

CRITICAL POINTS Opening Wedge Femoral Osteotomy

- Indications, contraindications for surgical treatment are similar to those for an HTO except the osteotomy is designed to decrease weight-bearing forces on the lateral tibiofemoral compartment.
- Goal is to correct abnormal abduction moment at the knee joint but not to produce an abnormal adduction moment that would overload the medial compartment.
- Contraindications: absence of remaining lateral tibiofemoral articular cartilage and lateral joint tibial concavity, advanced lateral joint arthritis
- It is important to determine there is no abnormal opening of the medial joint space, which must be accounted for in the preoperative correction measurements.
- Target zone is a WBL at the 45%-47% intersection, equal to a 1- to 2-degree varus lower limb alignment, respectively.
- Cosmetic skin incision of limited length, with upper locking screws placed through small 3- to 4-mm skin incisions.
- Guide pins placed in the line of the osteotomy 15 mm proximal to the femoral trochlea region, slight oblique fashion to end at the proximal metaphyseal junction.
- Gradual distraction, leaves 8 mm of the medial femoral cortex intact
- Maintain equal anterior and posterior osteotomy gap to not change knee flexion or extension in the sagittal plane.
- Use autogenous iliac crest bone graft, locking plate and screws.

The clinical evaluation includes an analysis of the patient's gait and observation for a valgus thrust. There are usually lateral joint line tenderness to examination and mild lateral joint crepitus with a valgus loading of the joint during flexion and extension. This maneuver is frequently painful and reproduces the patient's symptoms. It is important to examine specifically for associated patellofemoral arthritis and articular cartilage damage to the lateral patella facet and trochlea. The valgus lower limb alignment increases the lateral deviation of the patella, producing increased lateral patellofemoral joint loading. Accordingly, symptoms related to the patellofemoral joint may be permanent and should be considered in determining whether the patient is a suitable candidate for the femoral osteotomy.

The radiographic assessment for lower limb alignment has already been presented, including obtaining weight-bearing 45-degree PA views, axial patellofemoral views, lateral view for tibial slope, and a full-standing radiograph for measurement of the hip-knee-ankle mechanical alignment and WBL. Determine that there is no abnormal opening of the medial joint space that must be accounted for in the preoperative correction measurements. In Figure 26-14, the normal tibiofemoral coronal alignment is shown. In valgus-angulated knees, there is frequently a coronal obliquity to the joint line because of the lateral joint damage primarily effecting the lateral femoral condyle. Owing to this obliquity, an opening wedge tibial osteotomy is contraindicated because this would increase the joint obliquity. A lateral opening or medial closing wedge femoral osteotomy would theoretically correct the joint obliquity. Even though there are reports in the literature on opening wedge tibial osteotomy, we have observed clinical cases in which the increased joint obliquity leads to abnormal loading of the lateral tibial tubercle and lateral femoral condyle with subsequent loss of articular cartilage and arthritis. References of publications of closing wedge femoral osteotomy are provided for the

reader[20,65,87,133]; this section deals primarily with the surgical technique for an opening wedge femoral osteotomy.

The preoperative planning for the opening wedge osteotomy follows the same rules as previously presented, and the measurement techniques are the same except that a final WBL intersection at the tibia is just medial to the 50% tibial width. The target zone is a weight-bearing line at the 45% to 47% intersection, which is equivalent to a 1- to 2-degree varus lower limb alignment, respectively. A WBL more medial to this point would induce a varus overcorrection. The degrees of correction and the corresponding osteotomy opening gap in millimeters (rule of triangles, Table 26-7) are usually in the 5- to 8-mm range because of the narrow width of the femur at the osteotomy site. This means that a few millimeters of error would have a major effect in producing an undercorrection or overcorrection. For this reason, the careful and accurate fluoroscopic measurements at surgery of the desired correction and new WBL tibial intersection are important.

The operative steps the senior author follows in performing the opening wedge femoral osteotomy are detailed in Figure 26-40. Important steps in the operative procedure include a cosmetically placed skin incision of limited length, with upper locking screws placed through small 3- to 4-mm skin incisions. The surgeon sits adjacent to the lateral aspect of the lower limb with a headlight on to visualize beneath the raised skin flaps. The guide pins are placed in the line of the osteotomy 15 mm proximal to the femoral trochlea region and in a slightly oblique fashion to end at the proximal metaphyseal junction. The osteotomy involves a gradual distraction process that leaves 8 mm of the medial femoral cortex intact. If the medial femoral cortex is thick and dense, it may be necessary to weaken the cortex with two to three small drill holes. It is important to maintain an equal anterior and posterior osteotomy gap to not change the tibiofemoral slope. An autogenous limited iliac crest bone harvest (discussed under "Operative Technique: Opening Wedge Tibial Osteotomy") is performed, and the width of the outer iliac crest that is harvested matches the opening osteotomy gap. Clinical data are insufficient to recommend allografts or synthetic grafts over autografts for femoral osteotomy, and I prefer an autograft (supplemented with a freeze-dried allograft) for prompt healing and faster resumption of full weight-bearing activities. A limited iliac crest autograft approach in combination with a locking plate and screw design provides for secure femoral fixation, avoiding the serious risks of delayed or nonunion and loss of the lower limb angular correction, which should be a rarity.

An alternative approach involves the Arthrex distal femoral osteotomy system, shown in Figure 26-41.

The rehabilitation program is the same as for an HTO. Full standing radiographs are obtained postoperatively to measure the operative correction obtained and the progression of osteotomy healing. It is usual to begin partial weight bearing at 4 weeks and full weight bearing at 7 to 8 weeks after surgery.

A prospective study is in progress at our institution. Twenty DFOs have been performed, with complete healing noted in all cases. Ten patients have been followed for 10 years or more, two patients for 7 to 8 years, and eight patients for 2 years. There have been no failures as of the time of writing.

OUR CLINICAL STUDIES

Closing Wedge High Tibial Osteotomy in Anterior Cruciate Ligament–Deficient Varus-Angulated Knees

A study was conducted which reported the results of 41 patients (100% follow up) who were followed an average of 4.8 years after closing wedge osteotomy (range, 2-7.2 years).[152] These patients also had ACL-deficient knees, of which 30 were treated with a reconstruction.

CRITICAL POINTS Our Clinical Studies: Closing Wedge Osteotomy in ACL-Deficient Varus-Angulated Knees

- 41 patients, 100% follow-up 2-7 years postoperatively.
- Statistically significant improvements in pain, swelling, function.
- 59% returned to low-impact sports activities.
- 88% satisfied.
- 22 knees had increased lateral tibiofemoral joint opening preoperatively (double varus knees), which resolved in 17 (77%) without a posterolateral reconstructive procedure.
- 27% did not require subsequent ACL reconstruction.
- Determined each patient's desired level of activity and instability symptoms. ACL reconstruction not required in all.
- Goal of HTO was return to daily activities, not athletics, in most patients.
- Goal of HTO in patients with recent onset of pain and no advanced joint damage may be return to athletics or strenuous work activities. ACL reconstruction frequently required in these patients.

Significant improvements were found for all symptoms; the most noteworthy finding was the decrease in pain (Fig. 26-42). Preoperatively, 41% of the patients had moderate to severe pain with activities of daily living, whereas only 10% had this level of pain at follow up. The decrease in pain could have occurred as a result of patient counseling on activity modification and owing to the fact that none of the patients returned to strenuous sports involving jumping, pivoting, and cutting.

Before surgery, 22 patients were participating in some form of sports activities with pain or functional limitations. At follow up, 24 patients (59%) had returned to sports with no symptoms; however, the majority were biking or swimming only.

A separate analysis was conducted on a subgroup of 15 patients who had subchondral bone exposed in the medial tibiofemoral compartment. These patients were followed a mean of 5.5 years (range, 3-7.4 years) postoperatively. A statistically significant improvement was noted in the mean overall rating score at follow up ($P < .01$). Nine patients returned to light sports activities, whereas the other six did not participate, thus following medical advice.

The radiographic evaluation performed in the early postoperative period showed that 37 of 41 (90%) patients were surgically corrected with a WBL between 50% and 80%. Three patients drifted back into varus, and one had settled into valgus. At the final follow-up examination, 25 patients (61%) still demonstrated optimal correction (mean WBL, 60%; range, 46%-79%). However, 11 patients (27%) were in varus (mean WBL, 37%; range, 25%-44%), and 5 (12%) had an increased valgus position (mean WBL, 90%; range, 81%-108%). These findings indicated that progression of the medial arthritis in the varus-angulated knee continues and long-term correction was not achieved in one out of four patients. Even in the knees that returned to a varus angulation, there was short-term relief of pain symptoms; however, the long-term function in these patients is expected to decline.

A statistically significant improvement was found between the preoperative and follow-up overall rating scores (scale, 0-100 points, $P < .01$). The mean increase between evaluations was 14 points (range, –8 to 38 points).

An interesting finding was that whereas 22 knees (54%) had abnormally increased lateral joint opening on varus stress testing preoperatively, only 5 (12%) had this abnormal joint opening at follow up. The valgus-producing osteotomy appeared to have unloaded the FCL and

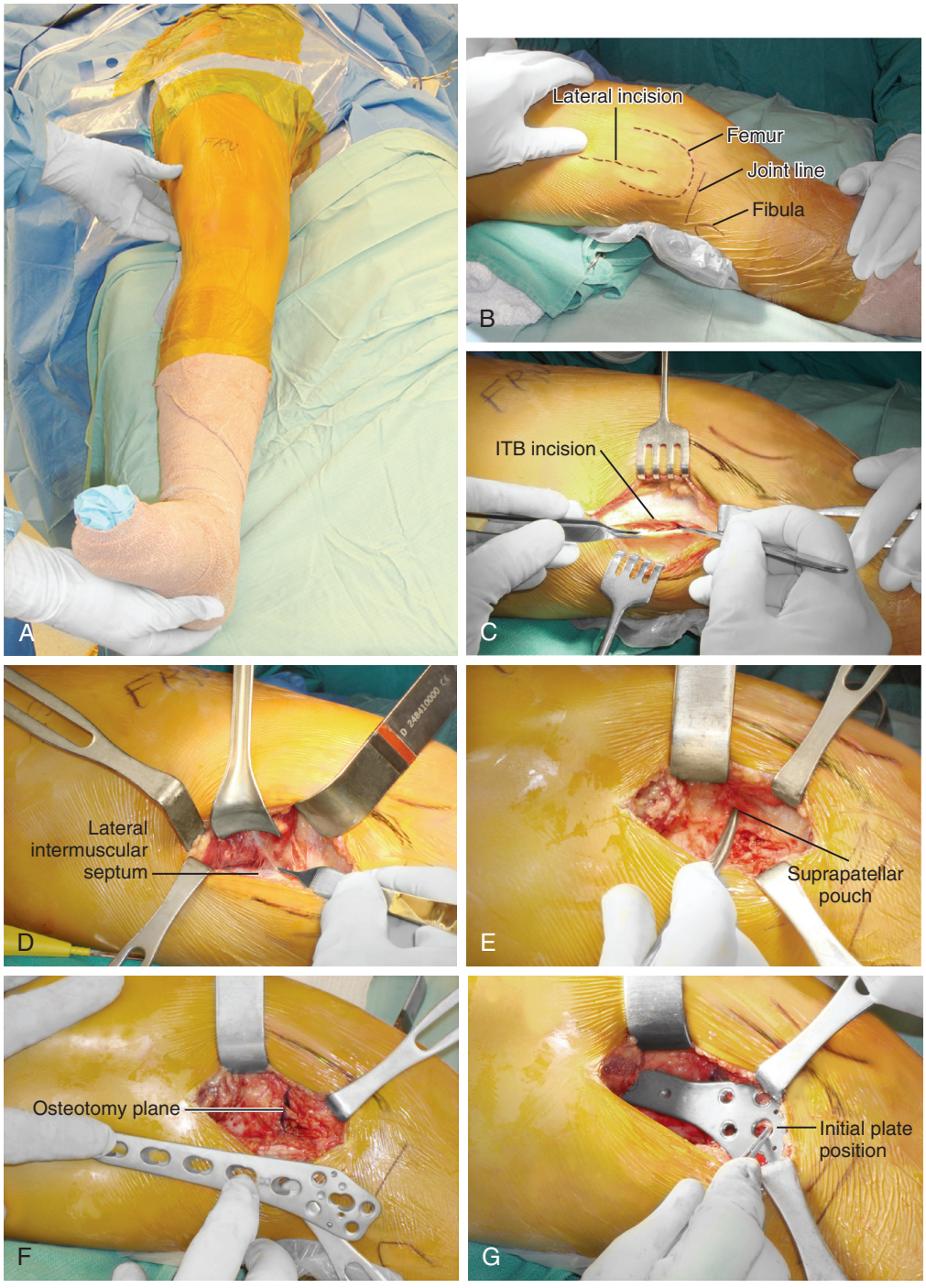


FIG 26-40 An opening wedge femoral osteotomy for correction of lower limb valgus malalignment. **A,** Surgical setup with high thigh tourniquet and the complete lower extremity draped, including the ipsilateral iliac crest (not shown) for bone graft procedure. **B,** Initial limited incision at the distal lateral thigh just above the joint line. The surgeon is seated with a headlamp for adequate visualization. A small posterior thigh roll is placed to prevent the popliteal neurovascular structures from being displaced anteriorly toward the operative site. **C,** Incision into the posterior third of the iliotibial band (ITB) that extends in a proximal subcutaneous plane. **D,** A careful dissection of the vastus lateralis insertion at the lateral intermuscular septum is shown with identification of perforating small arteries and veins for control of hemostasis and prevention of hematoma. **E,** An S retractor is placed underneath the vastus lateralis and the proximal joint suprapatellar pouch is identified, which is not opened. **F,** The approximate location of the femoral osteotomy site is identified by fluoroscopy and the locking plate is selected. **G,** Proximal to distal positioning of the locking plate in reference to the distal femoral condyle and osteotomy site.

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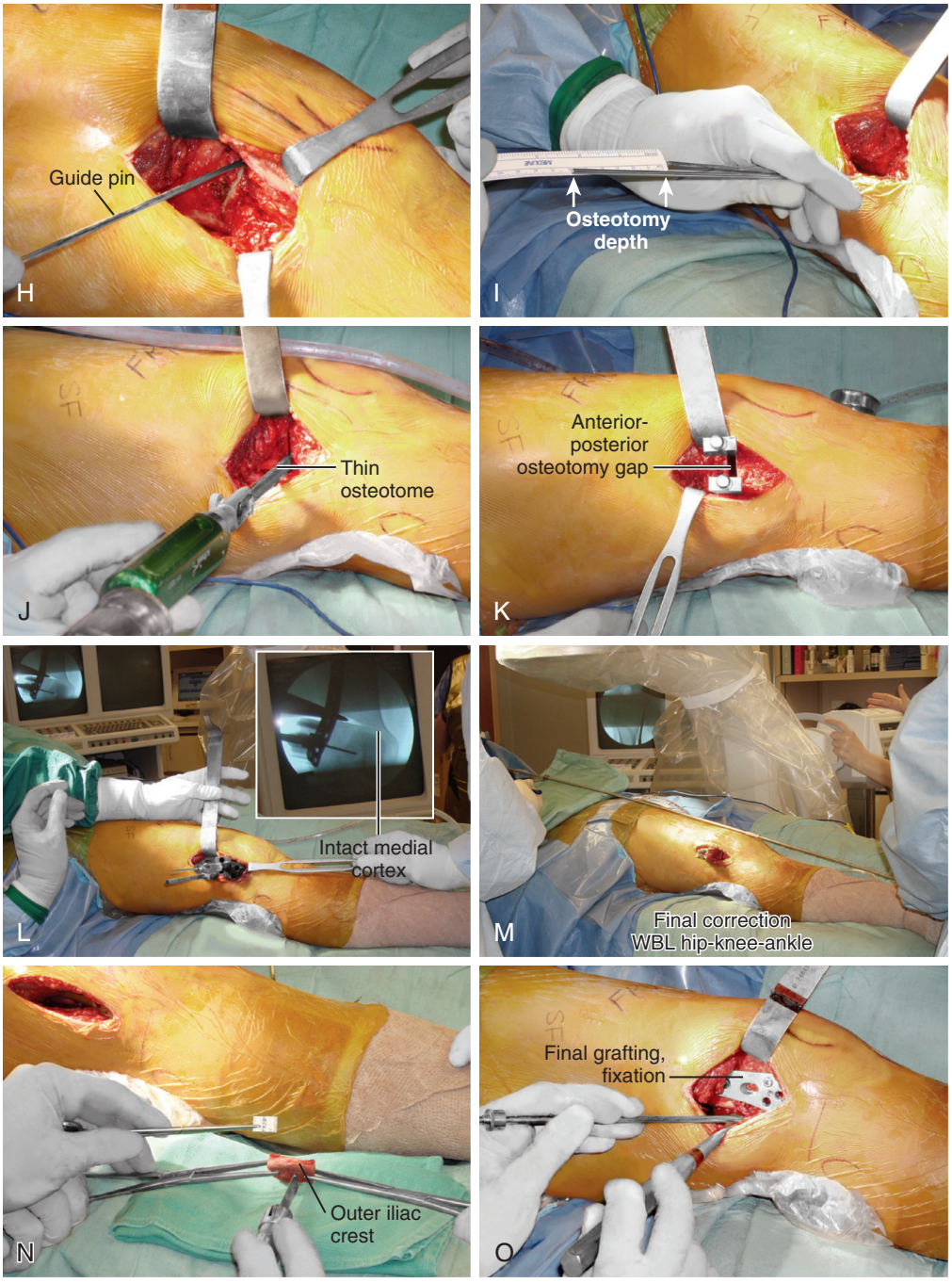


FIG 26-40, cont'd **H,** The anterior guide pin is placed in slight oblique line, 15 mm proximal to the femoral trochlea, which can be palpated and verified by fluoroscopy. The guide pin is placed to intersect the proximal medial metaphyseal flare, which is left intact and provides for medial stabilization. Note that that there has been no subperiosteal dissection even though the anterior and posterior cortex is visualized for later osteotomy. **I,** The posterior guide pin is placed perpendicular to the femoral shaft, and the depth of the planned osteotomy site is measured off a free guide pin. **J,** The initial osteotomy of the lateral cortex is started with a power saw and thin blade followed by a hand-held thin osteotomy blade, which provides better control as the osteotomy progresses. A malleable retractor may be placed posterior to the posterior cortex to protect the neurovascular structures. **K,** The osteotomy site has been gently distracted by thin spreader bars (not shown) and two wedges placed to maintain the opening gap. The medial metaphyseal cortex has been preserved as confirmed by fluoroscopy. **L,** The locking plate is fixed under fluoroscopy control. The monitor shows the osteotomy opening wedge and preservation of the medial metaphyseal cortex. The locking plate is bent to conform to the osteotomy and is fixed with only a few screws to verify the correction. **M,** A rigid rod is placed to establish the new weight-bearing line (WBL) tibial intersection and verify the lower limb alignment. The surgeon provides axial compression at the foot to maintain closure of both the medial and lateral tibiofemoral joints. An inadvertent joint opening of a few millimeters would result in an inaccurate alignment measurement. **N,** The iliac crest autograft is sectioned into anterior, middle, and posterior triangles and subsequently gently wedged into the osteotomy opening gap. Final plate fixation is performed. **O,** The final appearance of the osteotomy with bone graft in place.

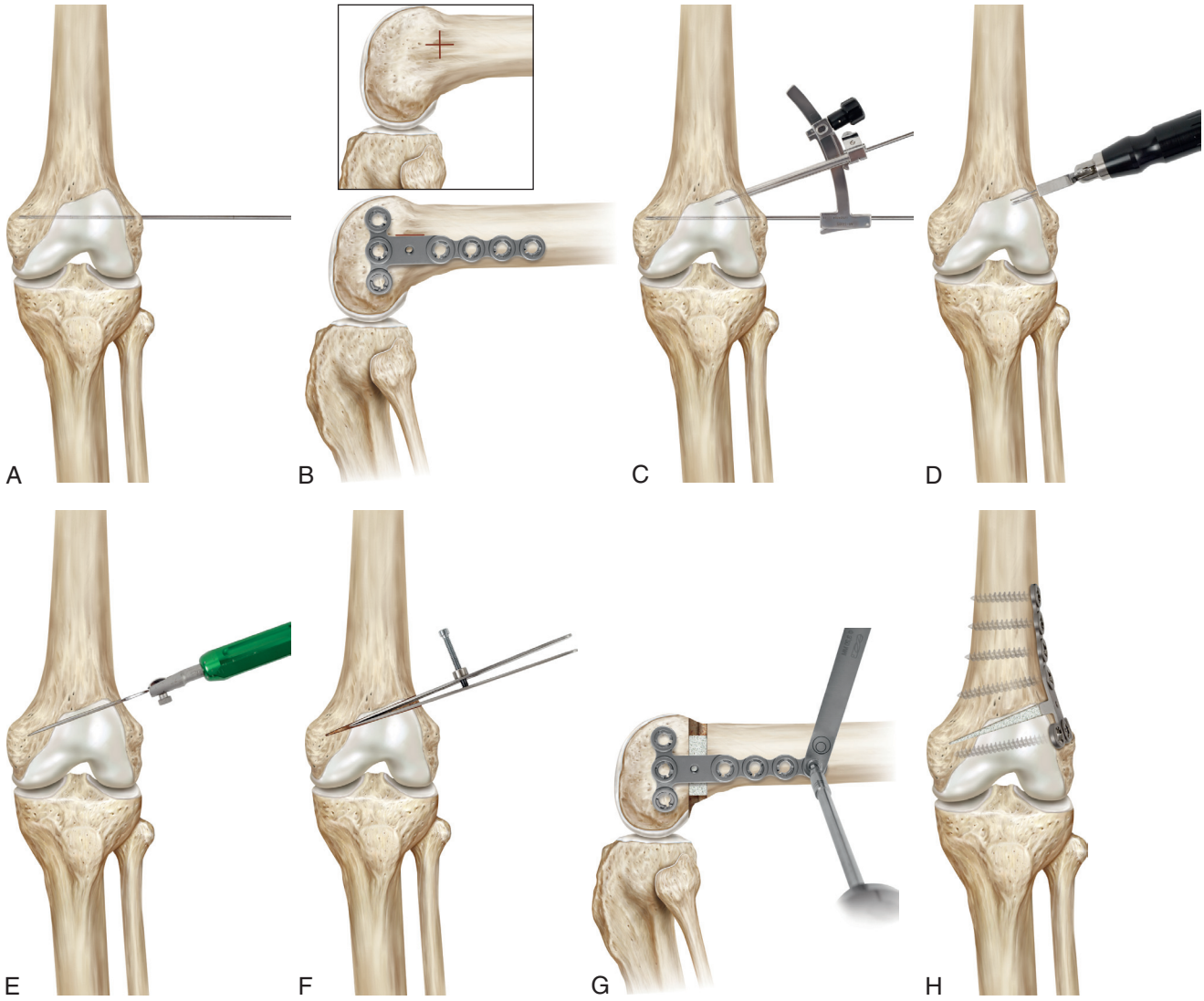


FIG 26-41 The Arthrex femoral opening wedge osteotomy system. **A,** The 3-mm Osteotomy Guide Pin is inserted under fluoroscopic control, transversely from the lateral epicondyle to the cortex of the medial epicondyle (parallel to the joint line). **B,** The Femoral Osteotomy plate is held up in the desired position, and a line is made parallel to the long axis of the femur. A second line (*inset*), perpendicular to the first, is then made at the desired osteotomy level. This will serve as a guide for the cut and assures the plate is centered on the femur. **C,** The osteotomy guide assembly is inserted onto the guide pin, ensuring the black laser line of the guide pin meets the back end of the guide housing. Two 2.4-mm osteotomy guide pins are drilled obliquely under fluoroscopic control from the lateral diaphyseal–metaphyseal junction, aiming at the origin of the medial collateral ligament on the medial epicondyle, making sure to avoid the femoral trochlea. **D,** Retractors are used to clear any soft tissue and an oscillating saw is used to cut the cortex superior to the guide. The pins will protect against accidental saw/osteotome migration into the joint. The cortical bone is cut laterally, anteriorly, and medially. **E,** An osteotome blade and handle are used to complete the cut, preserving approximately 1 cm of the medial cortex. **F,** The osteotomy wedge or an osteotomy jack is inserted to open the osteotomy to the desired height. This can be measured directly from the osteotomy wedge, the wedge trial, of the depth gauge for the osteotome jack. The osteotomy should be opened slowly to preserve the medial cortex. The correct weight-bearing line is confirmed by fluoroscopy as described in this chapter. **G,** Screws are inserted, starting distally with the 6.5-mm cancellous screws and then proximally using the 4.5-mm cortical screws. **H,** Once the osteotomy is complete, alignment is confirmed with x-rays and fluoroscopic guidance. Additional bone graft can be packed into the osteotomy site around the plate.

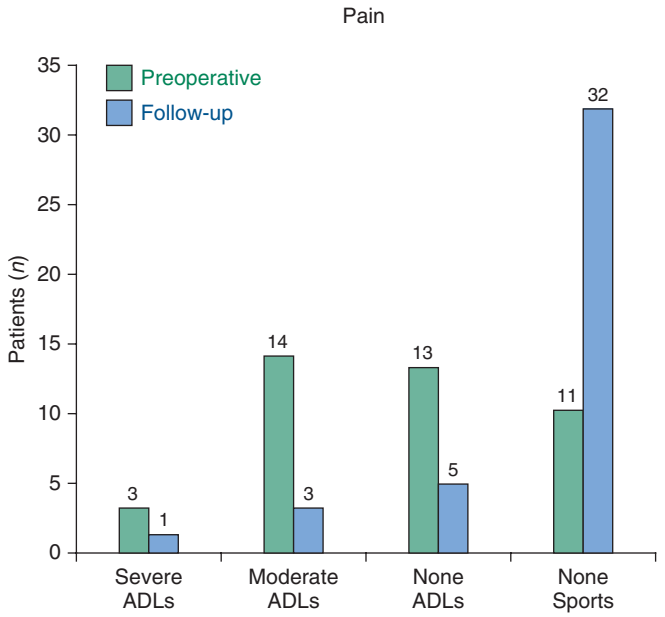


FIG 26-42 The distribution of patient responses to the pain scale are shown preoperatively and at follow up. The improvement was statistically significant ($P < .05$). *ADL,* Activities of daily living. (From Noyes FR, Barber-Westin SD, Hewett TE. High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. *Am J Sports Med.* 2000;28:282-296.)

posterolateral ligament tissues, allowing physiologic remodeling and shortening to occur. Therefore no associated posterolateral reconstruction was required during the subsequent ACL reconstruction. This clinical finding appears to support the recommendation to first perform the HTO in double varus knees and then assess knee stability and symptoms to determine the requirement for future ligament reconstruction.

There was no evidence of infection, peroneal nerve palsy, or tibial nonunion. One patient had a gentle manipulation under anesthesia, and full motion was successfully regained.

Three patients required a repeat osteotomy owing to complications. One patient settled into a valgus position 16 months postoperatively. One patient required a repeat internal fixation procedure 4 weeks postoperatively caused by a loss of fixation at the osteotomy site. A falling injury 3 weeks postoperative caused a 4-mm collapse at the osteotomy site in another patient who underwent an opening wedge osteotomy. In all three patients, follow-up examinations performed 2 to 3 years after the reoperation procedures demonstrated WBL and mechanical axes within the optimal range.

One patient had a nonunion at the distal fibula osteotomy site; the tibial osteotomy site healed in a satisfactory manner. The fibula nonunion site was resected 12 months postoperatively, and symptoms resolved.

Patients who had the ACL reconstruction typically had giving-way symptoms with daily or light sports activities. Because many patients modify their sports activities after surgery, it is not always necessary to perform an ACL reconstruction. Eleven knees in this study that were ACL deficient did not require ACL reconstruction. Patients should be individually profiled regarding the level of activity they wish to resume, and an ACL reconstruction done if symptoms warrant the procedure.

Two distinct groups of young, active patients exist in whom the goals of HTO may differ. One group has significant medial tibiofemoral arthritis and pain and swelling with daily activities. The goal of HTO for these patients is to diminish these symptoms, not to return to athletics. These patients are counseled regarding the extent of the disease process and the goal of the HTO, which is to buy time until total joint replacement is required.

The second group of patients does not have advanced joint arthritis; their pain symptoms are of relatively recent onset and occur with sports or manual labor activities. These individuals desire HTO to continue some form of athletics, or they may have strenuous occupations. These patients also usually require an ACL reconstruction because they have higher activity demands and frequently have experienced a giving-way injury. However, data are not available that accurately predict whether or not athletic activities are advisable after successful HTO. Large in vivo joint loading occurs with athletics, and patients who resume these activities do so at their own risk of further joint damage.

The Treatment of Double and Triple Varus Knees: Closing Wedge High Tibial Osteotomy, Anterior Cruciate Ligament Reconstruction, and Posterolateral Reconstruction

A second prospective investigation followed 41 knees (23 double, 18 triple varus) a mean of 4.5 years (range, 2-12 years) after HTO.[159] Before referral, 19 ACL reconstructions had been done in 15 patients that subsequently failed. Many of these ACL failures were attributed to an associated posterolateral deficiency that was not corrected at the time of the initial ACL reconstruction. Thirty patients (73%) had a partial or total medial meniscectomy before the HTO.

In 17 patients (12 double, 5 triple varus), gait analysis testing was conducted preoperatively and a mean of 2 years after HTO. The GaitLink system (Computerized Functional Testing Corporation) included a two-camera, a video-based optoelectronic digitizer for measuring motion, and a multicomponent force plate (Bertec) for measuring ground reaction force which was camouflaged under a 10 meter walkway. A control population of 28 age- and sex-matched normal subjects was used for comparisons. All moments were normalized to the product of body weight multiplied by height (BW × Ht) and were expressed as a percentage of that product.

Thirty knees had abnormal articular cartilage lesions. Twenty-six (63%) had abnormal lesions in the medial compartment.

In 21 (91%) of the double varus knees, the ACL was reconstructed a mean of 9 months after the HTO, and in two knees, the HTO and ACL reconstruction were done simultaneously.

In 13 (72%) of the triple varus knees, the ACL was reconstructed a mean of 8 months after the HTO. One patient had the HTO and ACL reconstruction done simultaneously. Four patients had the ACL reconstruction done before the HTO in an attempt to avoid HTO.

All triple varus knees had a posterolateral reconstruction; 12 (67%) had a proximal advancement of the posterolateral complex with the ACL reconstruction and 6 had an FCL femoral-fibular graft procedure. The knees that had the proximal advancement procedure had a definitive, although lax, FCL of normal width and integrity and intact popliteal muscle-tendon and fibular attachments, previously described as an indication for this procedure. The knees that had the FCL reconstruction had extensive damage to posterolateral tissues.

At follow up, statistically significant improvements were found for pain, swelling, and giving way (Fig. 26-43, $P < .001$). Before the HTO, 18 patients (44%) had severe to moderate pain with activities of daily living, whereas at follow up, only 7 (17%) had such pain. Overall, 29 patients (71%) improved their pain scores, and 28 (68%) improved their swelling score. Giving way was eliminated in 85%.

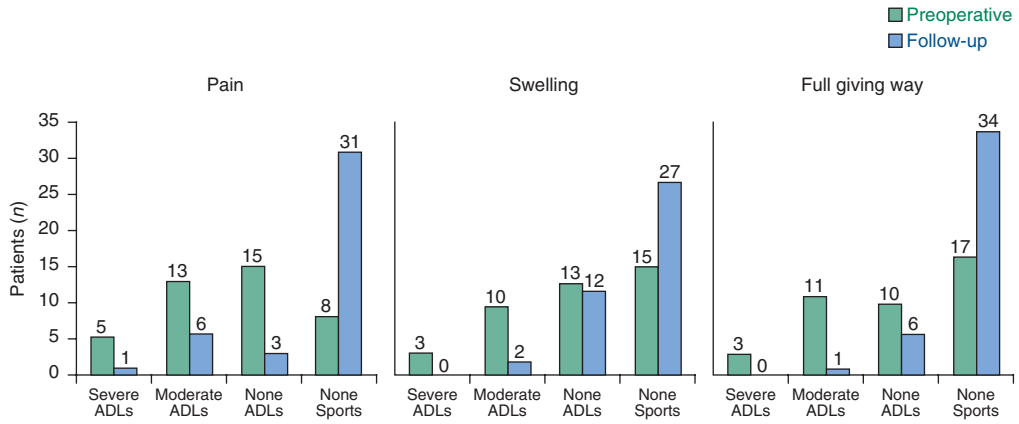


FIG 26-43 Statistically significant improvements were found for pain, swelling, and giving way from preoperative to follow up ($P < .01$). *ADL*, Activities of daily living. (From Noyes FR, Barber-Westin SD, Hewett TE. High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. *Am J Sports Med.* 2000;28:282-296.)

CRITICAL POINTS Our Clinical Studies: Treatment of Double and Triple Varus Knees: Closing Wedge Osteotomy, ACL Reconstruction, and Posterolateral Reconstruction

- 41 patients, 100% follow-up mean 4.5 years postoperatively.
- 73% had medial meniscectomy before HTO; 63% had abnormal articular cartilage lesions.
- Gait analysis conducted in 17 patients before and an average of 2 years after the HTO.
- Double varus knees: HTO + ACL reconstruction.
- Triple varus knees: HTO + ACL reconstruction + posterolateral reconstruction.
- Pain with daily activities: 44% before HTO; 17% after HTO.
- 66% returned to low-impact athletics.
- One patient rated the overall knee condition as normal; 14 as very good; 14 as good; 10 as fair; and 2 as poor.
- Triple varus knees: all but one rated functional or partially functional at follow-up for lateral joint opening and external tibial rotation.
- Double varus knees: all rated functional at follow-up for lateral joint opening and external tibial rotation.

Preoperative Gait Analysis

- Mean adduction moment 35% higher in patients compared with control population.
- Predicted medial compartment loads above normal in 71%.

Postoperative Gait Analysis

- Adduction moment decreased to lower than values of control group.
- Medial compartment loads decreased to values equivalent to control group.
- No complications related to knee motion, infection, peroneal nerve palsy.
- 80% knees in acceptable lower limb alignment at follow-up.

Twenty-seven patients (66%) were able to return to mostly low-impact athletics without symptoms. One patient rated the overall knee condition as normal, 14 as very good, 14 as good, 10 as fair, and 2 as poor.

Statistically significant improvements were found in the mean overall rating score from preoperative to follow up (63 ± 11 points and 82 ± 14 points, respectively, $P = .0001$). The average increase was 20 ± 10 points (range, 2-39 points).

At follow up, 19 knees (42%) had functional ACL reconstructions, 11 knees (24%) had partial function, and 15 knees (33%) failed. Ten of the 15 knees that failed represented ACL revision cases. A statistically significant difference was found in the failure rate for ACL revision cases compared with primary reconstruction cases (67% and 33%, respectively; $P = .03$).

Preoperatively, all of the triple varus knees had varus recurvatum, increases in lateral joint opening (mean, 8 mm; range, 3-15 mm), and increases in external tibial rotation (mean, 9 degrees; range, 3-15 degrees). At follow-up, 13 knees were rated as functional rating, 4 as partially functional, and 11 as failed.

Preoperatively, all patients with double varus knees had abnormal increases in lateral joint opening (mean, 4 mm; range, 2-10 mm). At follow up, no patient had more than 2 mm of increase in lateral joint opening, and none had an increase in external tibial rotation. All were rated as functional in lateral joint opening and external tibial rotation.

There was no significant difference in the mean preoperative adduction moment between the double varus and triple varus knees (4.1% ± 0.3% and 4.2% ± 0.3%, respectively). The preoperative mean adduction moment of the study group was 35% higher ($P < .001$) than the control group value; 10 of the 17 patients (59%) had values that were greater than one standard deviation above control values (Fig. 26-44). The study group also had a 22% higher calculated medial compartment load and a 40% higher lateral ligament tensile force compared with the control group (Table 26-8; $P < .01$). Above-normal medial compartment loads were predicted preoperatively in 71% of the involved knees, and above-normal lateral soft tissue forces during walking were predicted in 43% of the involved knees.

Postoperatively, the adduction moment and lateral ligament tensile force decreased to values that were significantly lower than controls. The medial compartment load decreased to values equal to those of controls (Fig. 26-45).

There was no evidence of infection, peroneal nerve palsy, patella infera, or knee motion limitations at follow up. No patient required additional treatment intervention for losses of knee flexion or extension.

Preoperatively, the mean WBL was 22% (range, 3%-49%), and the mean mechanical axis was –6.2 degrees (range, –12 to –1 degrees). At

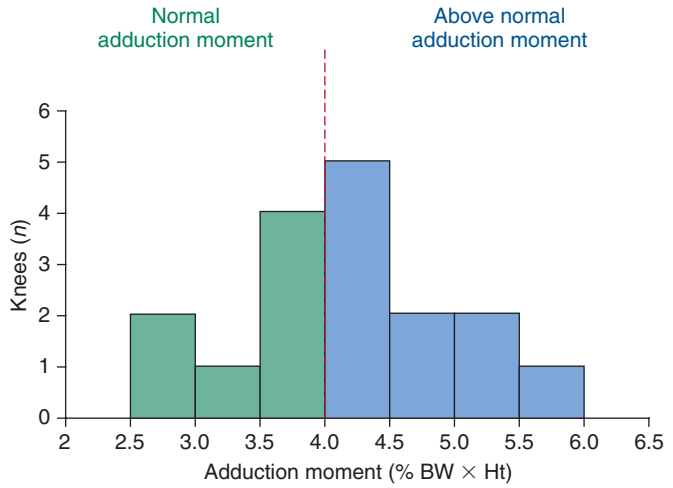


FIG 26-44 The distribution of the preoperative adduction moments of the 17 patients tested. The mean adduction moment for the study group was 35% higher than that for the control group ($P < .001$). *BW,* Body weight; *Ht,* height. (From Noyes FR, Barber-Westin SD, Hewett TE. High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. *Am J Sports Med.* 2000;28:282-296.)

TABLE 26-8 Gait Analysis Data: Measured and Predicted Peak Values (Mean ± SD)

Variable	Control Group ($n = 28$)	Study Group Preoperative ($n = 17$)	Study Group Postoperative ($n = 17$)	Change (%)
Measured Moment*				
Flexion	2.3 ± 0.8	2.2 ± 1.7	2.4 ± 1.3	9
Extension	2.4 ± 0.7	1.5 ± 1.4	1.4 ± 1.1	–7
Adduction	3.1 ± 0.7	4.2 ± 0.8†	2.6 ± 0.6‡	–38†
Predicted Tibiofemoral Loads‡				
Medial	2.3 ± 0.3	2.8 ± 0.3†	2.2 ± 0.5	–21†
Lateral	0.9 ± 0.3	1.1 ± 0.3	1.0 ± 0.4	–9
Predicted Ligament Tensile Force§				
Lateral	0.5 ± 0.2	0.7 ± 0.2¶	0.3 ± 0.2¶	–57†

*Percentage of body weight times height.
†Significant difference from control subjects ($P < .01$).
‡Significant difference between preoperative and postoperative values ($P < .01$).
§Percentage of body weight.
¶Significant difference from control subjects ($P < .001$).
SD, Standard deviation.

surgery, all knees were corrected to a WBL of 62%. In two knees, a valgus overcorrection occurred, and these were subsequently revised.

At follow up, 33 knees (80%) were in an acceptable position (mean WBL, 61%; range, 50%-75%), 7 knees were in varus, and 1 knee was in valgus (WBL, 81%).

Two knees required revision of the HTO. In both, the optimal correction in the 62% WBL range was obtained at surgery; however, excessive valgus (WBL, 86%) occurred with full weight bearing. A revision opening wedge osteotomy was done 2 months postoperative in one knee and 6 months postoperative in the other. At follow up, one knee had maintained the optimal WBL position, but the other had reassumed a varus position (WBL, 40%).

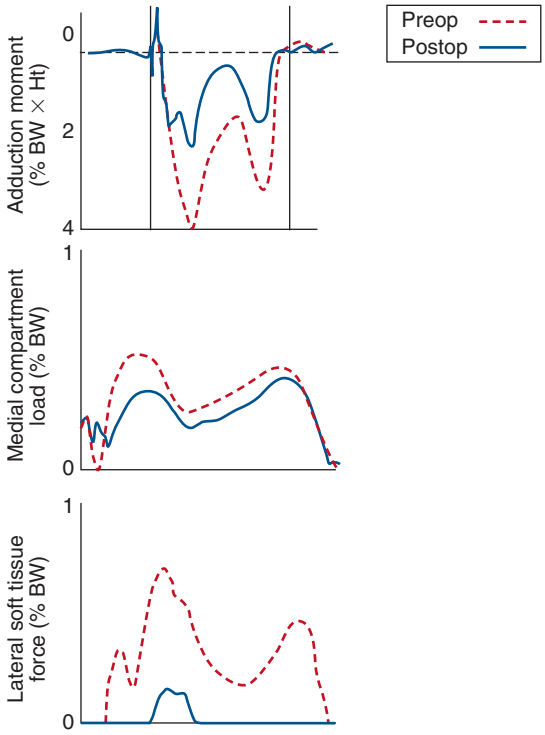


FIG 26-45 The preoperative and postoperative adduction moment, medial compartment load, and lateral ligament tensile forces for the 17 patients tested. Postoperatively, the adduction moment and lateral ligament tensile force decreased to significantly lower than control values. The medial compartment load decreased to values equal to those of controls. *BW,* Body weight; *Ht,* height. (From Noyes FR, Barber-Westin SD, Hewett TE. High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. *Am J Sports Med.* 2000;28:282-296.)

One knee had a loss of internal fixation of the osteotomy at the fourth postoperative week that was corrected. The HTO healed without difficulty. Two patients required resection of a distal fibular painful nonunion osteotomy site 12 and 26 months postoperatively.

Opening Wedge High Tibial Osteotomy: An Operative Technique and Rehabilitation Program to Decrease Complications and Promote Early Union and Function

A prospective study was conducted of 59 consecutive patients who had a medial opening wedge proximal tibial osteotomy.[166] All but four patients were followed for at least 6 months postoperative, the minimum follow-up time period required for this study. The 55 patients were followed a mean of 20 months postoperatively (range, 6-60 months).

The hypothesis was that a technique for opening wedge osteotomy that incorporated an autogenous iliac crest bone graft would prevent delayed or nonunion and allow early rehabilitation, weight bearing, and return in function. A second hypothesis was that a methodology for calculating the desired correction of valgus alignment would prevent undesired alterations in tibial slope.

Independent physicians examined radiographs preoperatively and postoperatively for tibial slope and patellar height and postoperatively for bony union. Postoperative radiographs were taken at 4 and 8 weeks after surgery and then as required until bone consolidation was evident. *Delayed union* was defined as lack of bridging callous and

CRITICAL POINTS Our Clinical Studies: Opening Wedge Osteotomy: an Operative Technique and Rehabilitation Program to Decrease Complications and Promote Early Union and Function

- 55 patients reviewed mean 20 months (range, 6-60 months) postoperatively.
- Independent physicians examined preoperative and postoperative radiographs for tibial slope, patellar height, and bone consolidation.
- Concurrent ACL reconstruction in four knees.
- Staged ACL and posterolateral reconstruction in three knees; staged ACL, PCL, and posterolateral reconstruction in one knee; staged PCL reconstruction in two knees; staged medial meniscus allograft in three knees.
- Delayed union in three patients (5%); healed 6 to 10 months postoperatively.
- Early postoperative loss of fixation in one patient (noncompliant with weight-bearing rules); HTO revised.
- No patellar infera, change in tibial slope, infection, arthrofibrosis, deep venous thrombosis, vascular injury, fracture, or problems at iliac crest harvest site.
- Full weight bearing achieved at mean of 8 weeks (range, 4-11 weeks) postoperatively.

presence of radiolucent areas within the opening wedge defect past a period of 3 months postoperatively.

In six knees, a concurrent operative procedure was performed and included ACL primary reconstruction in two knees, ACL revision reconstruction in one knee, ACL and MCL reconstructions in one knee, and an osteochondral autograft transfer procedure on the medial femoral condyle in two knees.

In nine knees, staged procedures were performed an average of 8 months (range, 3-19 months) after the osteotomy. These included knee ligament reconstructions of both the ACL and posterolateral structures in three knees; combined ACL, posterolateral, and PCL reconstruction in one knee; PCL reconstruction in two knees; and medial meniscus transplants in three knees. All nine knees achieved bony union at the osteotomy site and were full weight bearing before undergoing the staged procedures. No complications related to the HTO occurred in these nine knees.

Healing and union at the osteotomy site was radiographically evident an average of 3 months postoperatively in 52 patients (95%). A delay in union (with no loss of fixation or correction) occurred in three patients (5%). The size of the opening wedge osteotomy in these three patients ranged from 11.0 to 16 mm. In two of these patients, a bone stimulator was applied, and union was achieved by 6 to 8 months postoperatively. The other patient achieved union without intervention by 10 months.

An early postoperative loss of fixation occurred in one patient who admitted to full weight bearing immediately after surgery. The osteotomy was successfully revised 10 days postoperatively and proceeded uneventfully to union. There were no instances of shortening of the patellar tendon related to a patella infera syndrome.

There was no significant difference between the mean preoperative (9 degrees ± 4 degrees; range, 2-16 degrees) and postoperative (10 degrees ± 3 degrees; range, 3-21 degrees) tibial slope measurements. One patient with a PCL-deficient knee had an intentional increase in posterior slope.

There were no deep infections, loss of knee motion requiring intervention, deep vein thrombosis, nerve or arterial injury, fracture, or complications related to bone grafting.

Full weight bearing was achieved a mean of 8 weeks (range, 4-11 weeks) postoperatively.

The dissection was limited to include only 10 mm of the superior iliac crest. The iliac crest harvest procedure can be painful with trunk flexion activities for up to 4 weeks postoperatively, and patients are advised accordingly. The standard cortical iliac crest graft harvested was 40 mm in length, 12 mm in width, and 30 mm in depth, although larger osteotomies required a longer graft of approximately 45 mm. The width of the osteotomies varied from 5 to 15 mm, with 35% of the procedures being 10 mm or more.

The argument may be made that autogenous bone grafting is only required for large osteotomies, such as those over 10 mm, but in fact, no well-designed clinical studies have been published to date that provide evidence for such recommendations. When an opening wedge osteotomy proceeds to a delayed union or nonunion, there is usually a loss of correction and a prolonged course of restricted weight bearing, potential muscle disuse, and need for further surgical intervention. In these knees, failure to arrive at the desired goal of the osteotomy ensues, and therefore specific steps are taken to avoid this sequela in all patients regardless of the size of correction required.

The iliac crest graft harvest adds operative time and most likely increases the risk of complications at a second operative site. In this study, no patient complained of pain at the iliac crest harvest site with activities at follow up. Two patients had a small hematoma at the iliac crest harvest site, which resolved uneventfully. Despite this, patients should be advised of the expected postoperative pain and increased risk of complications.

Many commercial allograft wedges are available for opening wedge osteotomies. Allograft bone may have a marked delay in incorporation and healing at the osteotomy site. There may be a higher risk of delayed union, prolonged need for crutch protection, delay in allowing weight bearing, and disuse effects with both allografts and other substitute materials. A high rate of complications was reported in a series in which tricalcium phosphate was used to fill the wedge defect in 20 knees.[177] Nonunions occurred in 35%, loss of correction in 15%, infections in 10%, and material failure in 30%. No problems with union have been reported in several studies of opening wedge osteotomy when an iliac crest bone autograft was used.[48,126,173,176,218,226]

The following operative principles are promoted to prevent fracture: ensure that a proximal lateral tibial plateau width of at least 20 mm exists, avoid too much obliquity at the osteotomy site, and perforate to within 10 mm of the lateral cortex with the osteotome. Forceful completion of the osteotomy should be avoided. Several surgeon-controlled factors can help minimize the risk of inadequate or loss of correction (Table 26-9). Meticulous preoperative planning is imperative. Intraoperatively, the mechanical axis must be accurately verified. Because the size of the osteotomy is not set before fixation, opening wedge osteotomy affords the surgeon ample opportunity to adjust the angular correction and aids in producing the desired alignment. The alignment after surgery should be verified by the fourth postoperative week under partial weight-bearing conditions.

A prospective HTO investigation recently begun at our institution involves studying the effect of the Synthes locking plate and freeze-dried corticocancellous tibial allograft wedges. The hypothesis is that there will be no difference in the rate of nonunions and delayed unions and loss of angular correction compared with our prior clinical study owing to the added protection from the locking plate design. To date, 13 patients have been enrolled, and the preliminary results show no complications. It appears that locking plate techniques allow for allografts to be safely used, thereby avoiding the need for autogenous iliac crest procedures, except perhaps in cases of large (≥15 mm) opening wedge osteotomies.

TABLE 26-9 Technical Pearls to Avoid Complications for Opening Wedge High Tibial Osteotomy

1. Perform meticulous subperiosteal dissection to protect SMCL, posterior neurovascular structures.
2. Verify osteotomy starting point medial cortex; use anterior and posterior Keith needles to verify tibial slope.
3. Placement of guide pin and osteotomy too proximal can lead to lateral tibial plateau fracture.
4. Maintain approximately 15-degree pin angulation at medial tibial site; avoid large obliquity to osteotomy.
5. Measurement pitfalls: anterior tibial gap should be one half of posteromedial gap to avoid tibial slope increase. Verify coronal alignment with fluoroscopy, 5 degrees of knee flexion, medial and lateral tibiofemoral compartments closed and in contact.
6. Secure fixation SMCL repair to avoid valgus instability. No release of deep MCL.
7. Implement immediate knee motion, patellar mobilization, and quadriceps function to avoid patella infera.
8. Maintain lateral cortex hinge by leaving 10 mm laterally, gentle distraction opening wedge.
9. Autograft iliac crest bone graft if >15 mm opening.
10. Allograft bone grafts: expect delay in union; requires locking plate and screws
11. Postoperatively maintain close follow-up, prevent swelling, elevate limb, use thromboembolic hose, perform hourly ankle pumps, check for DVT, obtain routine ultrasound.

DVT, Deep venous thrombosis; *MCL*, medial collateral ligament; *SMCL*, superficial medial collateral ligament.

CRITICAL POINTS Results From Other Clinical Studies

Survival Rates Endpoints
- Conversion TKA
- Conversion unicompartmental knee replacement
- Low HSS score
- Patient dissatisfaction
- Failure to relieve knee pain

Survival Rates
Closing Wedge Osteotomy
- 5 years postoperative: mean 90% (range, 73%-99%)
- 10 years postoperative: mean 77% (range, 41%-98%)
- 15 years postoperative: mean 69% (range, 39%-93%)

Opening Wedge Osteotomy
- 5-8 years postoperative: 70%-97%
- 10 years postoperative: 85% (only 1 study)
- 15 years postoperative: 68% (only 1 study)

Opening vs. Closing Wedge
- No difference in survival rates
- No differences in pain scores, Lysholm score, HSS score, complications
- Lower patellar height, greater posterior tibial slope in some opening wedge studies

HTO and Associated Cartilage Restorative Procedures
- Microfracture, osteochondral allografts, osteochondral autograft, autologous chondrocyte implantation have been done with HTO
- Satisfactory mid-term survival rates reported in three studies

Long-Term Knee Symptoms and Function
- HTO alleviates knee pain and improves function in most studies, but longevity of improvements correlates with length of follow-up.
- Many patients able to return low-impact sports activities in short- to mid-term periods after HTO.
- Satisfactory relief of symptoms and improvement in knee function reported in most studies that combined HTO with ACL reconstruction.

HTO vs. Unicompartmental Knee Replacement
- Only a few studies available that compared HTO with modern unicompartment knee replacement procedures. No short-term differences found between operations.
- One long-term study reported equivalent 10-year revision rates in patients aged 30-64 years.

RESULTS FROM OTHER CLINICAL STUDIES

High Tibial Osteotomy Survival Rates

Survival rates that have been reported after HTO are shown in Table 26-10. Although conversion to TKA was uniformly used as an endpoint for survival, some investigators also incorporated additional endpoints such as a UKA, a low overall Hospital for Special Surgery (HSS) knee rating score, patient dissatisfaction, or failure to relieve pain. There is little agreement among studies regarding factors that may negatively affect survival rates after HTO. Preoperative factors reported include age greater than 50 years, obesity, Ahlback radiographic grade 2 or more, female gender, knee flexion less than 100 degrees, and varus malalignment greater than 9 degrees. After surgery, poor quadriceps strength and inadequate correction (that varied in studies from greater than 6 degrees valgus, less than 8 degrees valgus, more than 15 degrees valgus, and more than 16 degrees valgus) were associated with lower survival rates in a few studies.

In regard to closing wedge osteotomy, an analysis of 16 investigations that calculated survival rates (see Table 26-10) revealed an average 5-year rate of 90% (range, 73%-99%) and an average 10-year rate of 77% (range, 51%-98%). At the time of writing, 11 studies provided 15-year survival rates that averaged 69% (range, 39%-93%), and 5 studies calculated 20-year rates that were quite variable, ranging from 30% to 85%.

Fewer data are available regarding survival rates after opening wedge osteotomy. Six studies reported mid term (5-8 years) rates that ranged from 70% to 98.7%. Hernigou and Ma's series of 203 knees calculated 10- and 15-year survival rates of 85% and 68%, respectively.[88]

In 2013, Harris and associates[84] published a systematic review of 69 studies in which 57 assessed the outcome of isolated HTO, 9 assessed HTO with articular cartilage restorative procedures (microfracture, autologous chondrocyte implantation [ACI], osteochondral autograft transfer, or osteochondral allograft transplantation), and 3 assessed HTO with medial meniscus transplantation. The authors calculated survival rates for each study and found no significant differences between opening and closing wedge osteotomy at 5 and 10 years postoperatively. There was a slightly higher survival rate noted for HTO when done in conjunction with articular cartilage procedures at 5 years compared with isolated HTO procedures (98% and 92%, respectively; $P < .001$) and HTO combined with meniscus transplantation (91%; $P < .001$); however, differences in the length of follow up preclude comparison of longer term survival rates. The authors did

TABLE 26-10 Survival Rates After High Tibial Osteotomy

Study	Type of HTO	*N*	Age (yr)	Range (yr)	End Points for Survival Analysis	POSTOPERATIVE SURVIVAL RATES (%) 5-8 yr*	10 yr	15-20 yr†	Risk Factors Affecting Rate
Bonasia et al[30] (2014)	OW	9	54 ± 9		TKA or indicated for TKA owing to symptoms	98.7 75.9 at 7.5 yr	NA	NA	BMI >30, age >56 yr, postoperative knee flexion <120 degrees
Harris et al[84] (2013), systematic review	OW and CW, 69 studies	4557	53	10-81	TKA, UKA, revision HTO	92 OW 92 CW 98 + ACP 91 + MAT	82 OW 84 CW	~75 all ~72 at 20 yr	Not assessed
Sterett et al[202] (2010)	OW Puddu plate or external fixator, cortical bone powder and cancellous chips	106	52	30-71	TKA	97 91 at 7 yr	NA	NA	None
DeMeo et al[55] (2010)	OW Puddu plate, allograft bone	20	49	36-67	TKA	NA 70 at 8 yr	NA	NA	None
Sterett & Steadman[201] (2004)	OW external fixator	38	51	34-79	TKA, revision HTO	84	NA	NA	None
Hernigou & Ma[88] (2001)	OW plate, cement block and cancellous bone	215	61	48-72	TKA	94	85	68	None
Zaki & Rae[231] (2009)	OW TomoFix	50	39.5	30-49	TKA	98	NA	NA	None
Minzlaff et al[138] (2013)	OW and CW	74	38	19-62	TKA, UKA	95 90 at 8 yr	NA	NA	Higher amount of axial correction required, higher BMI
Weale et al[219] (2001)	OW	67	55	36-70	TKA, awaiting TKA, sepsis	89	63	NA	None
Nagi et al[143] (2007)	OW and CW	72	60	45-70	TKA, HSS score <70 points	NA	80	72 42 at 20 yr	None
Efe et al[62] (2011)	CW	199	54	25-72	TKA	93	84	68	Kellgren-Lawrence grade >2
Hui et al[97] (2011)	CW	413	50	24-70	TKA, UKA, revision HTO	95	79	56	Age >50 yr, BMI >25
van Raaij et al[214] (2008)	CW	100	49	24-67	TKA	90	75	NA	Female gender, Ahlback grade ≥2
Akizuki et al[6] (2008)	CW	118	63	45-76	TKA	99	98	90	BMI >27.5, flexion <100 degrees
Gstottner et al[80] (2008)	CW	134	54	19-74	TKA	94	80	65 54 >18 yr	Age >50 yr
Flecher et al[67] (2006)	CW	257	42	15-76	TKA, UKA, PFA, debridement, tibial tubercle medialization	95	93	90 85 at 20 yr	Age >50 yr, BMI >30, Ahlback grade ≥3, overcorrection >6 degrees valgus
Papachristou et al[174] (2006)	CW	44	51	30-60	TKA, no pain relief	91	80	66	None
Huang et al[94] (2005)	CW	93	57	38-73	TKA, patient dissatisfied	95	87	75	Preoperative >9 degrees varus
Tang and Henderson[211] (2005)	CW	67	49	22-74	TKA, no pain relief	90	75	67 67 at 20 yr	None

Continued

TABLE 26-10 Survival Rates After High Tibial Osteotomy—cont'd

Study	Type of HTO	*N*	Age (yr)	Range (yr)	End Points for Survival Analysis	POSTOPERATIVE SURVIVAL RATES (%) 5-8 yr*	10 yr	15-20 yr†	Risk Factors Affecting Rate
Koshino et al[114] (2004)	CW	75	59	46-73	TKA, UKA, moderate pain	98	96	93	None
Aglietti et al[3] (2003)	CW	91	58	36-69	TKA, HSS score <70 points	96	78	57	Postoperative <8 or >15 degrees valgus, poor muscle strength, female gender
Sprenger and Doersbacher[199] (2003)	CW	76	69	47-81	TKA, HSS score <70 points, patient dissatisfied	86	74	56 46 at 20 yr	<8 or >16 degrees valgus 1 yr postoperative
Flamme et al[66] (2003)	CW	101	58	19-79	TKA, UKA	90	81	NA	None
Stukenborg-Colsman et al[207] (2001)	CW	32	67	60-79	TKA	78	60	NA	None
Billings et al[27] (2000)	CW	64	49	23-69	TKA	85	53	NA	None
Naudie et al[145] (1999)	CW	106	55	16-76	TKA	73	51	39 30 at 20 yr	Age >50 yr, <120 degrees flexion
Coventry et al[47] (1993)	CW	87	63	41-79	TKA, moderate or severe pain	87	66	NA	Obesity, <8 degrees valgus 1 yr postoperative

*5-year survival rates shown unless otherwise indicated.
†15-year survival rates shown unless otherwise indicated.
ACP, Articular cartilage procedure; *BMI*, body mass index; *CW*, closing wedge; *HSS*, Hospital for Special Surgery rating system; *HTO*, high tibial osteotomy; *MAT*, medial meniscus allograft transplantation; *NA*, not available; *OW*, opening wedge; *PFA*, patellofemoral arthroplasty; *TKA*, total knee arthroplasty; *UKA*, unicompartmental knee arthroplasty.

not conduct a separate analysis that compared the survival rates according to the various types of cartilage restorative procedures.

High Tibial Osteotomy Opening Versus Closing Wedge Osteotomy

There does not appear to be a significant difference in survival rates between opening and closing wedge osteotomy procedures. The systematic review conducted by Harris and associates[84] previously described compared rates of 1850 opening wedge with 2665 closing wedge osteotomies and found nearly identical results up to 10 years postoperatively. However, there are longer follow-up time periods in closing wedge osteotomy studies, and data are currently lacking on 15- and 20-year survival rates of opening wedge procedures for comparison.

A meta-analysis by Smith and colleagues[193] compared radiologic and clinical outcomes and rates of complications of 324 opening wedge osteotomies to those of 318 closing wedge osteotomies from nine investigations. The follow-up time periods in the studies were short, ranging from 1 to 27 months postoperatively. There was no significant difference between procedures in visual analogue pain scores, Lysholm score, HSS score, or incidence of complications (including infection, deep venous thrombosis (DVT), nonunion, peroneal nerve palsy, revision surgery, or TKA). There were a significantly lower patellar height ($P < .001$) and a significantly greater posterior tibial slope ($P < .0001$) in the opening wedge group. There was no difference in the angle of correction.

Other investigators have reported significant differences between opening and closing wedge procedures in changes in regard to patellar height, posterior tibial slope, or both.[8,58,63,111,196] Unfortunately, the studies did not always provide detailed descriptions of the operative procedures and calculation of angular correction required at surgery. However, Hinterwimmer and colleagues[90] found no significant changes in tibial slope or patellar height following opening wedge osteotomy when techniques described in this chapter were used to prevent these changes. Song and associates[196] found no differences between opening and closing wedge procedures 3 to 4 years postoperatively in the average amount of patellar tilt, lateral patellar displacement, extent of anterior knee pain, and HSS scores.

High Tibial Osteotomy and Associated Cartilage Restorative Procedures

At the time of writing, 12 studies have been conducted in which HTO was combined with an articular cartilage restorative procedure. The restorative procedures included microfracture in four investigations,[130,175,202,223] osteochondral allografts in three,[79,132,134] osteochondral autograft transfer in two,[9,138] ACI in two,[24,29] and either microfracture or ACI in one.[148] Satisfactory mid term survival rates were reported 4.5 years after ACI by Bode and associates[29] (90%), 7 years after microfracture by Sterett and colleagues[202] (91%), and 7.5 years after osteochondral autograft transfer by Minzlaff and coworkers (90%).[138] The other investigations were either short term in duration or did not provide results of patients who underwent combined osteotomy-cartilage repair procedures compared with the rest of the study cohort.

Few authors have presented results of combined HTO-meniscus transplantation procedures,[41,77,215] and others only briefly mentioned that the procedure was done in small numbers of patients.[1,82,205,228,230]

Effect of High Tibial Osteotomy on Long-Term Knee Symptoms and Function

The ability of HTO to alleviate knee pain and improve function has been demonstrated in many studies; however, the longevity of improvement tends to correlate with the length of follow up achieved postoperatively in most investigations (Table 26-11). For instance, Benzadour and colleagues[25] followed 192 patients (224 knees) for 15 years postoperatively; 118 had an opening wedge and 106 had a closing wedge osteotomy. There were no significant differences in Knee Society rating scores between the two groups at 5, 10, and 15 years, with both showing a gradual deterioration in scores over time. Revision osteotomy or TKA was required in 60 knees (27%). The authors concluded that either procedure was effective for at least 10 years.

Functional limitations with daily activities such as walking and stair climbing are typically reported in the majority of patients before HTO. In addition, few patients are able to participate in even light sports

TABLE 26-11 Long-Term Clinical Outcome of High Tibial Osteotomy

Study	*N*	Mean Age (Range) (yr)	Pain, Patient Rating	Activities of Daily Living Scores	Failures
Sterett et al[202] (2010)	106 followed 3, 5, 9 yr	52 (30-71)	*Satisfaction score:* 3 yr, 7.9; 5 yr, 7.5; 9 yr, 7.5	*Lysholm:* 3 yr, 73; 5 yr, 73; 9 yr, 67	11% TKA
DeMeo et al[55] (2010)	20 followed 2, 8 yr	49 (36-67)	2 yr: 5 excellent, 14 good, 1 fair 8 yr: 6 excellent, 2 good, 11 fair/poor	*Lysholm:* 2 yr, 89; 8 yr, 83 *HSS:* 2 yr, 92; 8 yr, 87	35%: 25% TKA and 10% rated knee poor
Benzakour et al[25] (2010)	224 followed 15 yr	55 (40-72)	15% residual pain	*Knee Society Pain & Function:* Mean preoperative OW, 68; mean F/U, 101; mean preoperative CW, 81; mean F/U, 94	27%: 15% pain/limited ROM, 10% TKA, 2% revision HTO
Akizuki et al[6] (2008)	118 followed 16-20 yr	63 (45-76)	NA	*HSS:* 5 yr: 66% excellent, 25% good, 8% fair/poor 10-20 yr: 38% excellent, 35% good, 26% fair/poor	14%: 9% TKA and 5% rated poor on HSS
Papachristou et al[174] (2006)	44 followed 5-17 yr	51 (30-60)	84% marked pain relief, satisfied	*Authors' rating:* 5 yr: 64% excellent, 21% good, 14% fair/poor 10 yr: 57% excellent, 19% good, 24% fair/poor *HSS:* Mean preoperative, 52; F/U excellent/good results, 84; F/U fair/poor results, 59	20% TKA
Koshino et al[114] (2004)	75 followed 15-28 yr	60 (46-73)	98% satisfied	94% walk >1 km *Knee Society Function:* 5-9 yr, 93; 15-28 yr, 80 *HSS overall rating:* 5-9 yr, 69% excellent, 27% good, 4% fair; 15-28 yr: 65% excellent, 25% good, 9% fair	19%: 15% TKA and 4% no pain relief
Aglietti et al[3] (2003)	91 followed 10-21 yr	58 (36-69)	79% no/mild pain	*HSS overall rating:* 31% excellent, 16% good, 14% fair, 39% poor; 43% unlimited walking ability	41%: 33% TKA and 8% rated poor
Pfahler et al[179] (2003)	62 followed 6-9.5 yr	54 (20-67)	VAS mean preoperative 6.5, F/U 3; 90% satisfied	57% walk >1 hr *HSS:* mean preoperative, 60; F/U, 87 *Knee Society Function:* mean preoperative, 54; F/U, 86	43%: 33% TKA and 10% no improvement
Koshino et al[113] (2003)	21 followed 6.5 yr	66 (55-79)	All had relief of pain; AKS mean preoperative 22.9, F/U 47.4	89% unlimited walking distance *Knee Society Function:* mean preoperative, 48.1; F/U, 93.1 *HSS:* mean preoperative, 61.6; F/U, 95.8	0%
Marti et al[126] (2001)	36 followed 5-21 yr	43 (17-76)	NA	*Lysholm:* 26% excellent, 62% good, 12% fair/poor	3% TKA
Billings et al[27] (2000)	64 followed 5-13 yr	49 (23-69)	NA	*HSS:* mean preoperative, 71; F/U, 94	32% TKA

AKS, American Knee Society; *CW,* Closing wedge; *F/U,* follow up; *HSS,* Hospital for Special Surgery; *NA,* not available; *OW,* opening wedge; *TKA,* total knee arthroplasty; *VAS,* visual analogue scale.

activities without experiencing noteworthy symptoms. After surgery, the ability to walk an unlimited distance or more than 1 km is an important measure of daily function. Koshino and coworkers[114] reported that 94% of 75 patients could walk more than 1 km without pain at 15 to 28 years postoperative after a closing wedge HTO. However, the American Society Knee Function significantly decreased from 93 ± 13 points at 5 to 9 years postoperative to 80 ± 19 points at 15 to 28 years postoperative ($P < .0001$). Pfahler and associates[179] reported that 57% of 62 patients followed 6 to 14 years postoperatively could walk more than 1 hour.

Several studies have reported that, in the short- to mid term period after HTO, many patients return to mostly low-impact, recreational sports activities.[21,31,32,142,188,221] For instance, Salzmann and coworkers surveyed 65 patients who were 1.1 to 7 years after opening wedge osteotomy and reported that 91% were participating in activities such as bicycling, swimming, and fitness. There was no significant change in the frequency or duration of activities compared with preoperative levels, and no patients were involved in competitive sports. Bonnin and associates[32] surveyed 139 patients who were 2.5 to 6.1 years postoperative and reported that 71% participated in light, low-impact activities. However, 62% of the patients thought their activities were limited by their knee, and "several" patients had a high or very high level of discomfort during sports activities. Long-term data (>10 years) are lacking on the ability of patients to continue to participate in athletics and the effect of such participation on the knee condition.

Satisfactory relief of symptoms and improvement in knee function has been reported in most studies involving patients who had an HTO and ACL reconstruction either concomitantly or staged (Table 26-12). In a manner similar to that noted with isolated osteotomies, combined ACL-HTO procedures typically allow a return to recreational or low-impact activities.

High Tibial Osteotomy Versus Unicompartmental Knee Replacement

The outcomes of modern osteotomy and UKA techniques have been compared in only a few investigations.[33,56,210,216,227] Although several others have conducted comparisons of these operations prospectively, retrospectively, or in meta-analyzed data, these investigators combined different types of osteotomy techniques and older UKA prostheses, which had a higher rate of failure compared with more recently available designs.[38,69,100,197,207] In a randomized, prospective study, Borjesson and colleagues[33] found no differences in clinical outcome measures 5 years postoperatively for pain during walking, the patient's subjective opinion of improvement in the knee condition, and levels of physical activity between 18 patients who had HTO and 22 who had UKA. A short-term study by Dettoni and associates[56] reported similar Knee Society scores and survivorship rates between 54 HTO and 56 UKA patients who were 2 to 4 years postoperative. Yim and coworkers[227] also found no differences between 58 HTO and 50 UKA recipients in clinical outcome measures of Tegner and Lysholm scores and range of knee motion, 3 years postoperatively. Using data from the Swedish Knee Arthroplasty Register, W-Dahl and colleagues[216] reported equivalent 10 year revision rates for HTO and UKA (17%) in patients aged 30 to 64 years.

Opening Wedge Distal Femoral Osteotomy

Four clinical investigations have been published to date regarding the outcome of opening wedge DFO.[49,57,103,232] Three of the four investigations noted generally good outcomes but emphasized the need for clear indications of the procedure because patients with bicompartmental or tricompartmental arthrosis tended to have poorer results than those with isolated lateral arthrosis. Three of the four studies filled the osteotomy gap with some type of material (cement, autogenous bone, allograft bone). Fixation was accomplished with a Puddu plate in two studies, a Tomofix plate in one study, and a blade plate bent to 95 degrees in one study. Survival rates were provided by two studies at 7[57] and 8[232] years postoperatively.

Dewilde and associates[57] followed 19 consecutive patients a mean of 5.7 years (range, 2.6-10.6 years) postoperatively. There were six men and 13 women whose average age at surgery was 47 years (range, 30-51 years). The preoperative mechanical axis ranged from 3 to 10 degrees valgus (mean, 5.3 ± 2.5 degrees). The osteotomy gap was injected with bioresorbable calcium phosphate cement and secured with a Puddu plate. Patients began range of motion exercises 3 to 5 days postoperatively, were allowed partial weight bearing at 4 weeks, and progressed to full weight bearing after 8 weeks. At follow up, a statistically significant improvement was found in the mean Knee Society Knee Score (preoperative, 43 ± 8; follow up, 78 ± 23 points; $P < .0001$). The mean postoperative mechanical axis improved to −1.3 ± 4.0 degrees. Two patients were converted to TKA at 13 and 30 months postoperatively, and one patient required a revision because of a fall that occurred 2 months postoperatively. The 7-year survival rate was 82% (95% confidence interval [CI], 57%-93%).

Zarrouk and colleagues[232] followed 22 knees (in 20 patients) a mean of 4.5 years (range, 3-11 years) postoperatively. There were 7 men and 13 women whose average age at surgery was 53 years (range, 27-66 years). The preoperative mechanical axis ranged from 188 to 198 degrees (mean, 194.5 degrees). No bone grafting was used, and the osteotomy site was secured with a blade plate bent to 95 degrees. Patients were kept non–weight bearing for 3 months and were then progressed based on radiographic documentation of healing. The mean time to union was 14 weeks. Delayed union occurred in one patient. There were significant improvements in the mean International Knee Society score (preoperative, 49; postoperative, 74 points; $P < .001$), the function score (preoperative, 50 points; postoperative, 72 points; $P < .001$), and the pain score (mean improvement 26 points; $P < .001$). The postoperative mechanical axis ranged from 177 to 186 degrees. Twelve knees had a correction between 0 to 6 degrees valgus, eight knees had a slight overcorrection (<3 degrees varus), and two knees were overcorrected (>6 degrees varus). The 8-year survival rate was 91% (95% CI, 69%-100%).

Das and coworkers[49] performed an opening wedge DFO on 12 patients who were reviewed clinically a mean of 2.8 years (range, 1-4.1 years) and by telephone interview a mean of 6.1 years (range, 4.2-7.4 years) postoperatively. There were five men and seven women whose mean age at surgery was 55 years (range, 46-71 years). The osteotomy gap was filled with allograft bone and secured with a Puddu plate. Patients were kept partial weight bearing for 8 weeks until radiographic signs of healing were noted. The mean correction was 11 degrees valgus (preoperative, 10-21 degrees valgus and postoperative, 1-8 degrees). Full standing radiographs were not available, and therefore these values represented only "an indication of the real alignment." Two patients converted to TKA, and two others required plate removal. One delayed union (7 months) occurred. The Lysholm score improved only slightly, from 64 points preoperatively to 77 points at follow up. HSS score improved from 58 to 72 points.

Jacobi and associates[103] performed an opening wedge DFO on 14 patients who were followed a mean of 3.7 years (range, 2.3-5.2 years) postoperatively. There were eight men and six women whose mean age at surgery was 46 years (range, 28-63 years). In seven patients, an autogenous iliac crest bone graft was used, and in all patients, the

TABLE 26-12 Subjective Results of High Tibial Osteotomy and Anterior Cruciate Ligament Reconstruction

Study	Type of HTO, ACL Reconstruction	*N*	Mean Age (Range) (yr)	Pain	ADLs	Sports Activities	Satisfied (%)
Zaffagnini et al[230] (2013)	CW; ACL STG autograft with HTO in all	32 followed 4-10 yr	40 (27-54)	*VAS:* mean preoperative, 72; F/U, 42	*IKDC Subjective:* mean preoperative, 58; mean F/U, 72	*Tegner:* mean preoperative, 3; F/U, 5; 62% equal to higher level, 18% same level	NA
Bonin et al[31] (2004)	CW (25), OW (5); ACL PT autograft with HTO in all	30 followed 6-16 yr	30 (18-41)	NA	*IKDC Subjective:* mean F/U, 78.5	47% intense, 36% light	NA
Williams et al[221] (2003)	CW; ACL untreated (12), ACL reconstructed with HTO: PT autograft (2), STG autograft (2), PT allograft (9)	25 followed 2-8.8 yr	35	84% no pain with vigorous activity	*HSS overall rating:* mean preoperative, 81; F/U, 97 *Lysholm:* mean preoperative, 47; F/U, 81	16% strenuous, 76% recreational	76% very, 16% reasonably
Latterman & Jakob[117] (1996)	CW (17), OW (10); ACL untreated (11), ACL PT autograft with HTO (8), ACL PT autograft after HTO (8)	27 followed 1.5-10 yr	37 (24-56)	30% pain at rest, 70% pain with moderate sports	NA	NA	93%
Stutz et al[208] (1996)	CW; ACL PT with HTO (14), ACL PT/LAD with HTO (13)	27 followed 3.2-13.8 yr	36 (19-55)	*IKDC Symptom rating:* 52% normal/nearly normal, 48% abnormal	*IKDC subjective rating:* 67% normal/nearly normal, 33% abnormal	22% strenuous, 44% moderate, 30% light, 4% none	NA
Boss et al[34] (1995)	CW; ACL PT autograft with HTO in all	27 followed 2.6-13.8 yr	36 (19-55)	*IKDC Symptom rating:* 55% normal/nearly normal, 22% abnormal, 26% severely abnormal	80% normal/nearly normal knee function	55% higher level, 15% lower level	75%
Dejour et al[52] (1994)	CW; ACL PT autograft with HTO in all	44 followed 1-11 yr	29 (18-42)	27% no pain, 39% pain only after vigorous activity	NA	2% strenuous, 60% recreational	50% very satisfied, 41% satisfied

ACL, Anterior cruciate ligament; *ADLs,* activities of daily living; *CW*, closing wedge; *F/U*, follow up; *HSS*, Hospital for Special Surgery; *HTO*, high tibial osteotomy; *IKDC*, International Knee Documentations Committee; *LAD*, ligament augmentation device; *NA*, not available; *OW*, opening wedge; *PT*, patellar tendon; *STG*, semitendinosus-gracilis.

osteotomy site was secured with a Tomofix plate. The mean correction was 5.8 degrees (range, 3-9 degrees). Full weight bearing was allowed at 3 months in seven patients and was delayed in the others. At 6 months, two patients had insufficient healing, and one of them required spongious bone augmentation and an additional medial plate. The other knee healed within 9 months. Plate removal was required in 12 patients. The mean overall Knee Injury and Osteoarthritis Outcome Score improved from 31 ± 17 points before surgery to 69 ± 22 points at follow-up ($P = .002$). Bone grafting did not affect the slow healing time (3-12 months) and all patients were nonsmokers. These authors no longer perform this procedure, favoring medial closing wedge osteotomy instead.

PREVENTION AND MANAGEMENT OF COMPLICATIONS

Bony Instability, "Teeter Effect"

Kettlekamp and colleagues[110] described the teeter effect in 1975 as a contraindication to proximal tibial osteotomy. Excessive bone loss and concavity on the medial tibial plateau prohibits simultaneous weight bearing on both plateaus after HTO and results in an unstable knee in the coronal plane. A teeter effect occurs because tibiofemoral contact shifts, or teeters, from one plateau to the other depending on the relationship of the center of gravity to the center of the knee.

CRITICAL POINTS Prevention and Management of Complications

Bony Instability, Teeter Effect
- Preoperative radiographs determine bone loss, slope
- Intraoperatively, use fluoroscopy with both compartments loaded to confirm simultaneous medial and lateral tibiofemoral contact.

Inadequate or Loss of Axial Correction
- Caused by inadequate internal fixation, progressive loss articular cartilage medial compartment, stretching or deficiency of posterolateral soft tissues
- Preoperative: correct calculation mechanical axis and weight-bearing line.
- Intraoperative: confirm adequate correction with fluoroscopy, computerized navigation.

Delayed Union or Nonunion
Closing Wedge
- Perform osteotomy proximal to tibial tubercle to increase amount of cancellous bone surface contact.

Opening Wedge
- Use autogenous iliac crest bone graft for large corrections, corticocancellous allograft wedges for smaller corrections; locking plate and screw fixation in all.
- Toe-touch weight bearing at 4 weeks.

Tibial Plateau Fracture
- Ensure proximal lateral tibial plateau width is ≥20 mm.
- Avoid forceful closure of osteotomy.

Arterial Injury
- Recognize anterior tibial artery, popliteal artery at risk during surgical dissection caused by anatomic position.
- Flex the knee; gently retract popliteal structures.

Peroneal Nerve Injury, Palsy
- Caused by cast or bandage applied too tightly after surgery; double padding over peroneal nerve.
- Use internal fixation to avoid cast.
- Avoid injury to nerve during surgery.
- Avoid dome osteotomy below the tibial tubercle.

Arthrofibrosis, Patella Infera
Detection
- Bilateral, lateral radiographs preoperatively and postoperatively to measure patellar vertical height
- Inability of patient to perform strong quadriceps contraction
- Decreased patellar mobility and tension in patellar tendon
- Distal malposition of involved patella compared with opposite side

Minimize Risk
- Immediate rehabilitation: straight-leg raises, isometrics, electrical muscle stimulation, patellar mobilization
- Early recognition and treatment of limitation of knee motion

Iliac Crest Harvest Site Pain
- Limit dissection to only 10 mm of superior iliac crest.
- Meticulous subperiosteal exposure of outer iliac crest.
- Do not violate muscle plane or inner iliac cortex.
- Keep muscle attachments intact.

Deep Vein Thrombosis
- Before surgery, screen for any risk factors for DVT, including a prior history or family history suggestive of an inherited coagulation defect.
- Women should stop estrogen, oral contraceptives 1 month before surgery.
- Use aspirin twice daily after surgery.
- Use foot-ankle compression devices and thromboembolic hose.
- Early ambulation.
- Perform active ankle pumps hourly.

Osteotomy is contraindicated when bone loss makes simultaneous contact of both plateaus impossible. Preoperative radiographic evaluation of the bone loss on the tibial plateaus should be performed, specifically evaluating the slope of the plateaus to determine whether loading of both compartments will occur after HTO.

It has been suggested, but not experimentally confirmed, that if the combined cartilaginous and bony loss on the medial side is greater than 1 cm, it would be impossible to achieve loading of both the compartments after HTO. During surgery, the WBL should be evaluated under fluoroscopy with both compartments loaded to confirm that simultaneous medial and lateral tibiofemoral contact is present.

Inadequate or Loss of Axial Correction

Inadequate or overcorrection of lower limb alignment has been reported by many authors after HTO. Hernigou and associates[89] reported persistent varus occurring in 10 of 93 knees immediately after closing wedge osteotomy. In that investigation, 71 of 76 knees showed some degree of recurrent varus deformity 10 to 13 years postoperatively. Magyar and colleagues[121] described a loss of correction after closing wedge osteotomy, with 9 of 16 knees proceeding into increased valgus by 1 year postoperatively despite normal alignment achieved immediately postoperatively.

Marti and coworkers[125] followed 32 knees that had an opening wedge osteotomy with bone grafting. At follow up, 24 to 62 months postoperative, 31% demonstrated a recurrence of the varus deformity and 19% were in excessive valgus. Stuart and associates[206] evaluated standing tibiofemoral angles, which decreased from a mean of 9.3 degrees of varus to 7.8 degrees of valgus at final follow up. Using the Kaplan-Meier survival analysis method, the authors predicted that varus alignment was likely to occur in 18% of knees, lateral compartment arthritis was likely to progress in 60%, and medial and lateral compartment arthritis was likely to progress in 83% by 9 years after surgery.

In a biomechanic study, Stoffel and coworkers[204] showed that an intact lateral tibial hinge cortex largely determined the stability after opening wedge HTO. When the lateral cortex was disrupted, a locking plate and screw designed showed superior stability in both compression and torsion compared with the Puddu plate.

Loss of the axial alignment obtained at the time of surgery may be attributed to several factors. These include the use of inadequate internal fixation with collapse of the distal fragments settling into the cancellous bone of the plateau. Late drifting into a varus position may be caused by a progressive loss of the medial osteochondral cartilage complex or by stretching of the posterolateral structures. Coventry[45] reported no loss of surgical correction obtained immediately

postoperatively. He attributed the success of the procedure to stability of the closing wedge, the hinge effect of the medial periosteum and cortex, internal fixation, and avoidance of a shift of the fragments.

Careful preoperative planning is required to avoid inadequate correction, which begins with the calculation of the mechanical or anatomic axis using full-length standing radiographs. Stress radiographs may be used to evaluate medial osseocartilaginous complex loss and lateral joint opening.[60] Calculations to determine the amount of bone to be resected should be performed before the osteotomy as discussed.

During surgery, confirmation of adequate correction that was determined by preoperative measurements is done using fluoroscopy. The knee will be placed in an overall excessive valgus position if the amount of lateral opening is not evaluated and if too much bone is resected. Even though an ideal position may be verified during surgery, a change in alignment may be detected when postoperative standing radiographs are obtained. The alignment should be verified by the fourth postoperative week under partial weight-bearing conditions.

Delayed Union or Nonunion

Delayed union or nonunion has been reported following HTO. Warden and colleagues[218] reported incidence rates of delayed union (6.6%) and nonunion (1.8%) in 188 opening wedge osteotomies in which an iliac crest bone autograft was used in the majority of knees. There was a trend toward an increased incidence of delayed union or nonunion when a coral wedge was used either alone or in conjunction with the autogenous graft (15%, 5 of 33 knees) compared with when an iliac crest graft was used alone (6%, 8 of 128 knees). No problems with union were reported by Marti and associates,[126] Pace and Hofmann,[173] or Patond and Lokhande[176] after opening wedge osteotomy and iliac crest bone autograft procedures. Lobenhoffer and Agneskirchner[119] found that 6% of 101 knees that had an opening wedge HTO with a variety of bone graft substitutes and fixation with an Arthrex plate progressed to a nonunion.

The incidence of healing problems can be reduced by following several technical suggestions. First, the osteotomy should be performed proximal to the tibial tubercle because this will increase the amount of cancellous bone surface contact, which will enhance healing and inherent stability. The two surfaces should be cut in a manner that maximizes the amount of surface area that will be in contact in closing wedge osteotomies. In opening wedge osteotomies, a stable construct created by the use of an iliac crest autogenous bone graft (in the anterior, mid, and posterior portions of the osteotomy) and appropriate plate fixation with protection of the lateral tibial buttress (cortex) will sustain postoperative compressive and torsional loads. The argument may be made that autogenous bone grafting is only required for large osteotomies and that allograft or corticocancellous wedges with locking plate technology provides no increase in delayed healing or loss of osteotomy correction. No well-designed clinical studies with a sufficient number of patients have been published to date that provide evidence for such recommendations. Dallari and colleagues[48] showed that the addition of platelet gel or platelet gel combined with bone marrow stromal cells substantially increased the rate of bone healing in a small group of opening wedge osteotomies.

Many investigators have demonstrated that external fixators may accomplish adequate union and correction, such as the series reported by Sterett and Steadman[201] in which only 1 of 33 patients had a loss of correction early postoperatively. However, pin tract infections were reported in 45% of the patients. Several other investigations have reported high rates of pin tract infections, such as 67% (10 of 15 knees) from Adili and associates,[2] 62% (23 of 37 knees) from Bachhal and coworkers,[19] and 54% (12 of 22 knees) from Gerdhem and colleagues.[71]

Plate designs that incorporate locking screws provide added stability and are necessary in cases of any violation of the lateral tibial cortex to maintain stability under axial compressive or torsional loads. An alternative fixation method for a lateral tibial cortex fracture at osteotomy is to add a lateral two-hole plate through a separate incision; however, angulated locking screws from a medial plate may also be used.

The rehabilitation program allows toe touch weight bearing during the first 4 weeks and then allows progression over the next 4 weeks to full weight bearing based on radiographic signs of osteotomy healing. A delayed union can be treated, if the overall alignment is acceptable, by electric stimulation.

Tibial Plateau Fracture

The reported prevalence of fracture after closing wedge osteotomy ranges from 1% to 20%.[89,131] This complication appears uncommon after opening wedge osteotomy, although Amendola and associates[7] reported 7 of 37 patients (19%) in their initial series of opening wedge osteotomies had intraarticular fractures that extended into the lateral compartment. The fractures were believed to be caused by a combination of the osteotomy site closer to the lateral tibial plateau joint line than the lateral cortex and use of thick osteotomes. After adjusting the obliquity of the osteotomy and switching to thin, flexible osteotomes, the authors did not experience any further cases of fracture.

There are important operative techniques to prevent tibial plateau fracture as described. The proximal osteotomy should remain parallel to the joint surface. It is important to keep the proximal tibial portion 20 to 25 mm thick to avoid fracture. The cortex on the lateral side of the wedge may be penetrated by drill holes, and forceful closure of the wedge should be avoided. If a tibial plateau fracture does occur, anatomic reduction and internal fixation of the plateau fragments should be performed.

Arterial Injury

Vascular complications are exceedingly rare. Recognition of the anatomic relationship of the vessels to the surgical dissection is imperative. The anterior tibial artery is at risk because it pierces the proximal interosseous membrane. Injury to this artery may result in an anterior compartment syndrome, which must be recognized and dealt with promptly. The popliteal artery is at risk during posterior dissection and osteotomy of the posterior tibial cortex. By flexing the knee and gently retracting the popliteal structures, the risk of injury to these structures will be significantly reduced.

Peroneal Nerve Injury or Palsy

Jackson and Waugh[102] reported 27 of 226 cases (12%) of partial or complete injury to the peroneal nerve during osteotomy. Because there was a higher incidence of injury during curved osteotomies located below the tibial tuberosity, the authors concluded that osteotomy in this location was too dangerous. A 7% incidence of peroneal nerve injury was reported by Sundaram and coworkers,[209] and a 6% incidence was described by Harris and Kostuik.[85] Slawski and associates[192] reported a 4.3% incidence of peroneal neurapraxias in 225 pediatric tibial osteotomies.

Flierl and colleagues[68] compared the incidence of neurologic complications after opening wedge osteotomy between a technique using a conventional oscillating saw with a technique that created multiple drill holes and osteoclasis. After the conventional method, acute

transient peroneal nerve palsy developed in 15.7% of 89 patients, with persistent deficits found in 12.4%, 6 months postoperatively. In the osteoclasis group, 14% had acute transient events, and 4.7% reported permanent weakness. Other than the report by Flierl and colleagues,[68] nerve injury after opening wedge HTO appears to be extremely rare.

Peroneal nerve palsy may result from several causes; the most common is a cast or bandage applied too tightly after surgery. The use of internal fixation alleviates the need for casting. The nerve may also be directly injured during surgery.

Osteotomy of the fibula is performed at different sites by different authors depending on the operative technique. A risk of injuring the peroneal nerve exists if the osteotomy is performed in the proximal third of the fibula.[112] In addition, osteotomy in the middle portion of the fibula may injure the peroneal nerve innervation to the extensor hallicis longus. The rate of injury has been reported to be extremely high (25%) after dome osteotomy below the tibial tubercle.[102]

Arthrofibrosis and Patella Infera

Many early HTO studies cited unacceptably high rates of arthrofibrosis and patella infera after postoperative immobilization. Windsor and associates[222] reported that 80% of 45 knees had patella infera after closing wedge HTO and postulated that postoperative plaster immobilization allowed the decreased quadriceps muscle forces and shortening of the patellar tendon. Westrich and coworkers[220] demonstrated the beneficial effects of early motion after closing wedge osteotomy; 16 of 34 knees (47%) treated with cast immobilization developed patella infera compared with 3 of 35 (8%) that received immediate postoperative motion.

A decrease in the patellar height ratio as measured by the Blackburn-Peel ratio is expected after opening wedge osteotomy.[39] Wright and associates[225] reported that all 28 patients in their series of medial opening wedge osteotomies had a decrease in patellar height but no significant change in patellar ligament length (as measured by the Insall-Salvati ratio[99]). The authors explained that because the osteotomy increased the distance between the tibial tubercle and tibial articular surface, the patella migrated distally.

Similar findings in decreased patellar height following opening wedge osteotomy have been reported others.[39,88,144,146,212] Patella infera correlated with the magnitude of angular correction after HTO in two series.[212,225] For example, Wright and associates[225] evaluated patellar height and ligament length in 28 patients and found a relationship between the amount of infera and the degree of angular correction.

Postoperatively, lateral radiographs are taken to detect any decrease in the patellar vertical height ratio; these are repeated for any patient who shows early signs of developmental patella infera (inability to perform a strong quadriceps contraction after surgery, decreased patellar mobility, decreased palpable tension in the patellar tendon with failure of the patella to displace proximally on quadriceps contraction, or distal malposition of the involved patella compared with the opposite side). Rigid internal fixation should also help to reduce the occurrence of arthrofibrosis and a resultant patella infera.

In our opening wedge osteotomy study, the patellar height was not significantly affected by the magnitude of angular correction owing mostly to the desire not to change the tibial slope and ensuring that the anterior gap at the osteotomy site was less than half of the posterior gap. In addition, no patient had a limitation in knee motion that required treatment intervention such as manipulation or arthroscopic release of adhesions.

An immediate knee motion program and exercise protocol of straight-leg raises, multiangle isometrics, and electrical muscle stimulation are advocated to decrease the incidence of quadriceps weakness and knee motion limitation following HTO. In addition, a phased treatment program is begun for limitations of motion early in the postoperative course when restriction of either extension or flexion is noted.[161] This program is discussed in Chapter 28.

Iliac Crest Harvest Site Pain

Most, if not all, of the complications described in the literature related to iliac crest bone graft harvest may be avoided by the surgical technique described in this chapter. For example, the dissection is limited to include only a bicortical 12-mm width of the superior iliac crest. A meticulous subperiosteal exposure of the outer iliac crest is performed without violating the inner muscle attachments. The inner iliac cortex is never dissected, and the muscle attachments are kept intact. This minimally invasive harvest technique avoids the frequency of complications reported by larger exposures such as those used for spine fusions.

The standard cortical iliac crest graft harvested is 40 mm in length, 12 mm in width, and 30 mm in depth, although larger osteotomies require a longer graft of approximately 45 mm. The iliac crest harvest procedure may be painful with trunk flexion activities for up to 4 weeks postoperatively, and patients are advised accordingly. Even though there were no complications in our series, added time is required for the operative procedure and a complication is always possible, which must be weighed against the benefits of the rapid healing provided by autogenous bone at the osteotomy site.

Deep Vein Thrombosis

We reviewed HTO clinical studies and review articles that were published between January 2000 and March 2014 to determine the incidence of DVT and pulmonary embolism (PE) and prophylaxis protocols used to prevent these complications. A total of 118 studies were included in which 8340 knees in 7883 patients underwent HTO. Overall, 119 DVT (1.4%) and 8 PE (0.096%) events (with one fatality) were reported.[5,24,25,30,37,55,62,80,127,128,147,175,211,213] There appeared to be no difference in the incidence rate of thromboembolic complications between opening and closing wedge osteotomies or between investigations that used or did not use a thrombophylaxis protocol.

A thromboembolic prophylaxis program was described in only 26 studies (22%). There was no consistency among these studies regarding the choice of chemoprophylaxis agents, mechanical devices, or exercises. No study mentioned discontinuation of oral contraceptives before surgery. The use of low-molecular-weight heparin, without other mechanical devices or exercises, was the most frequently reported measure to prevent DVT. A few authors also recommended compression boots, antiembolism stockings, and/or ankle pump exercises.[5,76,116,136,159,166,195]

In conclusion, the occurrence of DVT after HTO is low, and the occurrence of a PE after HTO is exceedingly rare. The majority of publications did not provide recommendations for prophylaxis. In studies that provided recommendations, there is no consensus, and protocols vary widely. Even so, the incidence of DVT occurring in 4% to 7% in some studies[24,55,62,80] warrants the use of a reasonable prophylaxis protocol. Surgeons are urged to carefully screen all patients well before surgery to assess personal and family history of thrombotic events and to obtain appropriate blood and genetic testing when warranted. Women should be questioned regarding use of oral contraceptives and a decision reached on discontinuation of the medication 6 weeks before surgery. We have empirically used, in standard-risk patients, a program that includes intermittent pneumatic compression devices in both extremities for the first 24 hours, immediate knee range of motion exercises, early ambulation and partial weight bearing, antiembolism stockings, ankle pumps

performed for 5 minutes every hour the patient is awake, and aspirin (325 mg/twice a day for 10 days).[166] Whether or not this program is efficacious requires further study; however, in our opinion, based on the information available, the program appears to be safe, reasonable, and effective. We obtain a Doppler ultrasound if the patient demonstrates any suspicion of a DVT including abnormal calf tenderness, a positive Homans sign, or increased lower extremity edema. The use of ultrasound to screen for DVT of the lower extremities is used with even the slightest suspicion of calf tenderness and tibial edema or a positive Homans sign.

ILLUSTRATIVE CASES

Case 1: Treatment of Varus Angulation and Severe Articular Cartilage Damage to the Medial Femoral Condyle in a Patient Younger Than 20 Years old

A 19-year-old man presented with a complaint of pain to the medial aspect of his left knee with activities of daily living. He had a 4-year history of osteochondritis dissecans that had been treated elsewhere with internal fixation of the fragment that failed to heal. A subsequent arthroscopic debridement of the medial femoral condylar fragment was performed. Full-length, standing radiographs revealed a mechanical axis of 5 degrees varus and a WBL of 29% of the tibial width (Fig. 26-46, *A*). All ligamentous structures were intact. Medial tibiofemoral compartment narrowing of 50% was evident on posteroanterior 45-degree weight-bearing radiographs.

HTO was indicated to unload the damaged medial tibiofemoral compartment. The arthroscopic examination showed a 20 × 20 mm area of subchondral bone exposure on the medial femoral condyle (see

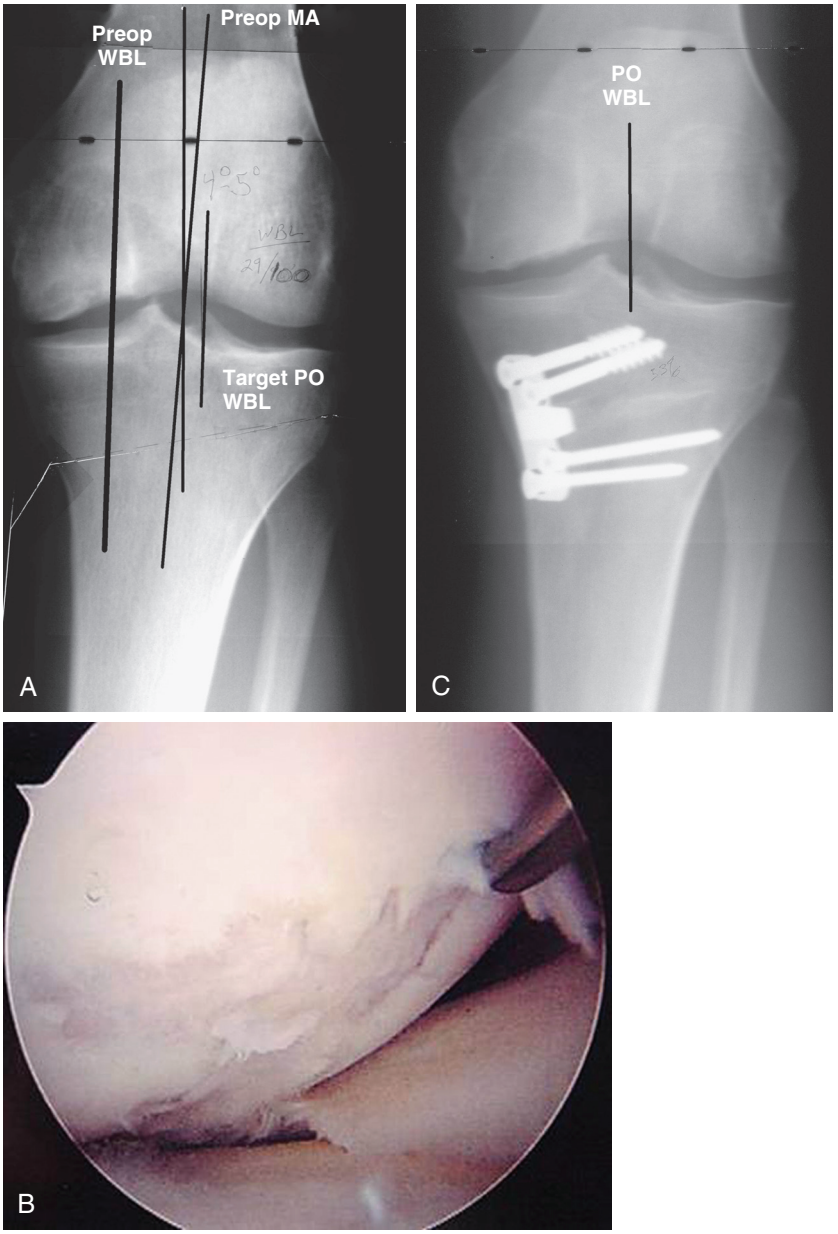


FIG 26-46 Case 1. *MA*, Mechanical axis; *PO,* postoperative; *WBL*, weight-bearing line.

Fig. 26-46, *B*). A biopsy was obtained for a staged autologous chondrocyte implantation, which was done 5 months later. The full standing radiograph showed correction to 62% WBL line (see Fig. 26-46, *C*). At the most recent follow-up evaluation, 7 years postoperative, the patient reported marked improvement in all symptoms with the ability to perform light recreational sports without problems. He rated his overall knee condition as nearly normal. The overall alignment was neutral.

Comments: There is the expectation that a repeat cartilage restorative procedure will be required in this patient. The importance of measuring the correction obtained at surgery with full-length, standing radiographs and close follow up of the patient to determine maintenance of the valgus overcorrection is stressed. Future magnetic resonance imaging including articular cartilage sequences will be obtained. The Puddu plate is historical; locking plate techniques are now used as described.

Case 2: Treatment Options in a Varus-Angulated, Anterior Cruciate Ligament-Deficient, Medial Meniscectomized Knee

A 33-year-old woman presented with moderate to severe medial joint pain and giving way with daily activities. She had a prior medial meniscectomy 15 years ago and a failed ACL allograft reconstruction 8 years ago. The examination showed a positive pivot shift and 15 mm of increased anteroposterior tibial displacement on KT-2000 testing. There was no increase in external tibial rotation, lateral joint opening, or posterior tibial translation. Full-length, standing radiographs revealed a weight-bearing line of 20% of the tibial width (Fig. 26-47, *A*) and early narrowing of the medial tibiofemoral compartment.

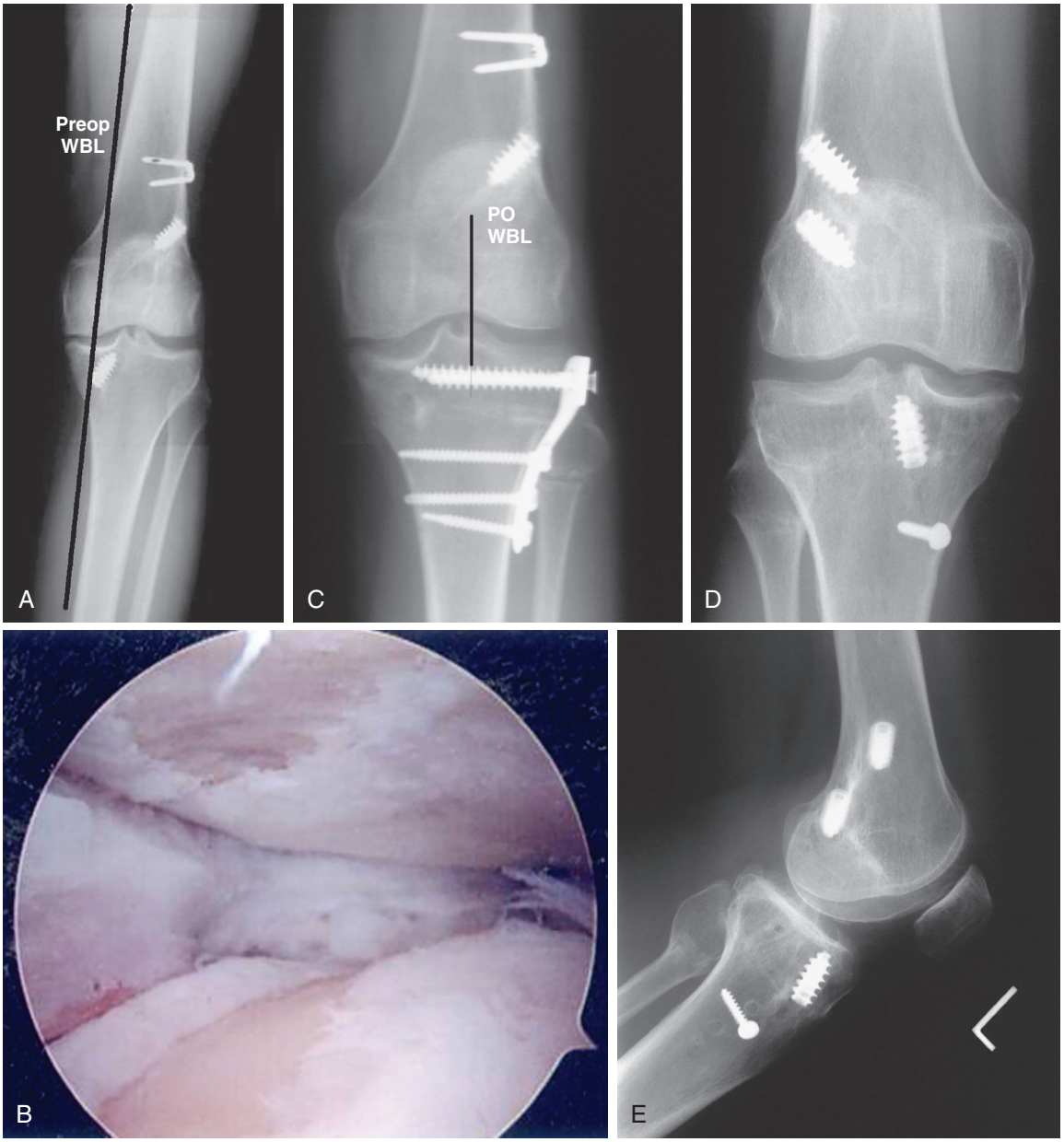


FIG 26-47 Case 2. *WBL*, Weight-bearing line.

Arthroscopy demonstrated subchondral bone exposure on the medial femoral condyle and tibial plateau and an absent medial meniscus (see Fig. 26-47, *B*). The lateral tibiofemoral compartment and lateral meniscus were normal. The lateral gap test showed 10 mm of opening under varus loading at 30 degrees of knee flexion.

A closing wedge osteotomy was performed followed 5 months later with a medial meniscus transplant and osteochondral autograft transfer for the medial femoral condylar defect.

Seven months after the high tibial osteotomy, a revision ACL bone-patellar tendon-bone autograft reconstruction was performed owing to continued instability symptoms. The lateral tibiofemoral compartment gap test was only slightly increased and therefore no posterolateral reconstruction was required.

The most recent follow-up examination, 16.4 years after the osteotomy, showed a valgus alignment of 2 degrees (see Fig. 26-47, *C*), but loss of the medial tibiofemoral compartment joint space. The patient had negative pivot shift and Lachman tests and was able to perform light recreational activities without problems.

Comments: In this case, either an opening or closing wedge osteotomy was indicated. The standing radiograph suggested increased lateral tibiofemoral joint opening (double varus knee), which was confirmed at arthroscopy, contraindicating a concurrent ACL reconstruction. The subsequent ACL revision used a B-PT-B autograft to provide a potentially higher chance of success compared with an allograft (in our opinion). The vertical femoral tunnel was bypassed with an outside-in reorientation of the femoral tunnel (see Fig. 26-47, *D* and *E*). A bone graft of prior tunnels was not required. A tibial graft suture and post is always performed in revision knees for added graft fixation strength.

Case 3: Treatment of a Varus-Angulated, Posterior Cruciate Ligament–Deficient Knee in a High School–Aged Athlete

A 17-year-old male high school athlete sustained a contact injury during football. A complete PCL rupture was verified by physical examination and arthroscopy performed elsewhere. He was referred to our center 3 months later for treatment. He complained of giving-way sensations and mild aching to the medial aspect of his knee with running and cutting activities. The preoperative radiographic evaluation demonstrated a WBL of 21% tibial width (Fig. 26-48, *A*) and 10 mm of increased posterior tibial translation (see Fig. 26-48, *B*). All other ligamentous structures were normal on examination. The patient's goal was to play collegiate football and have the "best knee possible."

The patient was treated with an opening wedge osteotomy followed 3 months later with a two-strand quadriceps tendon–patellar bone autogenous PCL reconstruction with a tibial inlay approach. All articular cartilage surfaces were normal and both menisci were intact.

At 13.6 years postoperative, the patient had a negative posterior drawer test result on physical examination (negative medial tibiofemoral step-off). Anteroposterior radiographs demonstrated 2 degrees of valgus (see Fig. 26-48, *C*), approximately 2 mm of decrease in medial tibiofemoral joint space, and posterior stress radiographs showed 3 mm of increased posterior tibial translation (see Fig. 26-48, *D*). He had no symptoms with strenuous athletics or his occupation as a surgical technician and rated the overall condition of his knee as normal.

Comments: The most controversial aspect of this case was defining the necessity for a corrective osteotomy before the PCL reconstruction. Most varus-aligned knees with an intact medial meniscus and ACL or PCL rupture do not require a staged osteotomy. Concurrent medial meniscus loss with early articular cartilage damage would be the usual indication for corrective osteotomy. However, in this knee, the varus angulation (20% WBL) was judged to be so advanced that operative correction was deemed necessary. In addition, early medial tibiofemoral compartment aching symptoms with activity were present. A second option would be to perform the PCL reconstruction and then follow the patient to define the subsequent need for a high tibial osteotomy.

Case 4: Treatment of Bilateral Varus Malalignment in a Middle-Aged Patient

A 40-year-old woman presented with bilateral varus malalignment and complaints of medial compartment pain with daily activities of many years' duration that had increased in severity over the previous 2 years. She expressed a lifelong difficulty with the visual appearance of her lower extremities. Initial evaluation showed an obvious varus malalignment (Fig. 26-49, *A*). Full-length, standing radiographs showed a WBL of 20% (right) and 13% (left) of the lower extremities. All ligaments were intact and no other abnormality was found.

Opening wedge osteotomies with autogenous iliac crest bone grafting were performed 3 months apart (see Fig. 26-49, *B*). The correction was made to a neutral alignment, avoiding an overcorrection. The medial tibiofemoral compartment showed early articular cartilage fibrillation, but no major damage. The postoperative correction is shown in Figure 26-49, *C*.

The most recent evaluation, conducted 9 years postoperative, showed resolution of medial compartment symptoms in both knees. The patient rated both of her knees as normal and stated she was able to wear shorts without feeling embarrassed for the first time.

Comments: Clinical data on the natural history of severe varus malalignment (WBL < 30%) over a patient's lifetime are insufficient. Clinicians have noted the frequent occurrence of medial joint pain in patients in their 40s and 50s, and degenerative medial meniscus tears are common. High tibial osteotomy is not a cosmetically indicated procedure and this patient did have an early onset of medial joint arthritis symptoms, which responded to the corrective procedure. Locking plate techniques are recommended as described.

Case 5: Treatment of Varus-Angulated, Anterior Cruciate Ligament–Deficient Knee: Simultaneous Osteotomy and Anterior Cruciate Ligament Reconstruction

A 43-year-old athletically active man presented 9 months after a knee injury sustained while playing basketball. The patient had been diagnosed with an ACL rupture and varus osseous malalignment. He wished to resume sports activities, including basketball and coaching soccer. The patient was referred for surgical management. The initial examination revealed a positive pivot shift, 10 mm of increased AP tibial translation on KT-2000 testing, and a WBL of 18% on full standing radiographs (Fig. 26-50, *A*). All other ligament tests were normal.

The patient elected a simultaneous opening wedge osteotomy and ACL reconstruction, which was done with a four-strand STG autograft using a two-incision technique. The menisci were intact, and fissuring and fragmentation (classified as 2-B damage) were noted in the medial tibiofemoral compartment and on the undersurface of the patella.

Intraoperative fluoroscopy during the osteotomy verified an adequate correction of the varus malalignment. The guide pin was placed to allow maximum width to the lateral plateau to avoid fracture (see Fig. 26-50, *B*). The technique of using thin spreader blades was performed to gradually spread the osteotomy site, which was maintained by a calibrated wedge (see Fig. 26-50, *C*). Placement of the osteotomy plate just before iliac crest bone grafting is shown in Figure 26-50, *D*. The high tibial osteotomy healed rapidly with the incorporation of the autogenous bone graft.

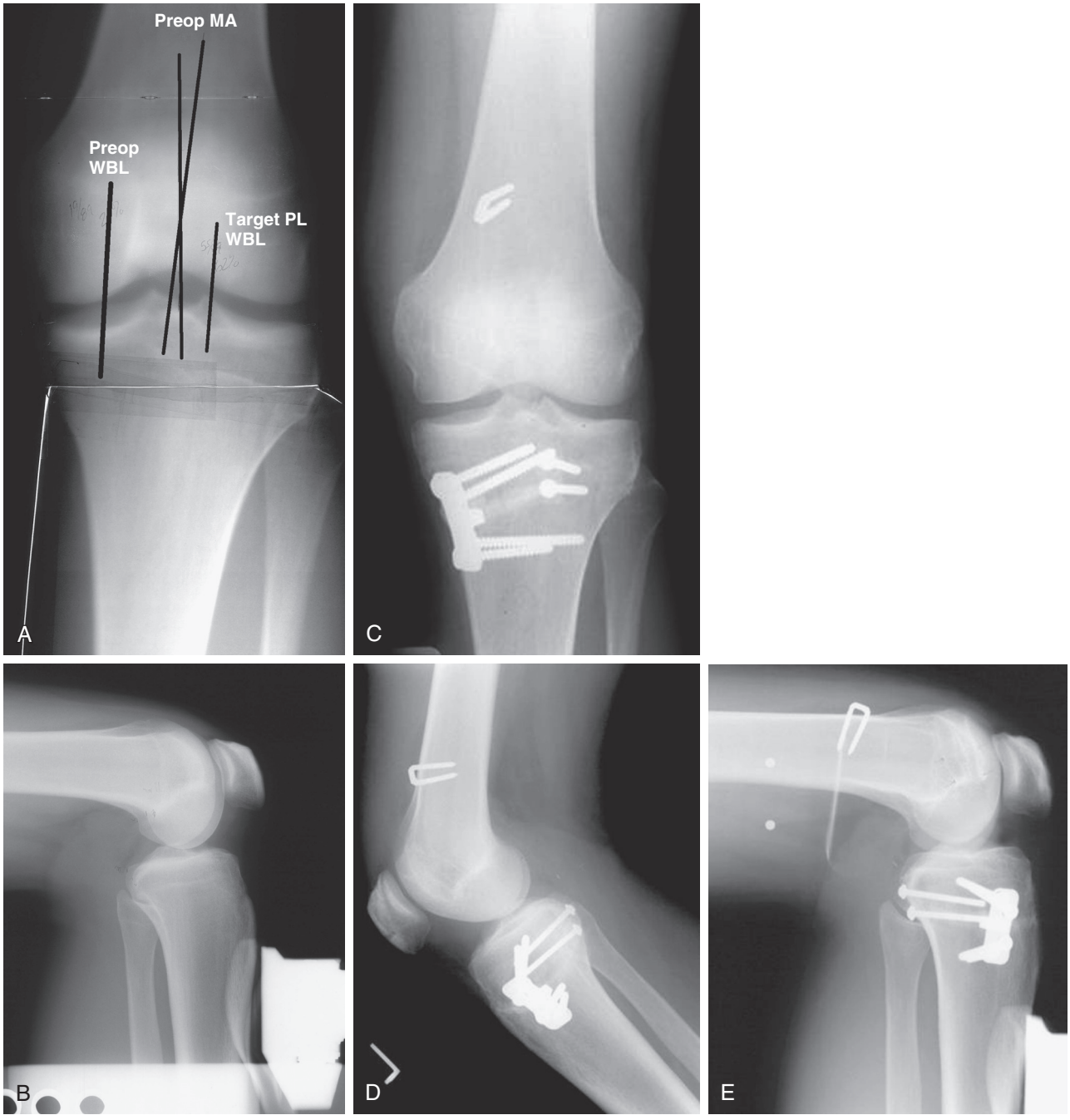


FIG 26-48 Case 3. *MA*, Mechanical axis; *PL*, posterolateral; *WBL*, weight-bearing line.

At the most recent follow up, 7.2 years postoperatively, the patient had no symptoms with recreational sports activities. Full-length, standing radiographs demonstrated a WBL of 52% (see Fig. 26-50, *E*), and KT-2000 examination revealed 4 mm of increased AP tibial translation (25 degrees of flexion, 134 N). He rated the overall condition of his knee as normal.

Comments: The operative fluoroscopy photographs show proper placement of the guide pin and distraction of the opening wedge, which was done gradually to preserve the lateral tibial cortex. Loss of the lateral tibial cortical buttress produces an unstable osteotomy that requires additional fixation such as a locking plate. The four-strand STG graft was anatomically placed at insertion sites using an outside-in technique to achieve a coronal graft with maximum femoral and tibial tunnel lengths. The STG graft fixation was achieved using both a suture post and absorbable interference screws.

Case 6: Treatment of Excessive Valgus Lower Limb Malalignment After Closing Wedge Osteotomy

A 26-year-old woman presented 9 months after a left lateral closing high tibial osteotomy performed for medial joint line pain and early medial tibiofemoral damage. The patient was unable to participate in any athletic activities, had developed hip pain over the past 3 to 4 months, and complained of increasing diffuse knee pain located primarily in the lateral aspect of the knee during standing and walking.

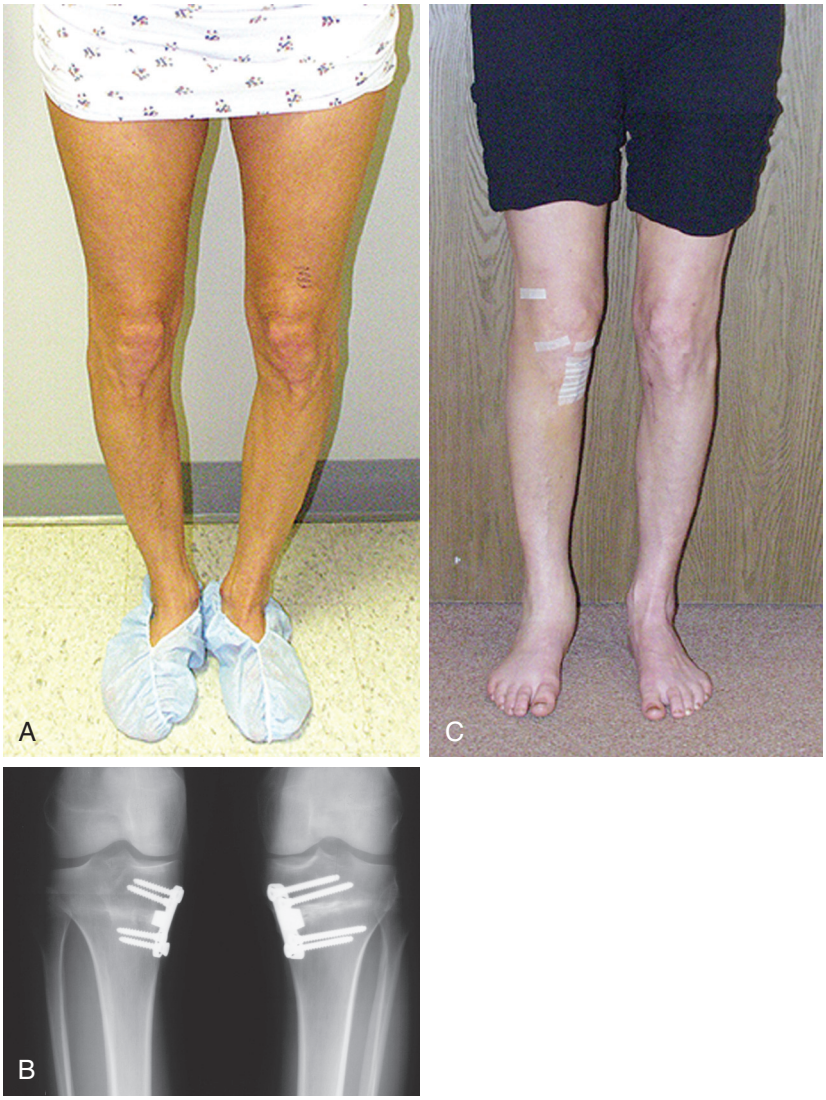


FIG 26-49 Case 4.

She was aware of the abnormal lower limb alignment and highly concerned with the cosmetic appearance (Fig. 26-51, *A*).

On physical examination, the patient ambulated with a marked valgus angulation and valgus thrust. The lower extremity neurovascular exam was normal, and the range of knee motion was 0 to 155 degrees. There was pain on palpation over the lateral joint line. There was no increase in anterior or posterior tibial translation. The patient had 15 degrees of increased external tibial rotation at 30 degrees of flexion but only 5 degrees of increased external tibial rotation at 90 degrees of flexion. Varus stress radiographs showed 10 mm of increased lateral joint opening. Full-length, standing radiographs revealed a healed lateral closing wedge HTO. The coronal joint line was sloped laterally, and the WBL was 80% (see Fig. 26-51, *B*).

Two major problems were identified in this patient. First, a valgus overcorrection was noted, which occurs when the WBL is more than 70% of the tibial width. A WBL of 62% normally represents an approximate 2 to 3 degrees of overcorrection. The overcorrection of the HTO in this patient was 6 degrees mechanical axis (80% WBL), which resulted in a cosmetically unacceptable appearance. This amount of overcorrection frequently results in arthritis of the lateral tibiofemoral compartment. To avoid this error, the degrees of correction of the WBL must be measured on full-length, standing double-stance radiographs, as described in this chapter. Single-stance radiographs allow abnormal lateral joint opening to occur, which must then be subtracted in the calculation for the true degrees of tibial correction required. In addition, the lower limb alignment must be verified at surgery and early postoperatively.

If an abnormal valgus alignment is detected, it can be easily corrected within the first 4 weeks postoperatively by readjusting the osteotomy gap. In this patient, osseous healing had already occurred, and the revision procedure was therefore more difficult.

The second problem was that a fibular osteotomy (either at the fibular neck or distal third region) had not been performed. The proximal tibiofibular joint was disrupted, which allowed the fibula to slide proximally. The abnormal fibular position produced laxity of the FCL and other posterolateral structures that attached to the proximal fibula. The operative plan was to restore the normal tibiofibular relationship to retension the posterolateral structures. The patient was warned that if the tibiofibular joint was destroyed, a tibiofibular fusion would be required, placing the fibula into a normal tibial relationship to restore

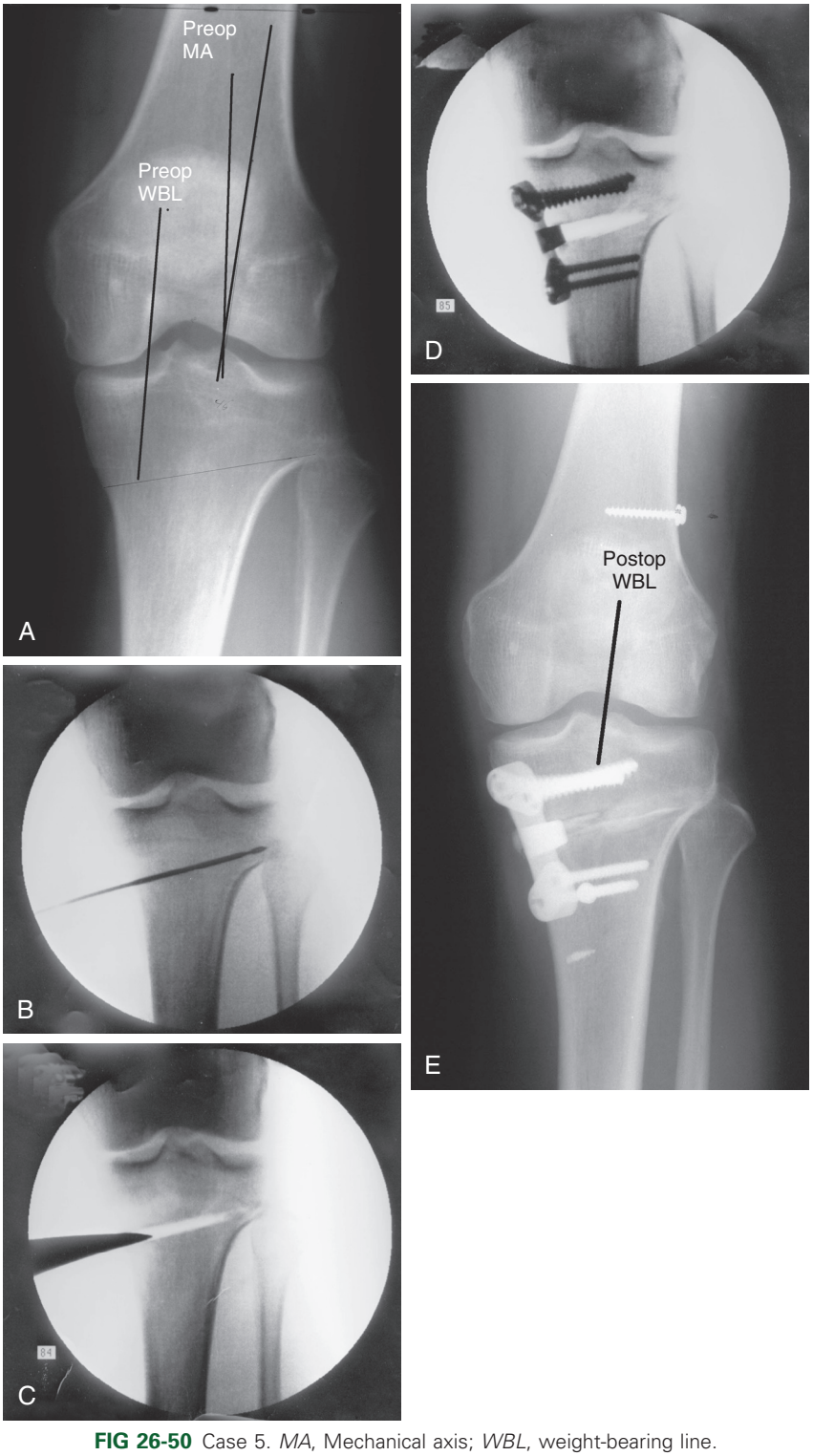


FIG 26-50 Case 5. *MA*, Mechanical axis; *WBL*, weight-bearing line.

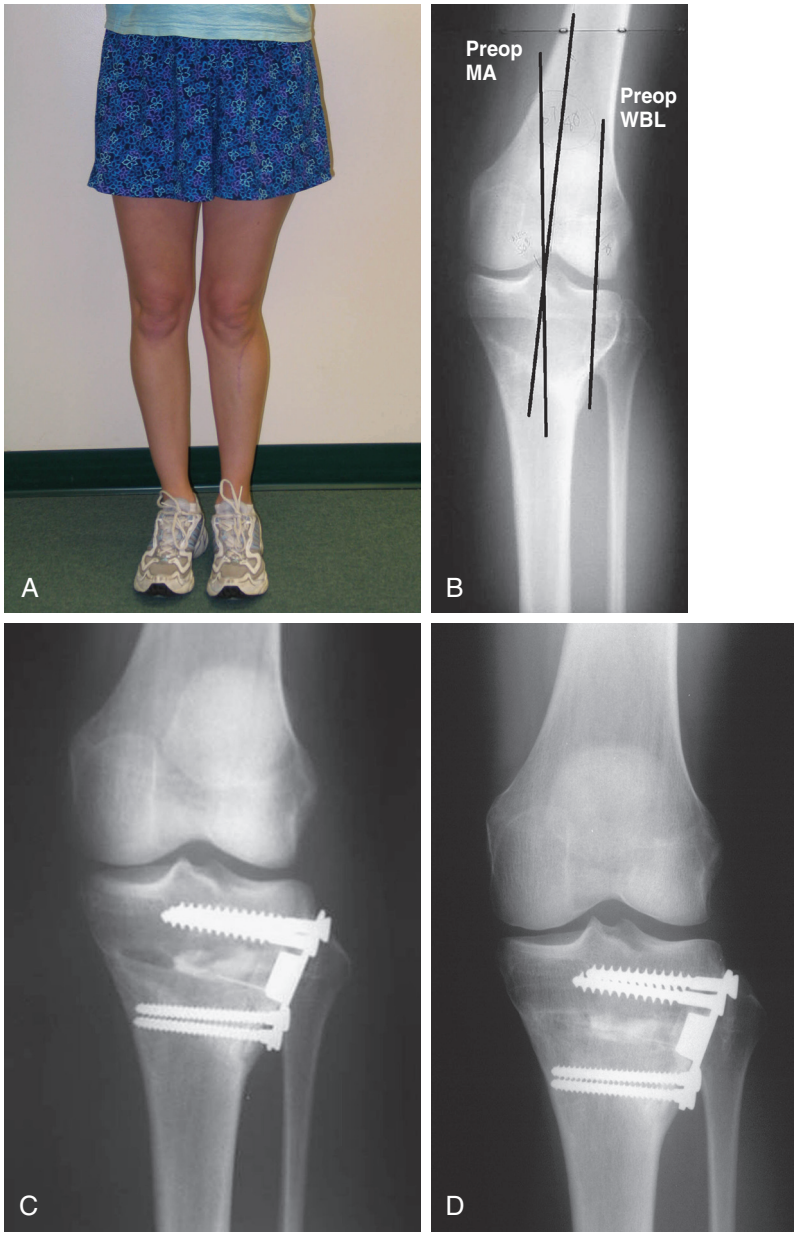


FIG 26-51 Case 6. *MA*, Mechanical axis; *WBL*, weight-bearing line.

the proper length-tension relationship of the native or reconstructed posterolateral structures.

The patient was treated with a revision opening wedge osteotomy. During surgery, the proximal tibiofibular joint and attached ligaments were carefully dissected after the common peroneal nerve was identified and protected. An opening wedge osteotomy was performed, preserving the medial tibial buttress. Careful distraction of the osteotomy with spacer plates that spanned the length of the osteotomy was performed to prevent fracture of the tibial plateau, which was osteopenic from the prior surgery. The fibula was gradually relocated to a normal position relative to the tibia. In other revision cases, the senior author has used two proximal tibiofibular 4.0 cancellous screws to provide temporary stabilization of the joint; however, this was not required. An autogenous iliac crest bone graft was used and healing successfully occurred.

Immediately postoperative, radiographs demonstrated correction of the abnormal valgus alignment and a normal tibiofibular position (see Fig. 26-51, *C*). The position was maintained at the most recent evaluation, 16 months postoperative (see Fig. 26-51, *D*).There was no increase in lateral joint opening or external tibial rotation with functional posterolateral ligament structures. The correction has been maintained over the years. Locking plate techniques are recommended as described.

Case 7: Treatment of Failed Internal Fixation After Opening Wedge Osteotomy

A 41-year-old man presented complaining of pain to the medial aspect of his right knee joint. He had previously undergone a partial medial meniscectomy, chondroplasty, and microfracture of the medial femoral condyle. The patient was employed as an automobile mechanic and had discomfort with squatting and kneeling.

On physical examination, the patient had an obvious varus malalignment and walked with a mild varus thrust. He had mild lateral joint line pain, moderate patellofemoral crepitus, and moderate

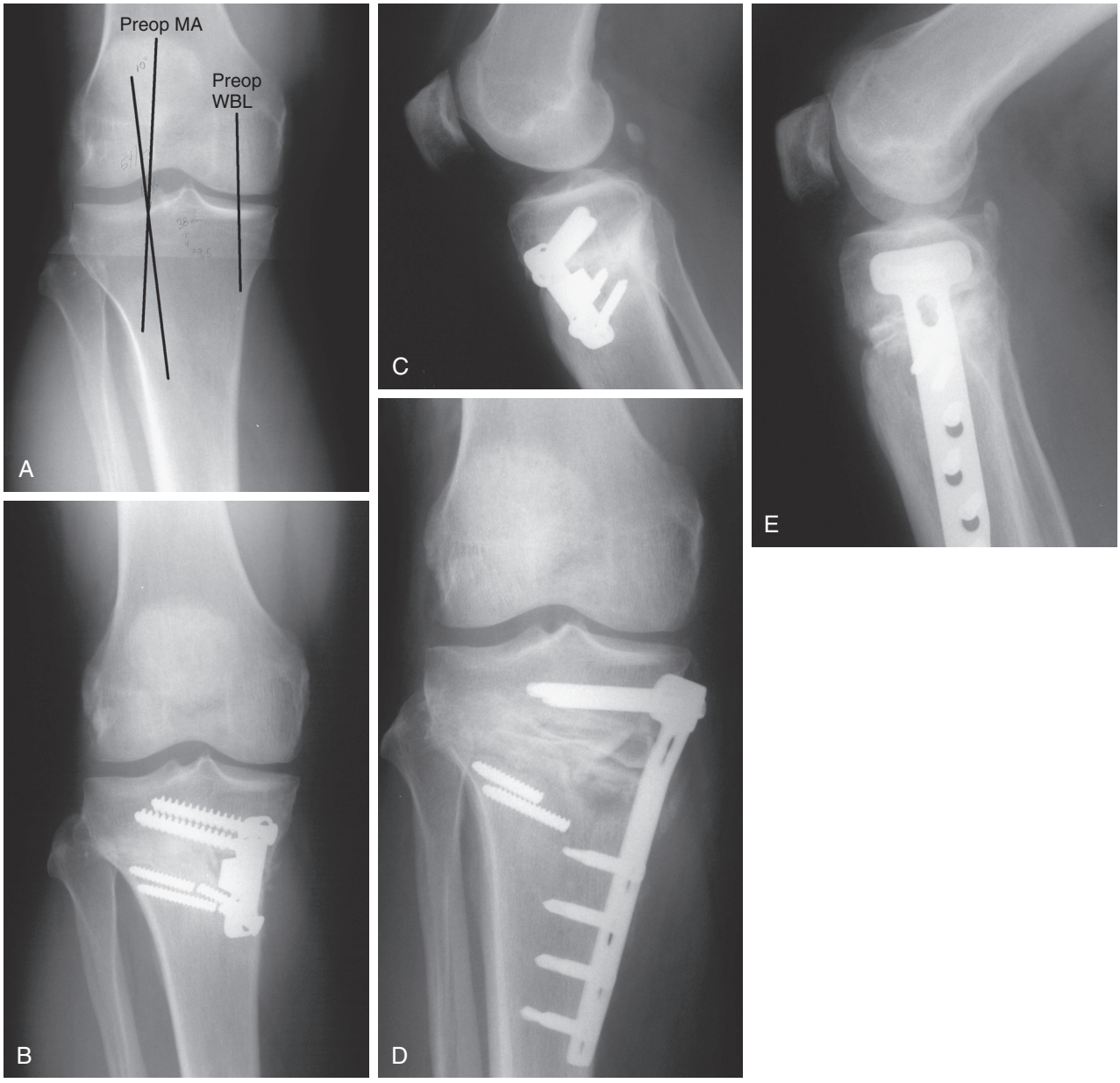


FIG 26-52 Case 7. *MA*, Mechanical axis; *WBL*, weight-bearing line.

patellar pain on compression. The ligament examination was normal. Radiographs demonstrated a WBL of 20% (Fig. 26-52, *A*) and preserved medial tibiofemoral joint space. Magnetic resonance imaging revealed a posterior horn medial meniscus tear and articular cartilage damage to the trochlea.

The patient underwent an opening wedge osteotomy with autogenous iliac crest bone graft and internal fixation with a Puddu plate. A 62% WBL was confirmed intraoperatively.

The initial postoperative course was normal with initial radiographs showing correction of the malalignment. However, at 5 months postoperative, the patient complained of a new onset of pain in the region of the anteromedial tibial osteotomy. Radiographs demonstrated nonunion of the osteotomy site and two broken distal screws with loss of the valgus alignment correction (see Fig. 26-52, *B* and *C*). The patient underwent a revision osteotomy with a locking plate (see Fig. 26-52, *D* and *E*), which successfully corrected the malalignment. The tibial slope was maintained, and the mechanical axis postoperatively was 2 degrees valgus. The osteotomy healed without problems.

Comments: This case demonstrates the potential inherent weakness of the Puddu plate. If there is any delay in healing after opening wedge osteotomy, even with autogenous bone grafting, early failure can be expected and revision indicated. A locking plate, which became available during the treatment of this patient, provides a more stable construct and is now our preference.

Case 8: Treatment of a Varus-Angulated Knee Following Failed Multiple Ligament Procedures

A 27-year-old man presented after a knee dislocation from an industrial accident, which had been treated with an ACL

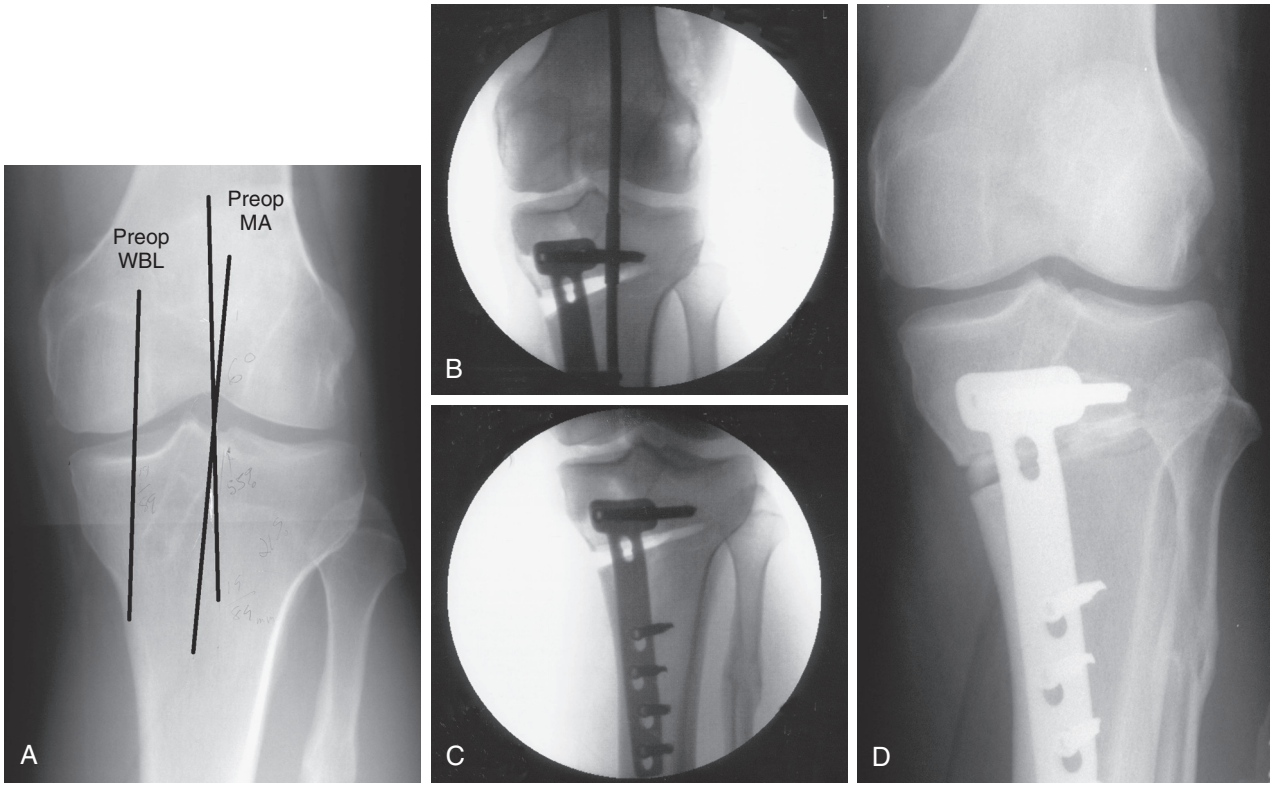


FIG 26-53 Case 8. *MA*, Mechanical axis; *WBL*, weight-bearing line.

semitendinosus-gracilis reconstruction and medial collateral ligament primary repair. The patient complained of medial tibiofemoral compartment pain and instability with daily activities.

On physical examination, the patient demonstrated varus malalignment and a varus thrust on ambulation. There were a mild effusion and a normal range of motion. A positive pivot shift was elicited indicating failure of the ACL reconstruction. In addition, an increase of 8 mm in lateral tibiofemoral opening was noted. Radiographs revealed a WBL of 20% and mild medial tibiofemoral joint space narrowing (Fig. 26-53, *A*). Posterior stress radiographs demonstrated 7 mm of increased posterior tibial translation compared with the contralateral limb, indicating partial posterior cruciate ligament deficiency.

The patient was treated with an opening wedge osteotomy with an autogenous iliac crest bone graft and a locking plate for secure fixation; fluoroscopy confirmed correction of the WBL at 62% (see Fig. 26-53, *B* to *D*). Six months later, a revision ACL reconstruction was performed using the contralateral patellar tendon autograft. The lateral tibiofemoral gap at surgery was 5 mm, and therefore no posterolateral reconstruction was required.

At the latest follow-up evaluation, 6.5 years postoperative, the patient had a valgus alignment of 2 degrees (see Fig. 26-53, *E*) and was satisfied with the overall condition of his knee.

Comments: With large angular corrections, we prefer to stage osteotomy and ACL revision reconstructive procedures. Staging the procedures ensures that the osteotomy correction will be maintained postoperatively and reduces the risk of complications, especially arthrofibrosis. In addition, adaptive shortening of the fibular collateral ligament and posterolateral structures occurred, avoiding a posterolateral reconstructive procedure.

Case 9: Treatment of Severe Bilateral Varus Malalignment

A 44-year-old male teacher presented with complaints of bilateral medial compartment pain of 16 months' duration. He had pain at rest, with walking tolerance of only 1 minute. He had undergone multiple cortisone injections of both knees and had also tried an unloading brace on the left knee, which made the pain worse. Physical examination revealed a full range of motion in both knees, severe bilateral medial joint line pain, no patellofemoral symptoms, intact ligaments, and a bilateral varus thrust on ambulation. Radiographs demonstrated severe medial tibiofemoral compartment narrowing in both the right (Fig. 26-54, *A*) and left (see Fig. 26-54, *B*) knees. Marked varus malalignment was present bilaterally.

Although another surgeon recommended an HTO, the patient was advised that the loss of joint space was too severe for an HTO to be effective. The patient underwent bilateral unicompartmental knee replacement, first in the left knee (see Fig. 26-54, *C*) and then 3 months later in the right knee (see Fig. 26-54, *D*). The patient recovered uneventfully from both procedures.

Case 10: Treatment of a Valgus-Angulated Knee After Lateral Meniscus Transplantation

An elite female gymnast initially presented to our center at age 16 years with complaints of aching pain in the posterior and lateral aspect of her left knee. She denied any specific episode of trauma. Arthroscopy and partial lateral meniscectomy were performed. The patient continued with high-level training for Olympic gymnastics competition, and subsequently, her symptoms of pain and swelling became worse, requiring repeat arthroscopy. Grade III changes were noted on the weight-bearing surface of the lateral femoral condyle (Fig. 26-55, *A*).

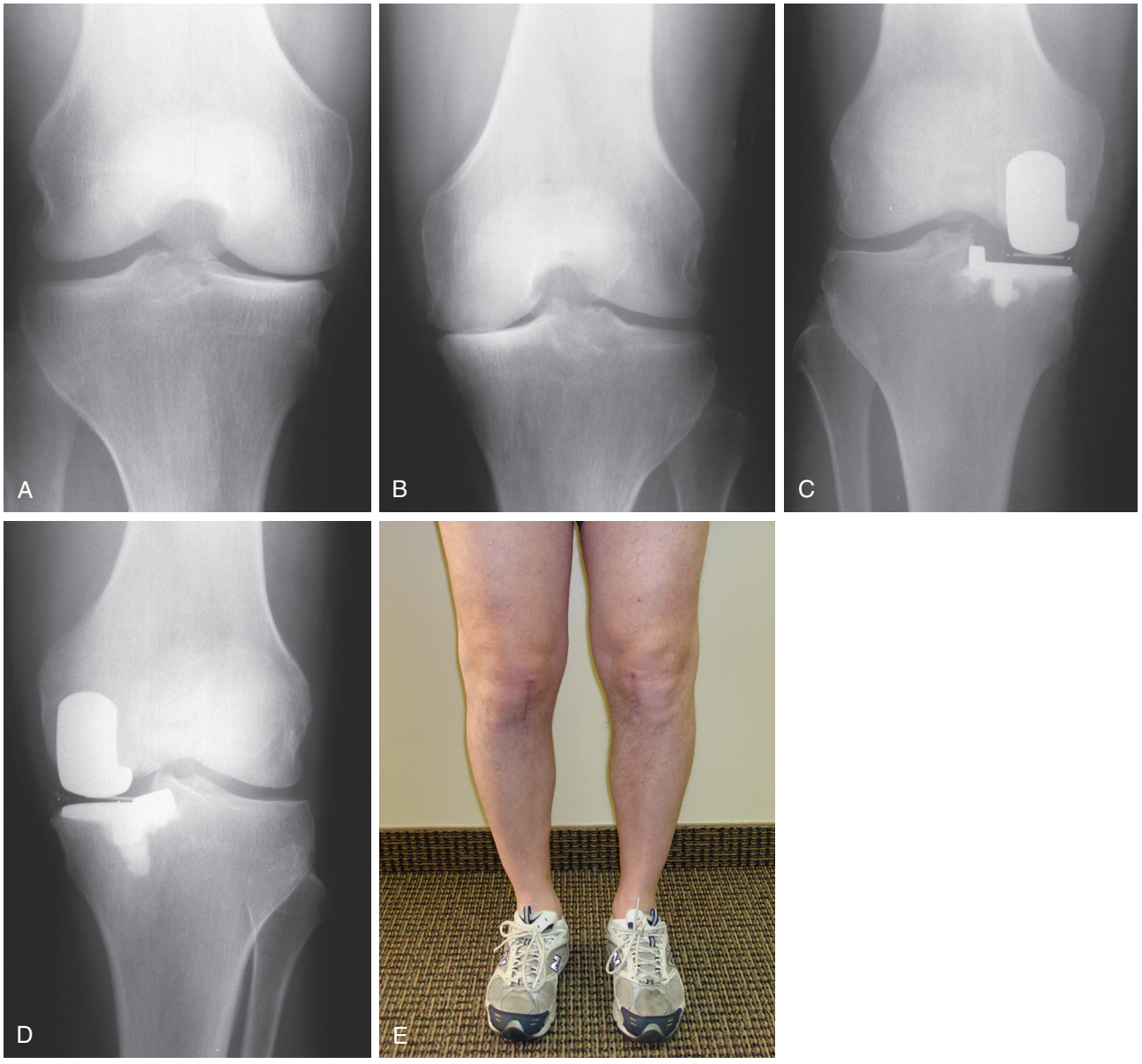


FIG 26-54 Case 9.

Two years later, physical examination demonstrated a mild increase in the valgus alignment (58%). Standing radiographs, at 30 degrees of knee flexion, demonstrated narrowing of approximately 50% joint width. The patient had tenderness to the lateral tibiofemoral compartment and mild swelling in the joint. She elected to have a lateral meniscus transplant and osteochondral autograft transfer procedure.

The patient did well for 7 years after the lateral meniscus transplant and osteochondral plug procedure. She returned with chief complaints of pain, catching, and swelling in the knee. Over the course of treatment, it had been noted that the patient had a progression of symptoms in the lateral compartment, as well as an increase in valgus malalignment. Physical examination revealed obvious valgus alignment present of the left lower extremity, full range of motion, no joint effusion, no ligamentous instability, and no crepitus to the lateral compartment. Standing 45 degrees posteroanterior radiographs demonstrated 50% narrowing of the lateral compartment. Full-length, standing radiographs demonstrated a 5 degrees valgus mechanical axis and a 65% WBL (see Fig. 26-55, *B*).

The patient underwent an opening wedge femoral osteotomy with an autogenous iliac crest graft (see Fig. 26-55, *C*) which obtained a correction to a 45% WBL. Postoperative radiographs show the correction of the valgus alignment and healing of the osteotomy site (see Fig. 26-55, *D*).

Case 11: Treatment of Valgus Malalignment in a Young Patient with Pain with Activities of Daily Living

A 20-year-old woman presented with a chief complaint of lateral knee pain with activities of daily living and anterior knee pain when ascending stairs. She had a total lateral meniscectomy 5 years previously. Prior arthroscopy demonstrated moderate articular cartilage damage to the lateral tibiofemoral joint. She had given up running and squatting activities as a result of the pain in her knee.

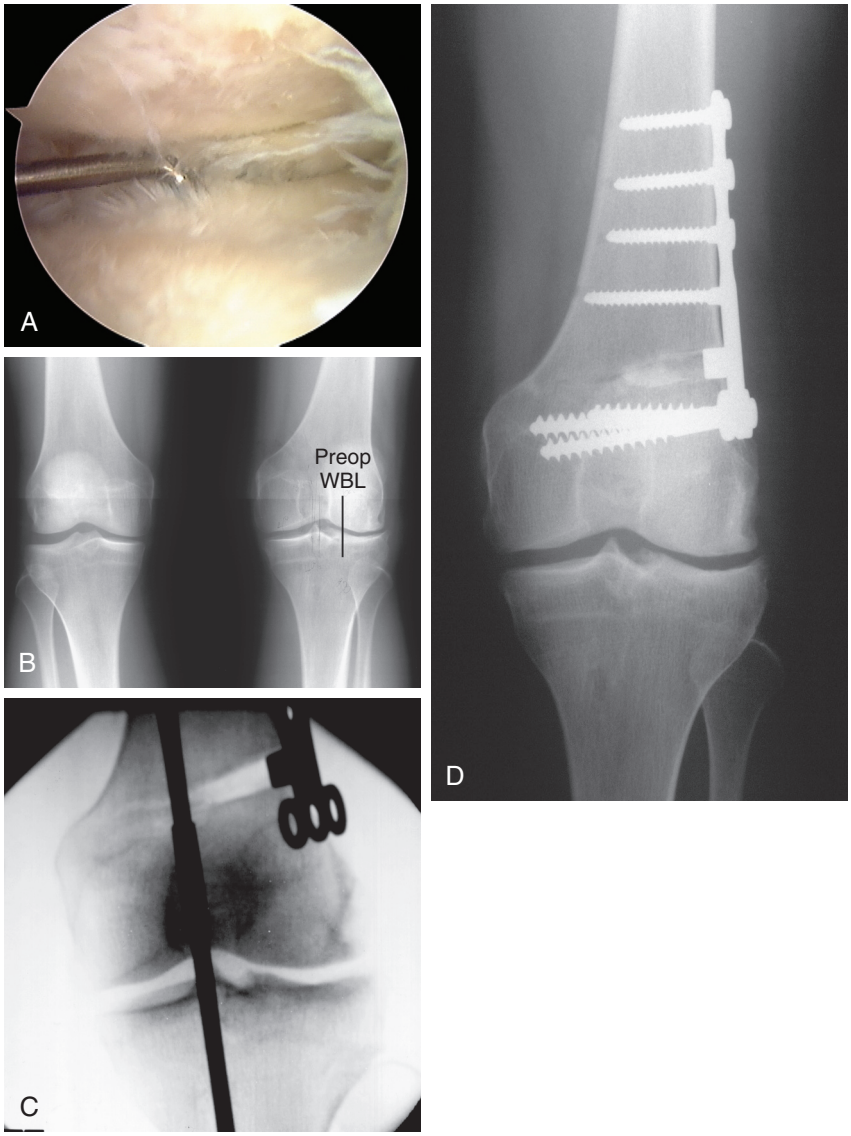


FIG 26-55 Case 10. *WBL,* Weight-bearing line.

Physical examination demonstrated a mild effusion, a standing valgus position of the lower extremity, and a valgus thrust on walking. The patient had normal ligamentous stability. Standing 45 degrees posteroanterior radiographs demonstrated 50% joint narrowing. Full-length, standing views showed a WBL of 71% and a mechanical axis of 4 degrees valgus (Fig. 26-56, *A*).

The patient underwent an opening wedge femoral osteotomy for correction of the valgus malalignment. A locking plate with screws was used with an iliac crest autogenous bone graft (Fig. 26-56, *B*). Postoperative radiographs show a correction to 45% WBL (see Fig. 26-56, *C* and *D*).

Case 12: Staged Femoral Osteotomy, Meniscus Transplantation, and Autologous Chondrocyte Implantation

A 23-year-old woman presented 8 years after an ACL reconstruction, lateral meniscus transplant (LMT), and autologous chondrocyte implantation (ACI) that had been done on the lateral femoral condyle. The ACL graft was intact and functional. However, two subsequent arthroscopic debridement procedures had been done in which the LMT had been removed. Posteroanterior radiographs showed 50% joint narrowing of the lateral tibiofemoral compartment and a marked valgus malalignment, with a WBL of 70% (Fig. 26-57, *A*). The patient had lateral tibiofemoral compartment knee pain with walking, knee stiffness, difficulty with stair-climbing and squatting, and was unable to participate in any recreational sports activities.

The patients underwent an opening wedge distal femoral osteotomy and autogenous bone graft from the iliac crest that was secured with a Tomofix locking plate and screws. At arthroscopy, grade 3-A (bone exposed, 20 × 20 mm) articular cartilage degeneration was found on the prior site of the ACI on the weight-bearing portion of the lateral femoral condyle (Fig. 26-57, *B*). The medial meniscus and articular cartilage in the medial compartment were intact. Eight months later, a revision LMT and ACI to the lateral femoral condyle were performed (Fig. 26-57, *C* and *D*). The osteotomy healed without complications, with the new WBL established at 45% of the tibial width. She is ambulatory and has no pain in the lateral tibiofemoral compartment and has been advised not to participate in any strenuous sports owing to the arthritis that has occurred. The goal of the procedure was to buy 10 years, at which time a unicompartmental knee replacement would be performed.

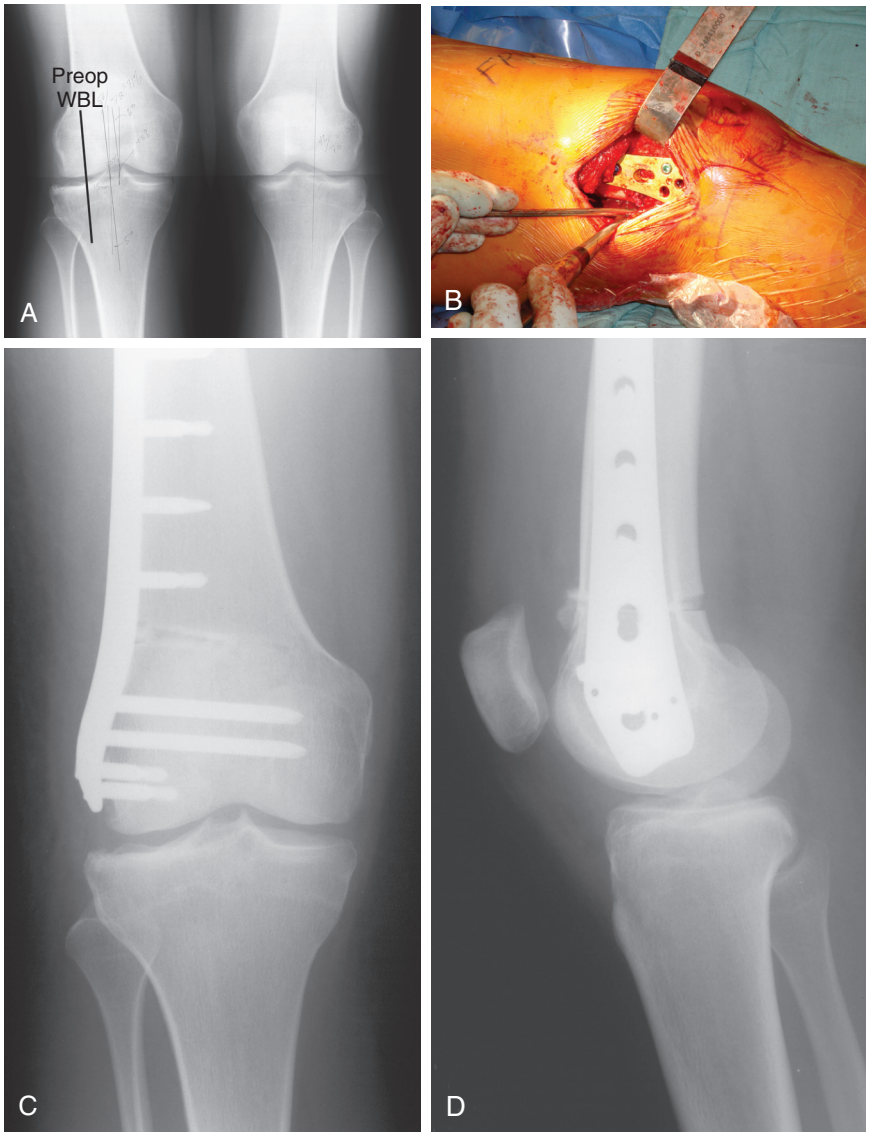


FIG 26-56 Case 11. *WBL*, Weight-bearing line.

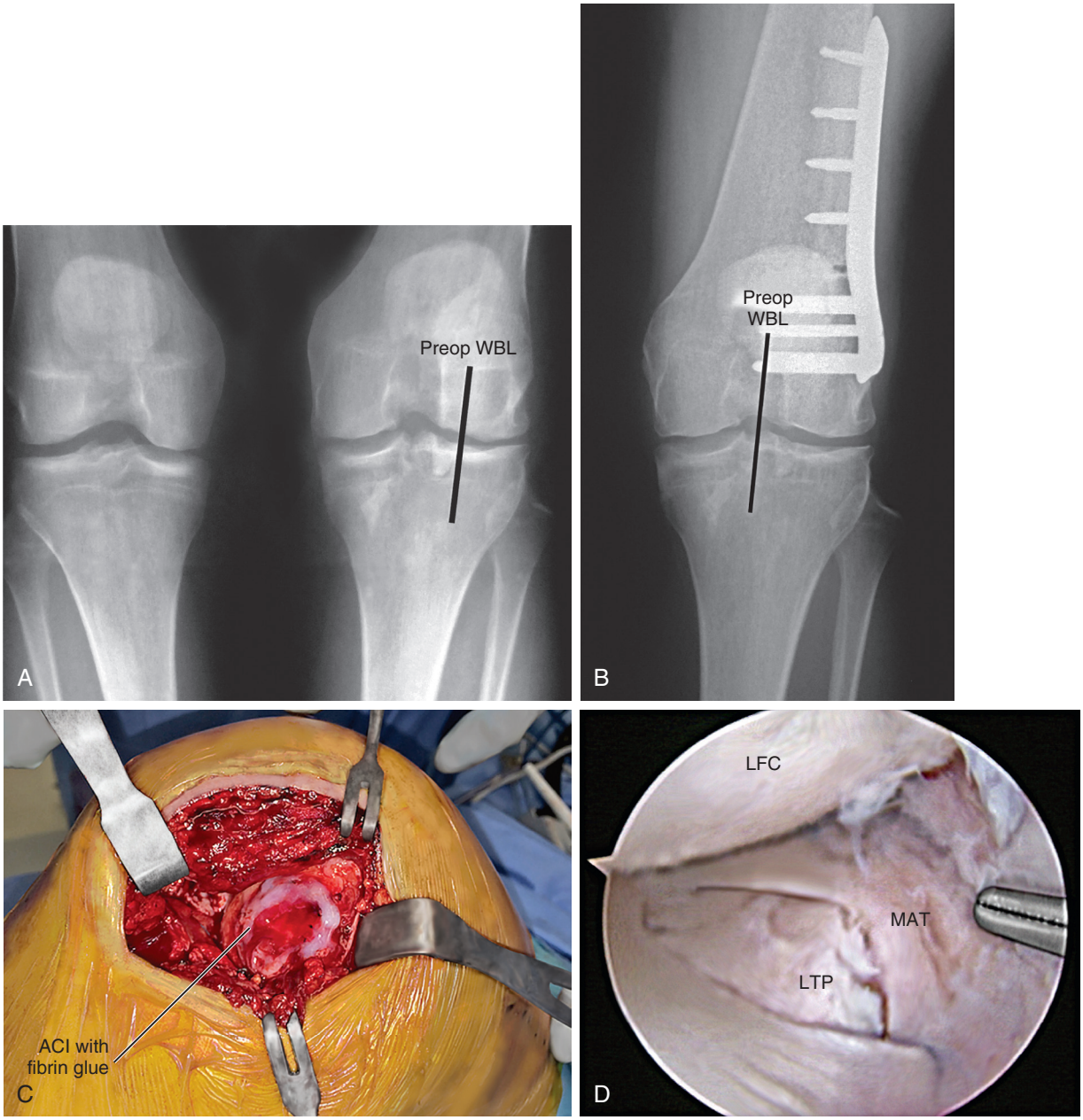


FIG 26-57 Case 12. *ACI*, Autologous chondrocyte implantation; *LFC*, lateral femoral condyle; *LTP*, lateral tibial plateau; *MAT*, meniscal allograft transplantation; *WBL*, Weight-bearing line.

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Video Content

Video 26-1
Video 26-2
Video 26-3

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27

Valgus Malalignment: Diagnosis, Osteotomy Techniques, and Clinical Outcomes

Simon Görtz, Guilherme C. Gracitelli, William D. Bugbee

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INTRODUCTION

The use of osteotomies has decreased, particularly in North America, caused by the advent of more reliable and predictable arthroplasty solutions for younger and middle-aged patients with knee arthrosis. However, interest in osteotomy has recently undergone resurgence with the advent of cartilage repair procedures, increased understanding of multiligament knee instability in the context of malalignment, and loss of meniscal tissue and function.

Fewer reports have been published regarding osteotomy for valgus knee arthrosis when compared with varus knee arthrosis. Opening-wedge osteotomy on the medial tibial side has been well established as the procedure of choice for varus deformity malalignment.[10] The majority of studies on femoral osteotomy have focused on medial closing-wedge procedures, and survivorship rates have varied from 64% to 87%.[2,9,21,24] Small case series have reported lateral opening-wedge distal femoral osteotomy survivorship rates of 82% at 7 years and 91% at 8 years.[14,25] Overall, these studies had statistically significant improvements in the functional outcomes.[6,14,23,25]

Osteotomy is a biologic treatment alternative for unicompartmental disease for patients in whom total knee replacement (TKR) is undesirable owing to age, life expectancy, or activity level, which would be considered inappropriate for prosthetic replacement. In this patient population, distal femoral osteotomy (DFO) can be an appropriate joint-preserving solution that relies on the redistribution of forces in the knee joint away from a mechanically overloaded, and thus symptomatic, lateral tibiofemoral compartment. In general, opening-wedge techniques allow a smaller approach and a reliable deformity correction and have gained popularity lately to adequately address cases of dysplastic lateral femoral condyles in valgus knees as well as medial tibial plateau defects in varus gonarthrosis.

INDICATIONS

Despite less predictable pain relief and relatively inferior long-term results compared with TKR, joint-preserving osteotomy is an appealing, yet reluctant, choice for high-demand patients with increased life expectancies and reservations about prosthetic replacement. The main indication for DFO is the correction of frontal plane deformities, especially in valgus knees with lateral compartment arthrosis, posttraumatic arthrosis, and in valgus knees eligible for lateral cartilage repairs and meniscal transplantation.[9,22] A second indication is to correct malalignment associated with medial ligamentous insufficiency, such as in valgus knees with *valgus thrust* or to unload any ligament reconstruction.[19] A less common and reliable indication is the correction of maltracking patella caused by excessive valgus deformity.[12] This chapter focuses on the main indication of DFO.

The DFO procedure has gained significance as part of a joint-preserving treatment for less advanced cartilage or meniscal disease of the lateral compartment. At our institution, osteotomy has also been used increasingly to unload and optimize the biologic environment of a compartment undergoing osteochondral or meniscal transplantation. Therefore different groups of patients with valgus limb malalignment may benefit from the procedure.

Primary osteotomy to correct malalignment will alleviate symptoms by reducing stresses on the articular cartilage and the underlying subchondral bone. Secondary osteotomy, adjunct to resurfacing procedures addressing osteoarticular lesions resulting from a pathologic biomechanic environment, protects the resultant repair tissue by correcting the underlying condition that contributed to the original lesion.

According to the International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) guidelines on the management of osteoarthritis of the knee before TKR[20], the ideal patient for DFO has isolated lateral compartment symptoms, ages 40 to 60 years, body mass index (BMI) less than 30, nonsmoker, high-demand activity but no running or jumping, alignment of less than 15 degrees valgus deformity in the distal femur, range of motion (ROM) with less than 10 degrees of extension loss, more than 90 degrees of flexion, normal medial and patellofemoral compartments, normal ligament balance, and no notch osteophytes. Although some have

CRITICAL POINTS Indications for Distal Femoral Osteotomy

- Valgus limb malalignment in a knee with symptomatic lateral compartment arthrosis in young and active patients
- Joint preservation in less advanced cartilage or meniscal disease of the lateral compartment
- Ancillary procedure to osteochondral repair or meniscal transplantation procedures

CRITICAL POINTS Contraindications

- Symptomatic medial or patellofemoral compartment arthrosis
- Gross ligamentous instability
- Inflammatory arthrosis including advanced crystal-induced arthropathy
- Metabolic bone disorders
- Severe angular deformity
- Limited knee ROM (>15 degree flexion contracture or <90 degrees of flexion)
- Poor motivation or rehabilitation potential

considered men to be better candidates for osteotomy than women, we have not found a correlation between gender and outcome.

Because of the generally good clinical results and survivorship of TKR, the threshold for considering osteotomy over arthroplasty is typically patients ages 65 and younger. Older, physically active patients may be candidates for DFO if they are expected to return to an activity level that would be inappropriate for TKR. Young, active patients (<50 years) are better candidates for joint-preserving osteotomy owing to the absence of implant-related activity restrictions despite the relatively inferior long-term results compared with TKA. In these individuals, the osteotomy should be considered a temporizing procedure amenable to possible future conversion to TKR. The 50- to 65-year-old group presents a unique challenge in determining whether or not osteotomy is the most appropriate treatment choice. Finally, young patients (<40 years) with even small amounts of valgus limb malalignment should be carefully evaluated for osteotomy when there is symptomatic loss of lateral compartment chondral or meniscal tissue. In this setting, it may be reasonable to consider (though not proven) that the osteotomy may delay the progression to more advanced arthrosis. When cartilage or meniscal restoration is performed in the lateral compartment, the adjunctive use of DFO may help protect the reconstruction as well.

CONTRAINDICATIONS

Absolute contraindications to DFO include the presence of symptomatic medial compartment arthrosis, inflammatory arthrosis including advanced crystal-induced arthropathy, and metabolic bone disorders that would significantly interfere with osseous healing of the osteotomy. Conversely, neuromuscular disorders are not a contraindication because the osteotomy may be a more reasonable and durable operation than TKR in this setting.

Relative contraindications include severe angular deformity (consideration in these cases should be given to a double osteotomy of the distal femur and proximal tibia), limited knee ROM (>15 degree flexion contracture or <90 degrees of flexion), poor motivation, or poor rehabilitation potential. Although excessive BMI has not been proven to be a contraindication, it may be assumed that the well-described orthopedic surgical risk factors associated with obesity also apply to osteotomy, and some surgeons consider a BMI greater than 30 a relative contraindication. Rehabilitation issues of concern include the inability to follow postoperative weight-bearing restrictions and the use of drugs or substances such as nicotine that may interfere with bone healing. The extent of lateral joint arthrosis (as defined by the amount of cartilage loss on the femoral and tibial surfaces) has not, to our knowledge, been shown to have a demonstrable effect on outcome, barring frank end-stage arthrosis. Therefore we do not use the amount of radiographic or clinical joint space loss as a criterion or contraindication. The presence of patellofemoral arthrosis as a relative contraindication is controversial. Some studies have shown that arthrosis of the patellofemoral joint has no bearing on the outcome, but others have even shown improvement in patellofemoral symptoms with DFO.[14]

CLINICAL BIOMECHANICS

The *weight-bearing line* (WBL) of the lower extremity is defined as the line drawn from the center of the femoral head through the center of the ankle mortise. Depending on where this line crosses the knee joint, overall limb alignment is considered varus (medial to the center of the knee), valgus (lateral to the center of the knee), or neutral relative to the center of the knee. Based on morphologic studies of normal subjects with neutral overall alignment, Hsu and coworkers[13] determined that 75% of weight-bearing forces are transmitted through the medial compartment of the knee in a one-legged simulated weight-bearing stance. Other studies have determined that 60% of the load is passed through the medial compartment during weight bearing.[1,16] Alterations in the overall alignment will change these forces and create an unfavorable mechanical environment, potentially leading to injury and degeneration of the overstressed compartment that may be stopped or slowed by timely correction of the malalignment.[18]

With a valgus deformity, the mechanical axis passes through (or lateral to) the lateral compartment of the knee, thus overburdening that compartment and leading to pain and development of arthritis. Additional pathologic features of the valgus knee include progressive posterolateral soft tissue contractures including the iliotibial band, popliteus, lateral collateral ligament, posterolateral capsule, lateral head of the gastrocnemius, lateral intermuscular septum, and long head of the biceps. In addition, these contractures may lead to attenuation of the medial collateral ligament and medial capsular laxity.

Osseous deformities should be understood in the context of "normal" anatomy and "physiologic" valgus. Kapandji[14a] illustrated that the average distal femoral angle is 7 to 9 degrees of valgus, and the average proximal tibial angle is 0 to 3 degrees of varus, producing the overall tibiofemoral angle of 5 to 7 degrees of valgus, which, after accounting for hip offset, leads to a mechanical limb axis through the center of the knee. Osseous deformities in the valgus knee are usually limited to the lateral femoral condyle, which is typically hypoplastic, thus leading to excessive distal femoral valgus. Conversely, the lateral tibial plateau is usually well preserved, except in the case of fracture.

The important distinction is that for the majority of valgus knees, the deformity lies in the distal femur and not in the tibia. In some cases, this excessive distal femoral valgus may be minimal, but in other more severe cases, the distal femoral angle can be around 15 to 20 degrees of valgus. Although the exact prevalence of valgus deformity of the knee is unknown, it is generally considered less common than varus deformity about the knee. Cooke and associates[3] examined full-length

CRITICAL POINTS Common Characteristics of the Valgus Knee

- Mechanical axis passes through (or lateral to) the lateral compartment of the knee
- Posterolateral soft-tissue contractures
- Medial collateral ligament and medial capsular laxity
- Osseous deformities of the distal lateral femoral condyle, usually hypoplastic lateral femoral condyle

radiographs of 167 white patients with osteoarthritis. Valgus alignment was seen in 24% and varus in 76%. In addition, valgus deformity has been noted to be more common in females, patients with inflammatory arthritis, and posttraumatic arthritis, as well as those with metabolic abnormalities such as rickets or renal osteodystrophy.

The rationale of the DFO is to correct the excessive tibiofemoral valgus by shifting the mechanical axis line from the lateral compartment to a more median or even medial position. Historically, this correction has been performed both above and below the level of the joint line. Initial reports of correction of painful valgus deformity described a proximal tibial varus-producing osteotomy. However, Coventry[4] recommended that deformity of greater than 12 degrees of tibiofemoral valgus should be corrected above the joint line to avoid excessive joint line obliquity, which leads to increased shear stresses across the joint, ligamentous and capsular attenuation, and subsequent joint subluxation. A general rule is that the osteotomy should be performed at the site of the primary deformity, which in most patients with valgus deformity lies in the distal femur.

CLINICAL EVALUATION

History and Physical Examination

Patients who are candidates for DFO are rare, but when they present, the deformity is quite evident. Symptoms are localized to the lateral compartment, and patients complain of difficulty ascending and descending stairs, often with a feeling of giving-way. On physical examination, ROM should be at least 90 degrees and any flexion contracture less than 15 degrees. The knee should be stable, and the medial and patellofemoral compartments should have minimal or no articular cartilage damage. Ambulation demonstrates genu valgum with an occasional abduction-type lurch and a stiff-knee gait, attempting to avoid the worn cartilage in the posterior aspect of the knee, which makes contact in flexion.

Radiographic Evaluation

All patients who are candidates for DFO obtain full-length, standing anteroposterior (AP) radiographs of bilateral lower extremities. In addition, standing AP views of both knees, standing posteroanterior (PA) views in 45 degrees of flexion (Rosenberg), lateral flexion views of the knee, and patellofemoral (Merchant) views are obtained. The long-alignment films help determine the overall mechanical axis of the limb and whether the lateral compartment is experiencing overload caused by overall genu valgum. The standing AP and Rosenberg views of the knee allow determination of the amount of joint space narrowing in the anterior and posterior portions of the lateral compartment, respectively. The lateral and patellofemoral views are helpful for determining the condition of the patellofemoral joint. If there is any concern, stress radiographs may be obtained to test for ligamentous stability and joint subluxation.

CRITICAL POINTS Radiographic Evaluation

- Full-length, standing anteroposterior (AP) radiographs of bilateral lower extremities
- Standing AP views of bilateral knees
- Standing posteroanterior view in 45 degrees of flexion (Rosenberg).
- Lateral flexion view of the knee.
- Patellofemoral (Merchant) view.
- Reestablish the mechanical axis to fall through the center or just medial to center of the knee.
- Correct distal femoral angle to a mechanical axis between 0 and 2 degrees varus (WBL, 45%-50%), depending on the patient's circumstance and proximal tibial anatomy.
- Millimeter value of the linear correction at the osteotomy site is roughly equivalent to the degree correction of axial alignment.
- Stage osteotomy to be the last of the concomitant procedures performed.

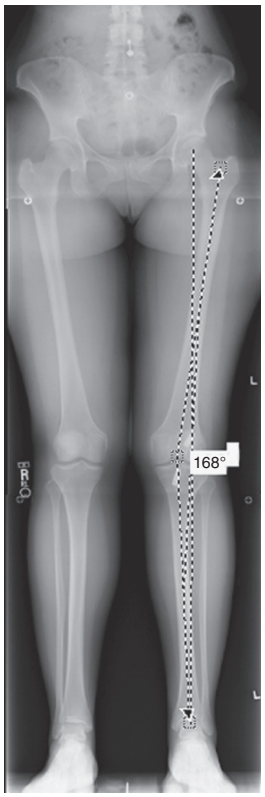


FIG 27-1 Preoperative weight-bearing long-leg anteroposterior radiograph shows valgus alignment of the left lower extremity in a 45-year-old woman with left lateral knee pain.

PREOPERATIVE PLANNING

Radiographic studies are essential in the preoperative planning of the intended corrections. These are determined by calculating the tibiofemoral angle and the proximal tibial and distal femoral angles (Fig. 27-1). The goal is to shift the mechanical axis so that it falls through the center or just medial to the center of the knee. Overcorrection of the deformity, as for example in high tibial osteotomy (HTO), will place extreme loads through the medial compartment. We recommend instead aiming for a mechanical axis of 0 to 2 degrees of varus

(representing an approximate WBL of 45% to 50%) that the literature suggests as acceptable. When performing an osteotomy as an ancillary procedure to cartilage repair in young patients, the goal of correction is to restore the WBL through the center of the knee because overcorrection may be detrimental to long-term joint health. When used to treat cases of arthritis, in which undercorrection can lead to a poor outcome, the minimum correction should result in neutral alignment with the maximum correction resulting in the WBL falling through the medial tibial spine. These corrections result in various degrees of tibiofemoral valgus alignment depending on other parameters such as hip offset. This is most easily determined preoperatively using tracing paper cutouts of the proposed osteotomy on standing long-alignment films.

The millimeter value of the linear correction at the osteotomy site is roughly equivalent to the degree of correction of axial alignment (e.g., a 10-mm opening will usually result in 10 degrees of correction). In general, the distal femoral angle is corrected to a mechanical axis between 0 and 2 degrees varus (WBL, 45%-50%), depending on the patient's circumstance and proximal tibial anatomy.

The use of arthroscopy preceding the osteotomy to indicate or predict outcome has not been well defined. Currently, no substantial scientific evidence exists that findings at arthroscopy predict the outcome of DFO, and therefore these data should not be used in isolation but rather used with careful correlation to clinical and radiographic evaluation. When considering realigning osteotomy as an adjunct procedure to an osteochondral graft of the ipsilateral lateral femoral condyle, staging the procedure is advised so as not to jeopardize the microvascularity of the recipient bone bed.

OPERATIVE TECHNIQUE

The patient is placed supine on a radiolucent operating table that will allow fluoroscopic imaging of the entire lower extremity from the hip to the ankle. Our anesthesia preference for surgery is a regional anesthetic that will provide 1 to 2 days of postoperative pain control. If the osteotomy is to be combined with an allografting procedure (e.g., lateral tibial plateau allograft), the osteotomy is generally the last procedure performed.

CRITICAL POINTS **Surgical Technique**

- Establish starting point under fluoroscopy, approximately 3 cm above the lateral femoral epicondyle.
- Angle guide pin medial and distal to exit the cortex at the level of the medial epicondyle.
- Palpate superior trochlea to ensure guide pin position proximally and avoid violating the patellofemoral joint.
- Second guide pin should completely overlap the first guide pin on anteroposterior view.
- Confirm symmetry and perpendicularity of the osteotomy on multiple fluoroscopic views before making bone cuts.
- Start osteotomy with an oscillating 1-inch saw using both pins as a guide.
- Complete osteotomy with wide osteotomes, preserving the medial cortex as a hinge.
- Insert the distraction device and distract osteotomy slowly.
- Assess weight-bearing line on fluoroscopy by stretching a radiopaque cord from the center of the femoral head to the center of the ankle.
- Secure the osteotomy plate with three unicortical cancellous screws distally and three bicortical cortical screws proximally.
- Bone graft can use autograft or allograft bone products or a combination thereof.

The operated limb, including the ipsilateral hip, is prepared free, and a small bump is placed under the hip to align the extremity in the coronal plane. For reasons previously described, a lateral opening wedge osteotomy fixed with an osteotomy plate and filled with either allograft or iliac crest bone graft is preferred. We generally use autologous bone graft in addition to allograft when the required correction is 10 mm or more. A sterile tourniquet is placed but is used only if necessary. An 8- to 10-cm incision is made over the lateral aspect of the distal femur. The iliotibial band is incised in line with the incision, and the vastus lateralis is dissected posteriorly off the lateral intermuscular septum to expose the femoral shaft and the metaphyseal flare (Fig. 27-2). The joint can be entered, if necessary.

Using fluoroscopy, the starting point for the osteotomy is located, which is approximately 3 cm above the lateral femoral epicondyle. The guide pin is angled medially and distally so that it exits the cortex at the level of the medial epicondyle (Fig. 27-3). The goal is to create the osteotomy in the metaphyseal bone, which has excellent healing potential without violating the patellofemoral joint. The superior most aspect of the trochlea should be palpated to ensure the guide pin is not too distal. If this is the case, the superior aspect of the joint will be

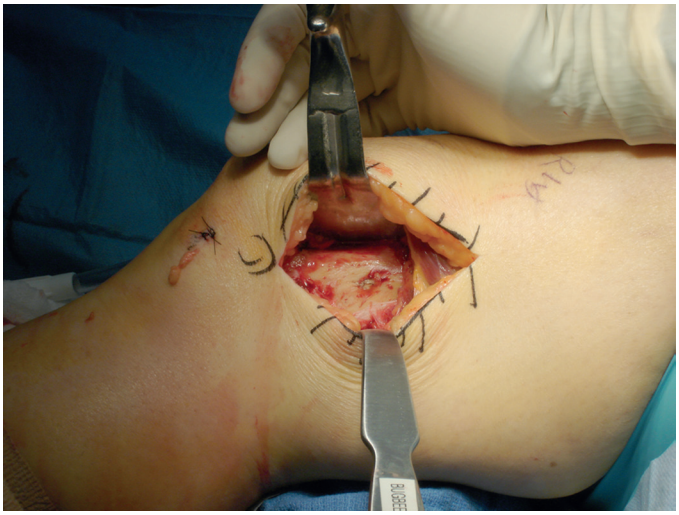


FIG 27-2 Intraoperative view of the left knee of the same patient shows exposure of the femoral shaft and the metaphyseal flare.

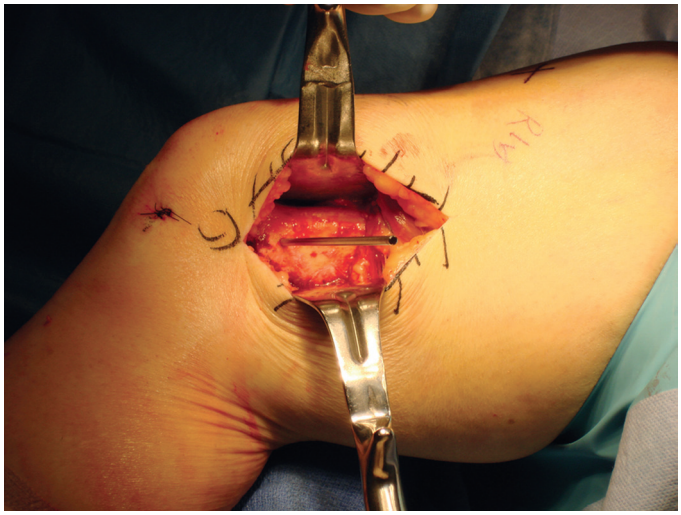


FIG 27-3 Intraoperative view of guide pin placement.

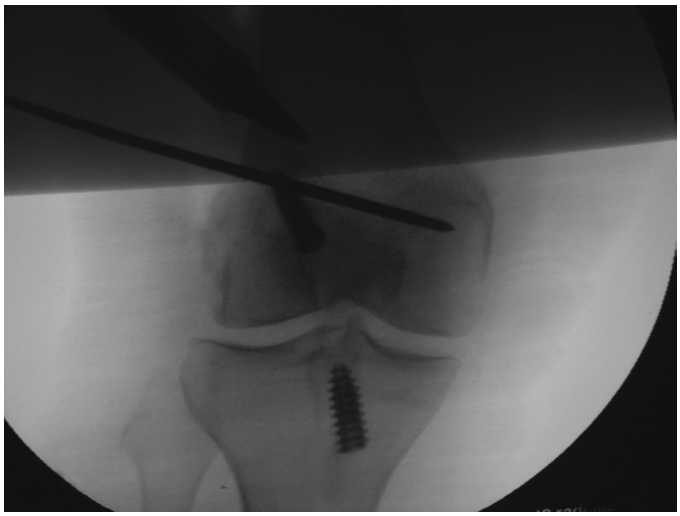


FIG 27-4 Fluoroscopic confirmation of guide pin placement, with retained interference screws from prior anterior cruciate ligament reconstruction.



FIG 27-5 The osteotomy is begun with the oscillating saw.

violated during the osteotomy. In these instances, the guide pin should be removed and placed more proximally.

Consider the angle of the osteotomy not only on the AP view but also in the lateral plane. To preserve the sagittal plane alignment of the femur, the osteotomy should be performed perpendicular to the axis of the femur in the lateral plane. Any deviation will create either excessive flexion or extension of the femur, depending on the angle of the osteotomy. This may be desirable, for example, if the patient has a fixed flexion contracture at the knee and the goal is to create a mild hyperextension of the distal femur to counter the contracture. In general, however, our preference is to create a symmetrical osteotomy perpendicular to the axis of the femur in the lateral plane.

Once the first guide pin is accurately placed, a second guide pin should be placed either directly anterior or directly posterior to that pin in the same plane, so that both pins completely overlap on an AP view of the distal femur. This ensures that an osteotomy created parallel to the plane of both guide pins will be perpendicular to the long axis of the femur in the lateral plane. After the guide pins have been placed in the appropriate position on the AP view (Fig. 27-4), the osteotomy may then be performed using both pins as a guide. An oscillating saw with a 1-inch saw blade is used to start the osteotomy, either just above or just below the guide pins, to create the proper plane (Fig. 27-5). Once this has been done, wide osteotomes are used to complete the osteotomy (Fig. 27-6). The goal is not to create a complete fracture but instead to keep the medial cortex intact to act as a hinge. Occasionally, the medial cortex is perforated to allow for opening of the osteotomy, which may be done with a small Kirschner wire.

Once the majority of the cortex has been freed, the distraction device is placed in the osteotomy site (Fig. 27-7) and slowly distracted (Fig. 27-8). The goal is for the mechanical axis to pass through the medial tibial spine. The amount of distraction required to attain this goal correlates with the amount of correction attained. For small osteotomies, this is usually 5 to 8 mm, and for large osteotomies, 10 to 15 mm. Once the desired amount of correction is obtained, fluoroscopy is used to evaluate the WBL. An electrocautery cord is stretched from the center of the femoral head to the center of the ankle, and the overall mechanical axis is assessed (Fig. 27-9). Undercorrection is associated with a higher rate of failure, whereas overcorrection places extreme loads on the medial side. If the mechanical axis is overcorrected or undercorrected, it can be adjusted at this time using the

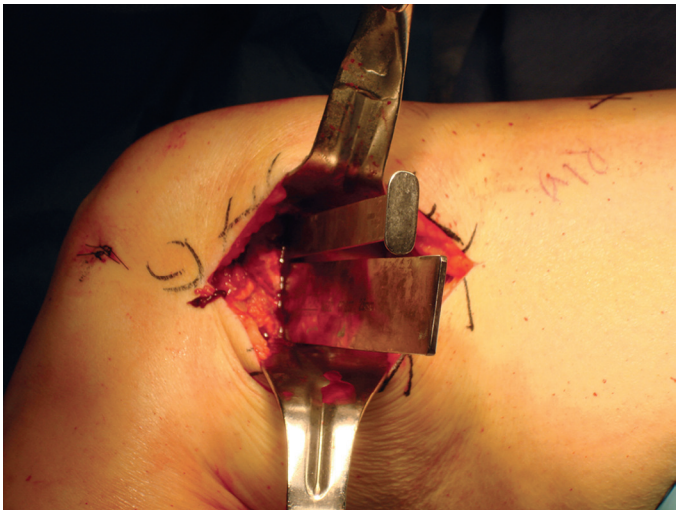


FIG 27-6 Osteotomes are used to complete the osteotomy.

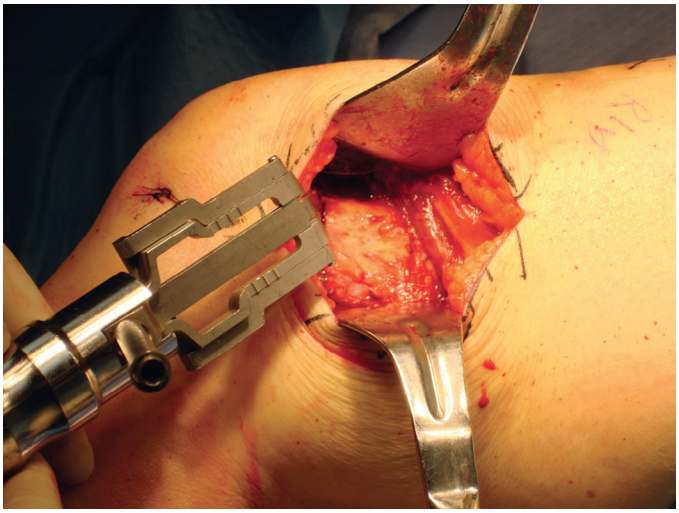


FIG 27-7 The distraction device is introduced into the osteotomy.

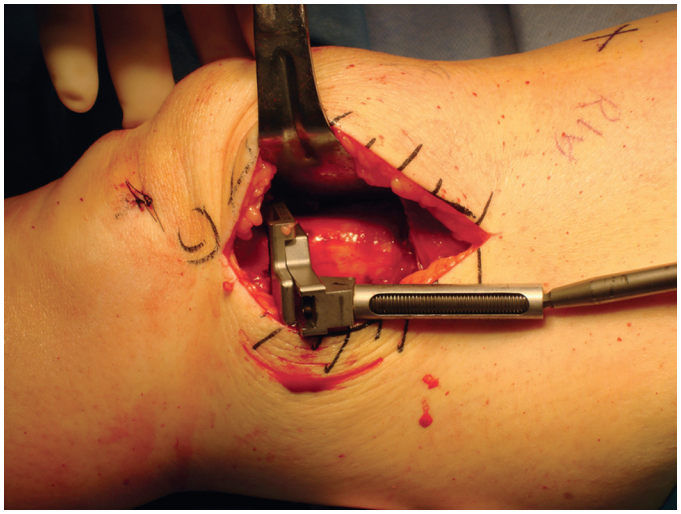


FIG 27-8 The osteotomy is distracted.

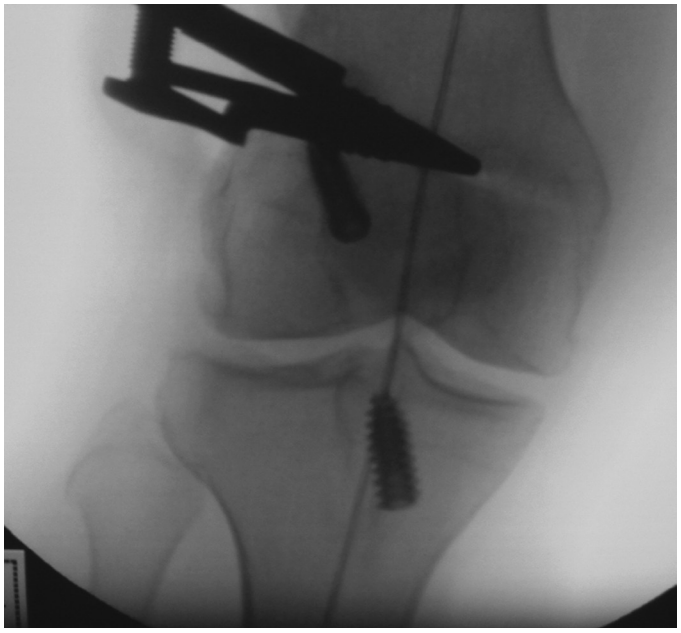


FIG 27-9 Fluoroscopic confirmation of distraction, with radiopaque cord indicating the approximate weight-bearing line.

CRITICAL POINTS Postoperative Regimen

- Knee immobilizer overnight for pain control.
- ROM brace for osteochondral allograft patients, unlocked on postoperative day 1.
- Start ROM exercises immediately and isometric strengthening when tolerated.
- Keep patients touch-down weight bearing for 8 to 12 weeks or until radiographic evidence of healing.
- Low-resistance exercise bike at 4 weeks.
- Resistance training after radiographic evidence of osseous healing.

distraction device. Once the correction is believed to be appropriate, a plate is used to secure the osteotomy. Most recently, our preference is to use the Biomet DynaFix VS plate (Biomet Trauma), originally designed for tibial osteotomy, owing to its strength of fixation and low profile (Figs. 27-10, 27-11, and 27-12). Large locking plates should be



FIG 27-10 The osteotomy is secured with an osteotomy plate.



FIG 27-11 Intraoperative anteroposterior fluoroscopic view shows plate and screw fixation of the osteotomy.

available in case of loss of medial hinge. Depending on the patient and magnitude of correction, either autologous iliac crest bone graft and/or allograft bone is used (Fig. 27-13). For younger, female patients and those concerned with cosmesis, allograft is preferred, but both methods of bone grafting have been equally successful.

Postoperatively, the patient is placed in a knee immobilizer overnight for pain control. If osteochondral allografting has also been performed, an ROM brace is placed and unlocked on postoperative day 1. We generally refrain from prophylactic anticoagulation in most

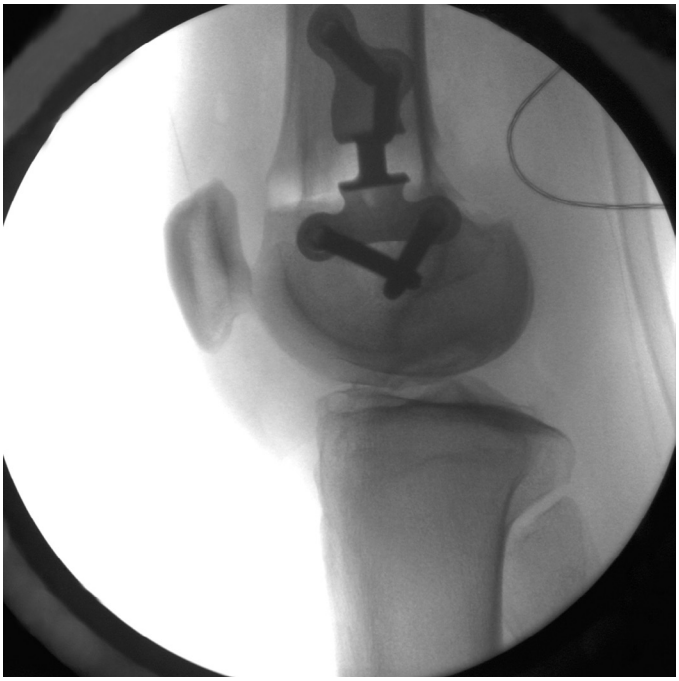


FIG 27-12 Intraoperative lateral fluoroscopic view shows plate and screw fixation of the osteotomy.

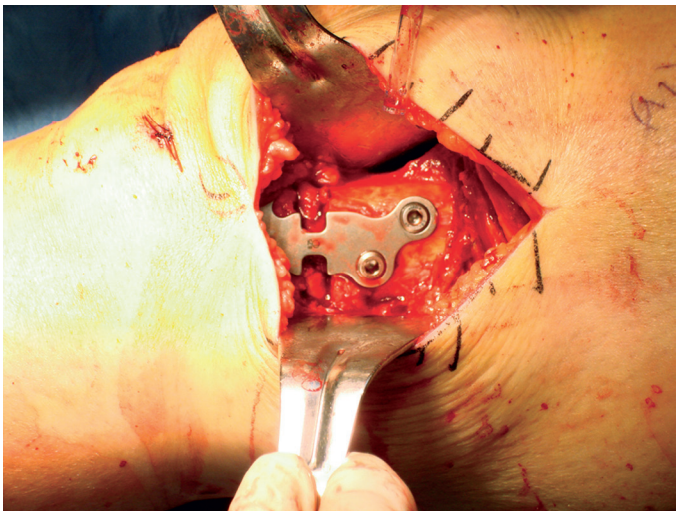


FIG 27-13 Intraoperative view of fixed osteotomy plate after placement of the autologous bone graft and bone matrix.

patients, but if risk factors are identified (e.g., age >50 years, oral contraceptive use, planned travel, or positive prior history of blood clots), we prefer to use low-molecular-weight-heparin or Coumadin and try to avoid nonsteroidal antiinflammatory medications owing to interference with bone healing. Patients begin ROM exercises immediately and isometric strengthening when pain and swelling subside. Patients are kept touch-down weight bearing for 8 to 12 weeks or until radiographic evidence of healing is confirmed. At 4 weeks, patients are started on a low-resistance exercise bike; resistance training is initiated when the osteotomy is healed (Fig. 27-14). Regular activities are usually resumed at approximately 6 months postoperatively, with continued improvement for up to 1 year.

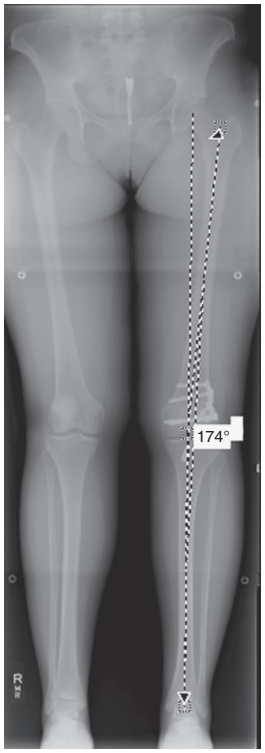


FIG 27-14 Postoperative weight-bearing long-leg anteroposterior radiograph shows physiologic valgus and normal alignment of the left lower extremity.

OUR CLINICAL OUTCOMES

Between 2000 and 2010, we performed 40 distal femoral osteotomies. Two knees (two patients) underwent a medial closing-wedge osteotomy and were excluded from the present study. Thirty-eight knees (97%) in 36 patients were lateral opening-wedge varus-producing osteotomies; of those, 31 knees (82%) in 30 patients had follow-up at a minimum of 2 years (mean, 5 ± 2 years; range, 2-12 years). The indications for osteotomy included symptomatic lateral compartment arthritis with clinical valgus deformity or a cartilage or meniscal defect in the lateral compartment with clinical valgus alignment. The study population was stratified into two groups based on reason for osteotomy: patients with isolated symptomatic lateral compartment arthritis (arthritis group; 19 knees, 61%) and patients who underwent joint preservation procedures, including osteochondral allograft transplantation or meniscal allograft transplantation (joint preservation group; 12 knees, 39%). Twenty-one of 31 knees had postoperative radiographic data available for review. Of these, 7 of 15 knees in the arthritis group and 3 of 6 knees in the joint preservation group were within the correction goal of ±3 degrees from neutral mechanical alignment. In the arthritis group, the mean International Knee Documentations Committee (IKDC) total score improved from 47 ± 15 preoperatively to 67 ± 10 postoperatively. In the joint preservation group, the mean IKDC total score improved from 36 ± 12 preoperatively to 62 ± 18 postoperatively. One nonunion occurred in the arthritis group. No postoperative complications were experienced. Ten knees in the arthritis group and six knees in the joint preservation group had additional surgery after the osteotomy, consisting primarily of hardware removal, arthroscopy for cartilage-related conditions, or conversion to arthroplasty. Survivorship at 5 years, with conversion to arthroplasty as the endpoint, was 74% in the arthritis group and 92% in the joint preservation group.

Lateral opening-wedge distal femoral osteotomy was less accurate in correction of valgus deformity than expected, but the procedure was associated with improved knee pain and function scores. These clinical and radiographic results are comparable with published series evaluating medial closing-wedge distal femoral osteotomy.

CLINICAL OUTCOMES FROM OTHER AUTHORS

Compared with HTO, very few reports have been published in the orthopedic literature on the results of distal femoral varus-producing osteotomy for painful lateral compartment gonarthrosis. The first study for lateral compartment gonarthrosis was published by Coventry in 1987,[4] who described the results of 31 knees that underwent a varus-producing proximal tibial osteotomy. In this report, 77% of cases were considered successful. Failures occurred in patients with a large valgus deformity or in whom the results of the surgery produced a tilt of the articular surface greater than 10%. For these patients, Coventry recommended a distal femoral varus-producing osteotomy.

The first report of varus-producing DFO was by Healy and colleagues in 1988.[11] The series included 23 patients (average age, 56 years) with painful valgus deformity of the knee with lateral joint space narrowing. Diagnoses included osteoarthritis in 15, posttraumatic osteoarthritis in three, rheumatoid arthritis in three, and renal osteodystrophy in two. The technique used in this series included a medial closing-wedge osteotomy in all patients, fixed with a blade plate. Results an average of 4 years postoperatively were good or excellent in 83% (19 of 23). In the osteoarthritis subgroup, 93% had good or excellent outcomes. The authors of this study concluded that 86% of the patients were satisfied with their outcome; however, they did not recommend the procedure in patients with rheumatoid arthritis or decreased ROM.

McDermott and coworkers[15] reported their experience with distal femoral varus-producing osteotomy in 24 patients with painful valgus deformity of the knee. The average age at the time of operation was 53 years. The goal of the procedure was to obtain a final mechanical tibiofemoral angle of 0%. A medial closing-wedge osteotomy technique was used, fixed with a blade plate in all patients. At follow-up 4 years postoperatively, 22 patients (92%) had a successful result and were satisfied. The greatest improvement was in the category of pain. There was one fixation failure, and one patient developed medial compartment gonarthrosis and converted to TKR.

Edgerton and associates[7] followed 24 knees for 5 to 11 years (average, 8.3 years) after DFO for painful valgus deformity of the knee. At follow-up, 71% of patients had good or excellent results, with no differences in those followed for longer periods. Complications occurred in 63% of the cases, including nonunion (25%) and loss of correction (21%). Both of these complications were associated exclusively with staple fixation, which the authors subsequently abandoned. Thirteen percent of the cases converted to TKR. The authors concluded that with current indications and techniques, a DFO is effective in up to 80% at long-term evaluation if the fixation is rigid, the correction is adequate, and the procedure is done relatively early in the course of the disease.

Finkelstein and colleagues[9] reported on 21 knees that underwent DFO for painful valgus deformity and were followed long term (mean, 133 months; range, 97-240 months) or until failure. A medial-based closing-wedge osteotomy fixed with a blade plate was performed. The study reported that 13 osteotomies survived, seven failed, and one patient died. The probability of survival at 10 years was 64%. The authors concluded that this is an effective procedure for relieving pain in patients with symptomatic valgus deformity of the knee.

Wang and Hsu[24] reported on 30 knees in 30 patients that were managed with distal femoral varus osteotomy (DFVO) for the treatment of noninflammatory lateral compartment arthritis of the knee associated with a valgus deformity. Twelve knees had isolated lateral compartment arthritis, 10 had mild to moderate degenerative changes in the other two compartments, and eight knees had severe patellofemoral arthritis in addition to lateral compartment disease. The osteotomy site was fixed with a 90-degree blade plate. At an average follow-up of 99 months, 25 patients (83%) had a satisfactory result, and two had a fair result according to the Hospital for Special Surgery (HSS) rating system. The remaining three patients converted to a TKR. With conversion to TKR as the endpoint, the cumulative 10-year survival rate for all patients was 87% (95% confidence interval [CI], 69%-100%). Improvement in patellar tracking, which persisted at the time of the latest follow-up, was observed in seven of eight knees with associated severe patellofemoral arthritis. The authors concluded that DFVO with blade plate fixation is a reliable procedure for the treatment of lateral compartment osteoarthritis of the valgus knee and that the result of the osteotomy does not appear to be affected by the presence of severe patellofemoral arthritis.

Backstein and coworkers[2] reported on 40 DFOs followed a mean of 123 months. At the most recent follow-up, 24 knees (60%) had good or excellent results, 3 (7.5%) had fair results, and 3 (7.5%) had poor results. Four in the fair or poor categories were awaiting TKR, and eight (20%) had been converted to TKR. The mean Knee Society objective score improved from 18 points (range, 0-74) to 87.2 points (range, 50-100). The mean Knee Society function score improved from 54 points (range, 0-100) to 85.6 points (range, 40-100). The 10-year survival rate of the DFO was 82% (95% CI, 75%-89%), and the 15-year survival rate was 45% (95% CI, 33%-57%).

Recently, Saithna and coworkers[21] reported on 21 DFOs; the mean follow-up population was 4.5 years (range, 1.6-9.2 years) with a cumulative survivorship of 79% at 5 years. Four patients underwent conversion to arthroplasty at a mean time of 3.3 years. In the remaining 17 osteotomies, all patients reported that outcome measures improved from baseline. The author found a high reoperation for non–arthroplasty-related surgery. The majority was caused by symptoms related to prominence of metalwork (10). Other reasons included nonunion (1), loss of correction (2), infection (1), and persistent symptoms (2).

Dewilde and colleagues[6] reported on the outcome of 19 patients who underwent opening-wedge DFOs with the Puddu plate and calcium phosphate. Knee Society knee scores improved from 43 to 78. Four patients who had an opening-wedge osteotomy underwent hardware removal, one patient underwent fracture fixation, and two patients were converted to TKA. Survivorship at 7 years with revision surgery or conversion to TKA as endpoints was 82%.

Das and associates[5] reported on 12 patients whose average age was 52 years who underwent opening-wedge DFO with the Puddu plate. At 74 months follow-up, Lysholm scores improved from 64 to 77 and the HSS knee score improved from 42 to 64. One patient had a delayed union that prolonged rehabilitation, and 7 patients required hardware removal. Survivorship at 74 months with the endpoint of TKA was 83%.

Stahelin and coworkers[22] reported the results of 21 medial closing-wedge osteotomies in 19 patients whose mean age was 57 years at 2- to 12-years follow-up. The authors reported that 18 of 19 patients were satisfied. At latest follow-up, HSS knee scores improved from 65 to 84.

Medial closing-wedge distal femoral osteotomy studies have reported similar outcomes. Finkelstein and colleagues[9] reported outcomes of 21 knees in 20 patients with a mean 11-year follow-up. The authors reported a survivorship of 64% at 10 years, which included

seven failures (3 early and 4 late). Sternheim and associates[8] recently reported on the outcome of 45 knees treated with medial closing-wedge DFO for lateral compartment arthritis. Survivorship at 10, 15, and 20 years were 90%, 79%, and 21.5%, respectively. The authors concluded that osteotomy was indicated in younger (mean, 46 years) high-activity patients, but after 20 years most patients were converted to TKA. Wang and coworkers[24] reported results of 30 knees that had varus osteotomy with a medial blade plate. At an average 99-month follow-up, 83% were reported as satisfactory, and 3 had converted to TKA.

COMPLICATIONS

The complications reported for DFO are similar to those reported for HTO. It should be noted that this is mostly empirical because reports on the results of opening-wedge DFO in the literature are limited. Usual concerns include loss of fixation, nonunion, loss of correction, and conversion to arthroplasty. Joint stiffness after osteotomy has not been an issue with rigid fixation and early mobilization, although some patients do have preexisting flexion contractures that may persist for many months. As with HTO, particular attention to avoiding flexion or extension of the osteotomy site is critical to avoid an asymmetrical opening wedge.

One concern after DFO is the potential difficulty in performing a subsequent knee replacement, if necessary. Nelson and associates[17] retrospectively evaluated the results of TKR performed after varus osteotomy of the distal part of the femur. The study group included nine patients (11 knees) with an average age of 44 years. The mean interval from osteotomy to TKR was 14 years, and the average time to follow-up after TKR was 5 years. The Knee Society score increased from 35 points before TKR to 84 points after TKR. Of note, a constrained prosthesis was required in 5 of the 11 knees. Two knees reported excellent results, five had a good result, and four had a fair result. The authors concluded that whereas TKR is effective for pain relief and improvement of function after DFO, it is technically more challenging and the results are inferior when compared with the results of primary arthroplasty performed without prior osteotomy of the knee.

In contrast to the previous report, Finklestein and colleagues[9] reported on seven knees that converted to TKR after DFVO. The authors believed that at the time of conversion, there was little or no scarring, and there was no difficulty with exposure. Similarly, there was no difficulty gaining correct femoral alignment. The authors believed that in some patients in whom there is difficulty with soft-tissue balancing and patellar tracking because of severe valgus deformity, a varus osteotomy of the distal part of the femur could make a future TKR technically easier. It should be noted that these studies involved conversion of closing-wedge osteotomies rather than of opening-wedge osteotomies. These scarce and somewhat conflicting data reflect the limited experience with conversion of lateral opening-wedge osteotomies to TKR.

SUMMARY

The treatment of symptomatic lateral compartment gonarthrosis with a varus-producing DFO has proved to be a successful procedure at our institution. The indications for this procedure have been expanded to include unloading of an allograft performed for lateral compartment disease and genu valgum. Failure of fixation or healing of the osteotomy has not been a relevant problem, with sound union usually achieved at 6 to 8 weeks. The pain relief from osteotomy can be dramatic but usually is inferior to relief from knee arthroplasty. However, we believe this is an excellent biologic solution that preserves the native joint and is an excellent surgical option for younger patients who are too active to be considered for prosthetic joint replacement. The opening-wedge technique is technically less demanding than previously described techniques and may be more easily converted to TKR should this be necessary in the future.

Acknowledgment

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28

Rehabilitation After Tibial and Femoral Osteotomy

Frank R. Noyes, Timothy P. Heckmann, Sue D. Barber-Westin

OUTLINE

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VIDEO CONTENT

Video 26-1 Correction of Varus Malalignment: Opening Wedge Tibial Osteotomy Using Fluoroscopic and Computer Navigation to Achieve Optimal Correction

Video 26-2 High Tibial Osteotomy: Techniques and Surgical Results

CLINICAL CONCEPTS

The protocol described in this chapter was designed for opening-wedge high tibial osteotomy (HTO) and distal femoral osteotomy (DFO). The operative techniques, detailed in Chapter 26, prevent delayed union or nonunion and collapse at the osteotomy site and allow a rehabilitation program of immediate knee motion and early weight bearing, preventing the complications of arthrofibrosis and patella infera[1-5] As discussed in Chapter 26, allograft instead of iliac crest autograft is frequently used in opening-wedge HTO cases. In these knees, a more cautious approach is required for resuming weight bearing because healing is delayed approximately twofold. An iliac crest autograft is still favored in opening-wedge DFO to promote prompt healing because of the larger torques placed across the femoral osteotomy site. Full weight bearing is not allowed until the surgeon advises based on radiographic evidence of healing. In addition, the physical therapist should be informed whether or not a locking plate and screw fixation were used because they provide more rigid fixation. If a smaller non-locking plate and screws were used, protection from weight bearing is required until osteotomy healing is advanced. In rare cases when the opening-wedge has been compromised at the lateral tibial cortex or medial femoral cortex, no weight bearing is allowed until near complete healing of the osteotomy is verified.

Patients receive instructions before surgery regarding the postoperative protocol so they have a thorough understanding of what is expected after the procedure. The supervised rehabilitation program is supplemented with home exercises that are performed daily. The therapist routinely postoperatively examines the patient in the clinic to progress him or her through the protocol in a safe and effective manner. Therapeutic procedures and modalities are used as required to achieve a successful outcome.

The overall goals of the osteotomy and rehabilitation are to control joint pain, swelling, and hemarthrosis; regain normal knee flexion and extension; protect the osteotomy to prevent displacement; resume a normal gait pattern and neuromuscular stability for ambulation; regain lower extremity muscle strength, proprioception, balance, and coordination for desired activities; and achieve the optimal functional outcome based on orthopedic and patient goals.

Immediately after surgery, the lower limb is wrapped with cotton with additional padding placed posteriorly, followed by a double compression and cotton bandage, a postoperative hinged brace, and bilateral ankle-foot compression boots. A commercial ice delivery system is used with the bladder incorporated over the initial cotton wrapping, a few layers from the wound. The neurovascular status is checked immediately in the operating room and carefully monitored in the initial postoperative period. A calf or foot compression system is used for the first 24 hours to promote venous blood flow. Aspirin is prescribed and, rarely in high-risk patients, low-molecular-weight heparin (LMWH) or warfarin sodium. During the first postoperative week, patients are ambulatory for short periods of time but are instructed to elevate the limb, remain home, and not resume usual activities. This program helps address the soft-tissue edema and limb swelling that may occur after surgery.

Prophylaxis for deep venous thrombosis (DVT) includes intermittent compression calf or foot boots on both extremities, immediate knee motion exercises, antiembolism stockings, ankle pumps performed hourly, and aspirin (325 mg 2 ×/day for 10 days). Doppler ultrasound is obtained if a patient demonstrates abnormal calf tenderness, a positive Homans sign, or increased edema.

Important postoperative signs to monitor include (Table 28-1):

- Loss of correction, reoccurrence of varus or valgus malalignment
- Swelling of the knee joint or soft tissues
- Abnormal pain response, increased pain with weight bearing
- Abnormal gait pattern
- Insufficient flexion or extension, limited patellar mobility
- Weakness (strength/control) of the lower extremity

TABLE 28-1 Postoperative Signs and Symptoms Requiring Prompt Treatment

Signs and Symptoms	Treatment Recommendations
Failure to meet knee extension and flexion goals	Overpressure program, early gentle manipulation under anesthesia if 0-135 degrees not met by 6 weeks postoperatively
Decreased patellar mobility (indicative of early arthrofibrosis)	Aggressive knee flexion, extension overpressure program or gentle manipulation under anesthesia to regain full ROM and normal patellar mobility
Decrease in voluntary quadriceps contraction and muscle tone, advancing muscle atrophy	Aggressive quadriceps muscle-strengthening program, EMS
Persistent joint effusion, joint inflammation	Aspiration, rule out infection, close physician observation
Loss of angular correction	Immediate referral to physician for revision
DVT: abnormal calf tenderness, a positive Homans sign, or increased edema	Immediate ultrasound evaluation

DVT, Deep venous thrombosis; *EMS*, electrical muscle stimulation; *ROM*, range of motion.

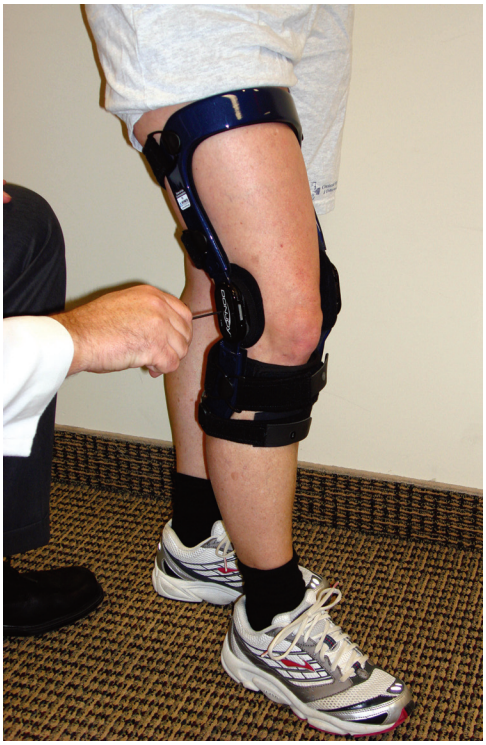


FIG 28-1 An unloading brace may be used and adjusted based on patient pain response.

- Insufficient lower extremity flexibility
- Peroneal nerve palsy
- DVT (calf pain, Homans, tibial edema)
- Delayed union or nonunion

POSTOPERATIVE REHABILITATION PROTOCOL

Modalities

The postoperative rehabilitation protocol following tibial and femoral osteotomy is summarized in Table 28-2. In the immediate postoperative period, knee pain and effusion must be controlled to avoid quadriceps muscle inhibition or shutdown. Electrogalvanic stimulation (EGS) or high-voltage electrical muscle stimulation (EMS) may be used in addition to ice, compression, and elevation to control swelling. The treatment duration is approximately 30 minutes, and the intensity is set to patient tolerance.

Once the joint effusion is controlled, functional EMS is begun for muscle reeducation and facilitation of an adequate quadriceps contraction. One electrode is placed over the vastus medialis obliquus and the second electrode is placed on the central to lateral aspect of the upper third of the quadriceps muscle belly. The patient is instructed to actively contract the quadriceps muscle simultaneously with the machine's stimulation. The treatment duration is 20 minutes. A portable EMS machine for use at home may be required in individuals whose muscle rating is poor. EMS is continued until the muscle grade is rated as good.

Biofeedback therapy is an important adjunct to facilitate an adequate quadriceps muscle contraction early postoperatively. The surface electrode is placed over the selected muscle component to provide feedback to the patient and clinician regarding the quality of active or voluntary quadriceps contraction. Biofeedback is also useful in enhancing hamstring relaxation if the patient experiences difficulty achieving full knee extension secondary to knee pain or muscle spasm. The electrode is placed over the belly of the hamstring muscle while the patient performs range of motion (ROM) exercises.

Cryotherapy is begun immediately after surgery. The standard method is an ice bag or commercial cold pack. However, patients prefer motorized cooler units because they maintain a constant temperature and circulation of ice water, which provides excellent pain control. Gravity flow units are also effective; however, temperature maintenance is more difficult with these devices than with the motorized cooler units. Cryotherapy is used from three times a day to every waking hour for 20 minutes at a time depending on the extent of pain and swelling. In some cases, the treatment time is extended owing to the thickness of the buffer that exists between the skin and the device. Cryotherapy is typically done after exercise or when required for pain and swelling control and is maintained throughout the entire postoperative rehabilitation protocol.

Postoperative Bracing and Weight Bearing

A long-leg postoperative brace is worn for the first 7 to 8 postoperative weeks. Patients then discontinue use of the brace, but if they continue to experience pain, Visco (Bauerfeind) heel pads are used to unload the affected compartment. A lateral wedge is used for patients who underwent HTO, whereas a medial wedge is used for those who had a DFO. If pain remains, an unloading brace, used initially in a neutral position and then adjusted based on patient response, is recommended (Fig. 28-1).

Initially, patients are only allowed toe-touch weight bearing. They are encouraged during this time period to lightly touch the ground with the toes of the operated limb while standing, with the visual image of stepping on a sponge, as frequently as possible during the day. At 4

TABLE 28-2 Rehabilitation After High Tibial or Femoral Osteotomy

	WEEKS					MONTHS		
	1-2	3-4	5-6	7-8	9-12	4	5	6
Brace								
Long-leg postoperative	X	X	X	X	(X)*			
Unloading						(X)*	(X)*	(X)*
Range of Motion Minimum Goals								
0-110 degrees	X							
0-130 degrees		X						
0-135 degrees			X					
Weight Bearing								
None to toe touch	X	X						
25%-50% body weight			X					
Full (fracture site healed)				X	(X)*			
Patella Mobilization	X	X	X	X				
Modalities								
EMS	X	X	X	X				
Pain/edema management (cryotherapy)	X	X	X	X	X	X	X	X
Stretching								
Hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X
Strengthening								
Quadriceps isometrics, straight leg raises, active knee extension	X	X	X	X	X			
Closed-chain: gait retraining, toe raises, wall-sits, minisquats		(X)	X	X	X	X		
Knee flexion hamstring curls (90 degrees)				X	X	X	X	X
Knee extension quads (90-30 degrees)				X	X	X	X	X
Hip abduction-adduction, multihip				X	X	X	X	X
Leg press (70-10 degrees)			X	X	X	X	X	X
Balance/Proprioceptive Training								
Weight shifting, minitrampoline, BAPS, BBS, plyometrics				X	X	X	X	X
Conditioning								
UBC		X	X	X				
Bike (stationary)			X	X	X	X	X	X
Aquatic program			X	X	X	X	X	X
Swimming (kicking)					X	X	X	X
Walking					X	X	X	X
Stair-climbing machine					X	X	X	X
Ski machine					X	X	X	X
Recreational Activities								X

*Activity based on patient symptoms, function, resumption of weight bearing, and fracture site healing.
BAPS, Biomechanical Ankle Platform System (Patterson Medical); *BBS*, Biodex Balance System (Biodex Medical Systems, Inc,); *EMS*, electrical muscle stimulation; *UBC*, upper body cycle.

weeks postoperative, double-stance, full-length anteroposterior radiographs are taken to determine osteotomy alignment and healing. Patients are then allowed to bear 25% of their body weight if the radiographs demonstrate adequate healing and maintenance of the osteotomy position and fixation implant (Fig. 28-2). A normal gait pattern that encourages normal knee flexion throughout the gait cycle is advocated. This technique allows for normal patterning of heel-to-toe ambulation, quadriceps contraction during midstance, and hip and knee flexion during the gait cycle. Average healing of the fracture site occurs at approximately 8 to 10 weeks postoperatively. In patients in whom allograft bone is used to fill the osteotomy gap, an additional delay in full weight bearing may be required for up to 12 postoperative weeks to allow for bony consolidation.

Range of Knee Motion

The postoperative goals for knee flexion and extension are shown in Table 28-3. Patients are encouraged to regain 0 to 90 degrees within the first 2 weeks. Patients perform passive and active ROM exercises in a seated position for 10 minutes per session, approximately three to four times per day.

Patients who have difficulty regaining at least 0 degrees by the second week are placed into an overpressure program using a propped

TABLE 28-3 Range of Motion, Flexibility, and Modality Use After Osteotomy

Time Postoperative	Frequency	Extension-Flexion Limits (Degrees)	Patellar Mobilization	Flexibility (5 reps × 20 sec)	Electrical Muscle Stimulation (20 min)	Cryotherapy (20 min)
1-2 wk	3-4 ×/day, 10-min sessions	0-90	Medial-lateral, Superior-inferior	Hamstring, gastrocnemius-soleus	Yes	Yes
3-4 wk	3-4 ×/day, 10-min sessions	0-110	Medial-lateral, Superior-inferior	Hamstring, gastrocnemius-soleus	Yes	Yes
5-6 wk	3 ×/day, 10-min sessions	0-130	Medial-lateral, Superior-inferior	Hamstring, gastrocnemius-soleus	Yes	Yes
7-8 wk	2 ×/day, 10-min sessions	0-135	If required	Hamstring, gastrocnemius-soleus	Yes	Yes
9-52 wk	2 ×/day, 10-min sessions	Should be full		Hamstring, gastrocnemius-soleus, quadriceps, iliotibial band		Yes

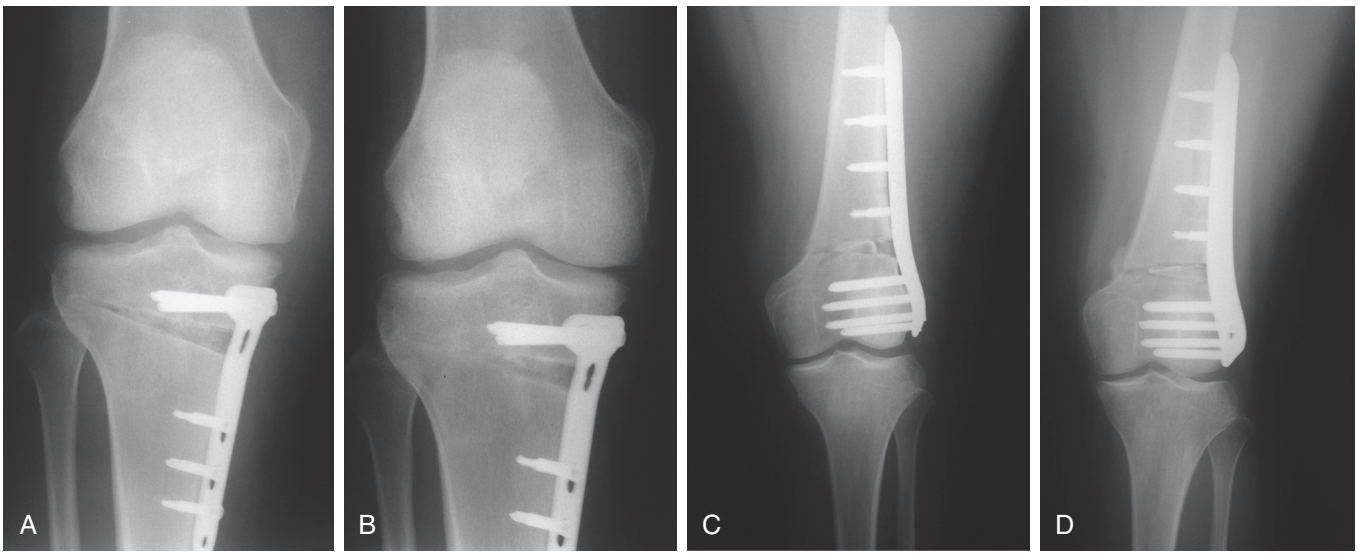


FIG 28-2 **A** and **B,** Postoperative radiographs of an 18-year-old male athlete with varus malalignment. The patient underwent an opening-wedge high tibial osteotomy with a Tomofix locking plate and screw configuration (DePuy Synthes). This fixation construct provides great stability to the osteotomy site, allowing for freeze-dried allograft bone to fill the opening wedge defect. **A,** Radiograph at 6 weeks shows good healing and consolidation over half of the osteotomy site. Although there is no osseous healing adjacent to the plate, there is sufficient healing for full weight bearing. **B,** Radiograph at 12 weeks shows complete healing of the osteotomy defect. This demonstrates the role of radiographs to assess healing before full weight bearing. **C** and **D,** Postoperative radiographs of an 18-year-old woman with valgus malalignment who underwent an opening-wedge distal femoral osteotomy. **C,** The iliac crest autograft, freeze-dried allograft, and Tomofix locking plate and screws 1 week postoperative. **D,** Maintenance of the correction with early healing at the osteotomy site 7 weeks postoperatively. The internal fixation allows for resumption of normal weight bearing.

foot/ankle position (Fig. 28-3). This position is maintained for 10 minutes and repeated four to six times per day. A 10-lb weight may be added to the distal thigh and knee to provide overpressure to stretch the posterior capsule. If this method is not successful in achieving full extension or if the clinician notes a firm end feel, then an extension board or additional weight of 15 to 20 pounds may be used up to six times a day.

Knee flexion is gradually increased to 110 degrees by the third to fourth postoperative week, 130 degrees by the fifth to sixth week, and 135 degrees by the seventh to eighth week. Methods to assist in achieving flexion greater than 90 degrees include chair rolling, wall slides, knee flexion devices, and passive quadriceps stretching exercises (Fig. 28-4).



FIG 28-3 Overpressure extension exercise.



FIG 28-4 Flexion overpressure exercise options include rolling stool (**A**), wall slides (**B**), and use of commercial device (ERMI Knee Flexionater) (**C**).

Patellar Mobilization

The resumption of normal patellar mobility is critical to regain a normal range of knee motion. The loss of patellar mobility is often associated with arthrofibrosis and, in extreme cases, the development of patella infera. Patellar glides are performed in all four planes (superior, inferior, medial, and lateral) beginning the first postoperative day with sustained pressure applied to the appropriate patellar border for at least 10 seconds (Fig. 28-5). This exercise is done for 5 minutes before ROM exercises. Caution is warranted if an extensor lag is detected because this may be associated with poor superior migration of the patella, indicating the need for additional emphasis of this exercise. Patellar mobilization is performed for approximately 8 weeks postoperatively.



FIG 28-5 Patellar mobilization.

Flexibility

Hamstring and gastrocnemius-soleus flexibility exercises are begun the first day after surgery. A sustained static stretch is held for 30 seconds and repeated five times. Common methods for stretching these muscle groups include the modified hurdler stretch and the towel pull. These

exercises help control pain because of the reflex response created in the hamstrings when the knee is maintained in the flexed position. As well, the towel-pulling exercise can help lessen discomfort in the calf, Achilles tendon, and ankle. Quadriceps and iliotibial band flexibility exercises are begun at the ninth postoperative week.

Strengthening

The strengthening program is begun on the first postoperative day (Table 28-4). Isometric quadriceps contractions are done hourly using the repetition rules of 10-second holds, 10 repetitions, 10 times per day. The patient is taught to monitor the contractions by visual or manual means, comparing the quality with those achieved by the contralateral limb. The superior migration of the patella is observed and should be approximately 1 cm during contractions, with inferior migration also seen during the initial relaxation of the contraction. The knee is held in a slightly flexed position during isometric contractions. Biofeedback may be used to reinforce an adequate voluntary quadriceps contraction.

Open kinetic chain extension exercises are incorporated within the first few weeks to further develop quadriceps muscle strength. Caution is warranted owing to the potential problems these exercises may create for the patellofemoral joint. Resisted knee extension is begun with Velcro ankle weights from 90 to 30 degrees. The terminal phase of extension is avoided owing to the high forces placed on the patellofemoral joint. The patellofemoral joint must be monitored for changes in pain, swelling, and crepitus to avoid a patellar conversion in which painful patellofemoral crepitus develops with articular cartilage damage. A word of caution in DFO cases is to warn the patient against turning and twisting motions that may disrupt the osteotomy site before healing has occurred. Partial weight bearing is for forward walking only, and other activities are avoided in the early postoperative period (6-8 weeks).

Straight-leg raises are begun the first postoperative day in the hip flexion plane (supine position) only. These exercises are advanced to include the hip extension plane during the third week. Patients who underwent HTO begin straight leg raises in the abduction/adduction planes between 4 and 6 weeks postoperatively based on x-ray evidence of healing. These exercises are begun between 6 and 8 weeks postoperatively in patients who underwent DFO based on x-ray evidence of healing. As these exercises become easy to perform, ankle weights are added to progress muscle strengthening. Initially, 1 to 2 pounds of weight are used, and eventually, up to 10 pounds is added as long as this is not more than 10% of the patient's body weight. Initially, weight is applied above the patella to control forces to the healing fracture. The use of rubber tubing to provide increased resistance may also be of benefit starting at the seventh to eighth postoperative week.

Another common exercise effective in helping with quadriceps reeducation is the straight-leg plus raise (Fig. 28-6). The quadriceps is contracted, and the leg is lifted approximately 6 inches off the table or chair, held in the lifted position for 15 seconds, and then lowered and relaxed for 45 seconds. This 1-minute cycle is maintained and progressed in ratios (1:3, 1:2, and eventually 1:1) and then progressed from 5 to 10 repetitions, with additional ankle weight added to increase the difficulty of the exercise.

Toe raises are begun during the third to fourth week as tolerated. Closed kinetic chain exercises may be initiated during the fifth to sixth week. Minisquats from 0 to 45 degrees are begun when tolerated by the patient. Initially, the patient's body weight is used as resistance, and gradually, TheraBand or surgical tubing is added for resistance (Fig. 28-7). Quick, smooth, rhythmic squats are performed to a high-set/high-repetition cadence to promote muscle fatigue. Wall sitting



FIG 28-6 The straight-leg raise plus exercise.

exercises are also begun during this time period. The goal of wall sitting is to improve quadriceps contraction by performing the exercise to muscle exhaustion. If anterior knee pain is experienced, either the knee flexion angle of the sit or the toe-out/toe-in angle is altered. The exercise may also be modified by the patient squeezing a ball between the distal thighs, holding dumbbell weights, or shifting the body weight over the involved side to simulate a single-leg contraction. This exercise is promoted as an excellent one to perform at home four to six times per day to achieve quadriceps fatigue in a knee flexion angle that does not induce anterior knee pain. Leg press exercises in the range of 70 to 10 degrees are begun during this time period as well.

It is important that the physician provides the therapist with the results of radiographs that show healing and obliteration of the fracture line and incorporation of the bone graft. A delayed union or nonunion indicates that 25% to 50% weight bearing continues into the 5- to 6-week period, thereby necessitating a delay in full weight-bearing strengthening exercises.

Lateral step-ups are initiated when the patient has achieved full weight bearing, at approximately 7 to 8 weeks. The height of the step is gradually increased from 4 to 8 inches based on patient tolerance. Strengthening is also initiated during this time for hip abductors, adductors, flexors, and extensors by using either a multihip or cable system machine or a seated hip abductor/adductor machine. Hamstring curls on a weight machine are begun at 9 to 12 weeks postoperative.

Balance, Proprioceptive, and Perturbation Training

Cup walking is an exercise that promotes symmetry between the surgical and uninvolved limbs. This exercise helps develop hip and knee flexion and quadriceps control during midstance of gait to prevent knee hyperextension (see Chapter 29). In addition, cup walking controls hip and pelvic motion during midstance, gastrocnemius-soleus activity during push off, and excessive hip hiking (Fig. 28-8). This exercise may be initiated during the partial weight-bearing phase.

Balance and proprioceptive training are initiated when the patient has resumed full weight bearing. Initially, the patient stands and shifts the body weight from side to side and front to back. This activity encourages confidence in the leg's ability to withstand the pressures of weight bearing and initiates the stimulus to knee joint position sense.

Double-leg and single-leg balance exercises in the stance position are also beneficial. During the single-leg exercise, the foot is pointed straight ahead, the knee flexed 20 to 30 degrees, the arms extended

TABLE 28-4 Muscle Strengthening Exercises Following Osteotomy

Time Postoperative	Frequency	Quadriceps Isometrics (Active)	Straight-Leg Raises	Knee Extension (Active Assisted) 90-30 Degrees	Toe Raises	Wall-Sits (to Fatigue)	Minisquats	Lateral Step-ups (5- to 10-cm Block)	Hamstring Curls (0-90 Degrees)	Multihip (Flex, Ext, Abd, Add)	Leg Press (70-10 Degrees)
1-2 wk	3 ×/day, 15 min	1 set × 10 reps (every hour)	Flex, 3 sets × 10 reps	3 sets × 10 reps							
3-4 wk	2-3 ×/day, 20 min	Multiangle 0, 60 degrees, 1 set × 10 reps each	Flex, ext, 3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps						
5-6 wk	2 ×/day, 20 min	Multiangle 30, 60, 90 degrees, 2 sets × 10 reps	Add ankle weight ≤10% of body weight, 3 sets × 10 reps	Active, 3 sets × 10 reps	3 sets × 10 reps	3 sets to fatigue	3 sets to fatigue				3 sets × 10 reps
7-8 wk	2 ×/day, 20 min		Add abd, add 3 sets × 10 reps; add rubber tubing, 3 sets × 30 reps*	Active, 3 sets × 10 reps	3 sets × 10 reps	3 sets to fatigue	3 sets to fatigue; add rubber tubing, 0-30 degrees	3 sets × 10 reps		3 sets × 10 reps	3 sets × 10 reps
9-12 wk	1-2 ×/day, 20 min		3 sets × 10 reps; add rubber tubing, 3 sets × 30 reps	With resistance, 3 sets × 10 reps	3 sets × 10 reps	3 sets to fatigue	Add rubber tubing, 0-40 degrees, 3 sets × 20 reps	3 sets × 10 reps	Active, 3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
13-26 wk	1-2 ×/day, 20 min		Rubber tubing, high speed, 3 sets × 30 reps	With resistance, 3 sets × 10 reps			3 sets × 20 reps		Active, 3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps

*Opening-wedge distal femoral osteotomy with locking plate and screw fixation; physician must confirm healing on radiographs across osteotomy with obliteration of the fracture line to progress to these exercises.
abd, Abduction; *add*, adduction; *ext*, extension; *flex*, flexion.



FIG 28-7 Closed-chain exercise examples of minisquats (**A**) and wall sits (**B** and **C**).



FIG 28-8 Cup (or cone) walking.

outward to horizontal, and the torso positioned upright with the shoulders above the hips and the hips above the ankles. The patient is encouraged to remain in this position until balance is disturbed. A minitrampoline or unstable platform may be used to make this exercise more difficult. Patients may assume the single-leg stance position and throw or catch a weighted ball against an inverted minitrampoline until fatigue occurs.

Perturbation training techniques are also performed during balance exercises. The therapist stands behind the patient and disrupts her or his body posture and position periodically to enhance dynamic knee stability (Fig. 28-9). The techniques involve either direct contact with the patient or disruption of the platform the patient is standing on, and the patient is instructed to then correct the unbalanced position.

Half foam rolls are also used in this time period as part of the gait-retraining and balance program (Fig. 28-10, *A*). This technique helps the patient develop balance and the dynamic muscular control required to maintain an upright position and be able to walk from one end of the roll to the other. Use of a balance board or other unstable platform in double-leg and single-leg stance is another effective measure (Fig. 28-10, *B*). Developing a center of balance, limb symmetry, quadriceps control in midstance, and postural positioning are benefits obtained from this type of training.

Conditioning and Return to Activities

Depending on accessibility, a cardiovascular program with an upper body cycle may be initiated as soon as tolerated by the patient (Table 28-5). The surgical limb should be elevated to minimize lower extremity swelling. Stationary bicycling is begun during the fifth to sixth postoperative week. Based on incision healing, water walking is also begun during this time period.



FIG 28-9 Perturbation-training techniques.



FIG 28-10 Balance training techniques include walking on a half foam roll (**A**) and single-leg stance on an unstable surface (**B**).

TABLE 28-5 Aerobic Conditioning Exercises After Osteotomy

Time Postoperative	Frequency	Upper Body Cycle	Bicycle (Stationary)	Water Walking	Swimming	Walking	Stair-Climbing Machine (Low Resistance, Low Stroke)	Ski Machine (Short Stride, Level, Low Resistance)
3-4 wk	1-2 ×/day	10 min						
5-6 wk	2 ×/day	10 min	10 min	10 min				
7-8 wk	1-2 ×/day	15 min	15 min	15 min				
9-12 wk	1 ×/day (select one activity per session)		15-20 min	15-20 min	15-20 min	15-20 min	15-20 min	15-20 min
13-26 wk	3 ×/week (select one activity per session)		20 min	20 min	20 min	20 min	20 min	20 min

Cross-country ski, elliptical, and stair climbing machines are permitted 9 to 12 weeks postoperatively. Protection against high stresses to the patellofemoral joint is required. The seat height of the bicycle is adjusted to its highest level based on patient body size, and a low resistance level is recommended. Stair-climbing machines are adjusted to produce a short step with low resistance. An aquatic program that includes lap work using freestyle or flutter kicking, water walking, and water aerobics is encouraged if the patient has access to a pool. To improve cardiovascular endurance, the program should be done at least three times per week for 20 to 30 minutes, with the exercise performed to at least 60% to 85% of maximal heart rate.

The majority of patients who undergo HTO or DFO are advised to return to only light, low-impact activities to maintain an active and healthy lifestyle and weight control. Patients who express the desire to return to higher-impact sports activities are advised of the risk of further cartilage deterioration if damage was noted during the operation. The usual goal of osteotomy is to buy time before the necessity for a partial or total joint replacement; therefore participation in high-loading activities is discouraged.

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Video Content

Video 26-1
Video 26-2

29

Correction of Hyperextension Gait Abnormalities: Preoperative and Postoperative Techniques

Timothy P. Heckmann, Frank R. Noyes, Sue D. Barber-Westin

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VIDEO CONTENT

Video 29-1 Gait Abnormalities, Retraining Techniques, and Role of Unloading Braces

INTRODUCTION AND DIAGNOSIS

Patients with chronic insufficiency of the lateral and posterolateral structures of the knee may develop a gait abnormality that is characterized by excessive knee hyperextension during the stance phase (initial contact or heel strike, loading response, midstance, and toe off) of the gait cycle (Fig. 29-1). The primary lateral and posterolateral structures of the knee joint are the fibular collateral ligament (FCL) and popliteus muscle-tendon-ligament unit (PMTL), including the popliteofibular ligament (PFL) and posterolateral capsule (PLC). These structures function together to resist lateral tibiofemoral compartment opening, posterior subluxation of the lateral tibial plateau with tibial rotation, knee hyperextension, and varus recurvatum (see Chapter 15).[8,9,12,13,19,27] Posterolateral injuries are frequently accompanied by a rupture to the anterior cruciate ligament (ACL) and, in some cases, a rupture to the posterior cruciate ligament (PCL).[5,7,11] In addition, many knees with insufficiency to the posterolateral structures also have varus osseous malalignment. The comprehensive physical examination and radiographic evaluation required to determine all of the abnormalities that exist in these complex knee joint injuries are detailed in Chapters 16 and 26.

The gait abnormality described in this chapter is easily identifiable in the clinic if the examiner devotes a small amount of time to observation during the initial patient presentation. An abnormal knee hyperextension gait pattern involves increased extension (>0 degrees) in the sagittal plane and, frequently, associated varus malalignment in the coronal plane (varus recurvatum). The varus recurvatum position of the knee will be markedly worse if there is associated osseous tibiofemoral varus malalignment. The *triple varus knee*, described in detail in Chapter 26, refers to varus alignment caused by three factors: tibiofemoral varus osseous malalignment, increased lateral tibiofemoral compartment separation because of marked insufficiency of the FCL and PMTL, and varus recurvatum in extension. An abnormal increase in hyperextension usually indicates damage to not only the posterolateral structures but the ACL as well.

Some knees with uninjured but physiologically slack posterolateral structures demonstrate a passive varus recurvatum and excessive knee hyperextension. After a knee injury or muscle atrophy of any cause, the patient may demonstrate a hyperextension gait pattern caused by muscle weakness. Other patients with symptomatic patellofemoral arthritis develop a hyperextension gait pattern to avoid knee flexion that loads the patellofemoral joint and causes anterior knee pain. These patients are the most difficult to manage because the knee arthritis symptoms require treatment to relieve the painful state in addition to correcting quadriceps weakness and the knee hyperextension gait pattern.

In our experience, patients with knee hyperextension gait problems present with varying amounts of altered gait mechanics, symptoms, and functional limitations. Some may demonstrate a markedly abnormal gait that is severely disabling and limits ambulation, requiring crutch or cane support. Others may have a less noticeable alteration, with the abnormal knee hyperextension occurring only after excessive walking (or other weight-bearing activities) and muscle fatigue. The degree of the gait abnormality during the stance phase depends on the magnitude of associated ligamentous deficiencies, quadriceps muscle atrophy, and symptomatic patellofemoral arthritis.

Subjective complaints of knee instability of either partial or full giving-way during routine daily activities often accompany the knee hyperextension gait abnormality. Pain is frequently located in the medial tibiofemoral compartment, which is caused by increased compressive forces owing to the varus malalignment. Pain in the posterolateral tissues also occurs from increased soft tissue tensile forces. In addition to the pain and instability caused by this gait pattern, there is an increased risk of failure of posterolateral reconstructions if the gait abnormality is not corrected before surgery. This is because of the excessively high tensile forces from high knee extension and adduction

moments that are expected be resumed during weight-bearing activities after surgery.[16] In addition, patients with associated ACL or PCL deficiency may have an increased risk of failure of cruciate ligament reconstructions if the hyperextension pattern is not corrected before surgery.[14,15] Therefore, gait retraining and avoidance of the gait hyperextension pattern are paramount for both resolution of patient symptoms and reduction of the risk of failure of soft tissue ligament reconstructive procedures.

Many investigators have described a quadriceps-avoidance abnormal gait pattern in patients with ACL ruptures.[1,2,6,18,20,28] An investigation at our center[18] documented diminished quadriceps activity and enhanced hamstring muscle activity in half of 32 ACL-deficient varus-angulated knees. Although the increased hamstring muscle force could be assumed to be beneficial because it provides a protective mechanism in decreasing anterior tibial translation, the increased muscle force creates high axial compressive forces and therefore increases medial and lateral joint compartment (calculated) loads. These loads could be deleterious to the joint over the long term, especially in knees with associated varus osseous malalignment. The abnormal gait characteristics of the ACL-deficient knee are discussed in detail in Chapter 6.



FIG 29-1 A lower limb varus deformity and hyperextension gait abnormality is evident in this 32-year-old man with chronic deficiency of the posterolateral structures and varus malalignment.

A hyperextension gait abnormality pattern is also found in patients who have had a stroke or traumatic brain injury, cerebral palsy, or poliomyelitis.[10] In these instances, the disorder may occur owing to many factors, including quadriceps weakness, ankle plantar flexion spasticity, heel cord contracture, and gastrocnemius-soleus weakness. The concern is that the abnormal knee hyperextension may cause stretching of the posterior ligamentous and capsular structures from the increased external extensor torque that is placed across the knee during stance. It is not the purpose of this chapter to discuss the treatment of this problem in patients with neurologic pathology. Rather, this chapter focuses on the treatment of this gait disorder in patients with chronic insufficiency of the posterolateral structures, with or without cruciate ligament ruptures or varus malalignment.

ABNORMAL KNEE HYPEREXTENSION PATTERNS

The normal pattern of knee motion that occurs during the gait cycle is shown in Figure 29-2. A detailed description of normal human gait mechanics is beyond the scope of this chapter and has been presented by many authors.[3,4,21,24,25] The loss of the normal knee flexion and extension patterns throughout the stance phase noted in patients with hyperextension gait abnormalities has important functional implications. During the loading response, normal amounts of knee flexion are required for the knee joint to absorb shock. A limb that is instead hyperextended transfers body weight directly from the femur to the tibia, resulting in abnormally high compressive forces. The usual muscle energy absorption and cushioning effect a flexed knee provides are lost.[22,23] The thrusting hyperextension motion at the knee is associated with an abnormally high adduction moment, which tends to increase medial tibiofemoral compartment compressive forces and lateral distraction forces. The increased compressive forces manifest as pain in the medial tibiofemoral compartment and posterolateral soft tissues.

We have reported two distinct knee hyperextension gait patterns. In *pattern I*, the abnormal hyperextension occurs during two periods

CRITICAL POINTS Introduction and Diagnosis

- Patients with chronic insufficiency of the lateral and posterolateral structures may develop a gait abnormality characterized by excessive knee hyperextension during the stance phase of the gait cycle.
- Gait abnormality is easily identifiable in the clinic: increased extension (>0 degrees) in the sagittal plane, associated varus recurvatum.
- Patients with knee hyperextension gait problems present with varying amounts of altered gait mechanics, symptoms, and functional limitations.
- Degree of the gait abnormality during the stance phase depends on the magnitude of associated ligamentous deficiencies, quadriceps muscle atrophy, and symptomatic patellofemoral arthrosis.
- Complaints of either partial or full giving-way during routine daily activities are frequent.
- Pain is in medial compartment, posterolateral tissues.
- Increased risk of failure of cruciate and posterolateral reconstructions exists if the gait abnormality is not corrected before surgery.

CRITICAL POINTS Abnormal Knee Hyperextension Patterns

- Loss of normal knee flexion and extension patterns throughout the stance phase is noted in patients with hyperextension gait abnormalities.
- Pattern I: Abnormal hyperextension occurs during heel strike and terminal extension, with knee flexion noted during the loading response. Exceedingly high knee extension moments exist, along with an abnormal reversal of hip extension and ankle dorsiflexion.
- Pattern II: Prolonged knee hyperextension pattern from heel strike throughout midstance. Knee flexion moment is markedly below normal.
- Abnormal tibiofemoral alignment (varus-valgus osseous malalignment or anterior-posterior tibial slope) affects knee-thrusting motions in the sagittal or coronal plane.
- Varus thrust gait abnormality is caused by a varus tibiofemoral osseous malalignment. Thrusting motion occurs with the knee near full extension immediately after heel strike.

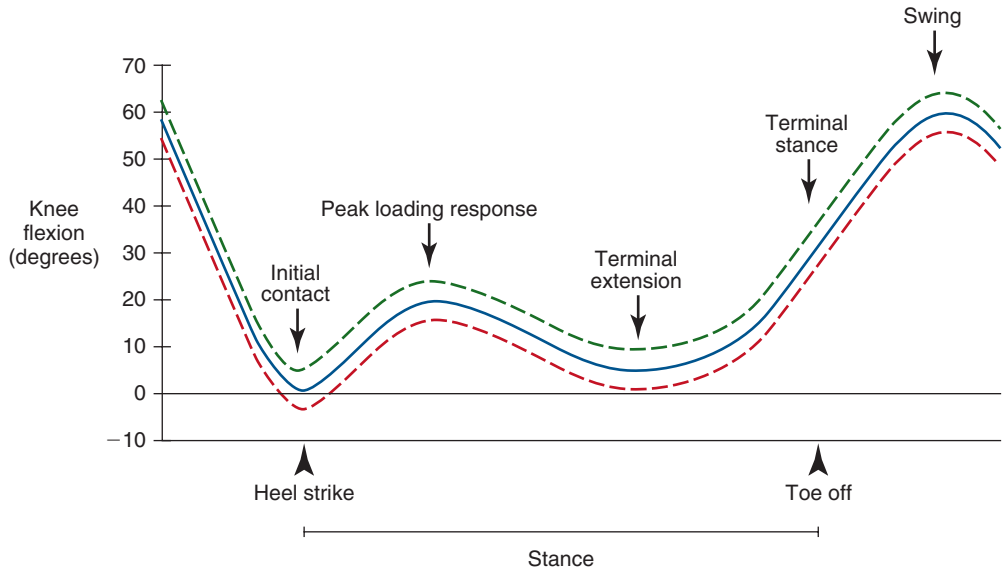


FIG 29-2 Knee motion (in degrees) during a normal gait cycle is shown. Phases of stance gait are indicated. (From Noyes FR, Dunworth LA, Andriacchi TP, et al. Knee hyperextension gait abnormalities in unstable knees. Recognition and preoperative gait retraining. *Am J Sports Med.* 1996;24:35-45.)

TABLE 29-1 Abnormal Knee Motion Patterns and Subluxations During Stance Phase

Stance Phase Event	Abnormal Knee Position	Motion Limit Increased	Phase of Stance	Possible Additional Subluxations	Comments
Hyperextension motion (thrust)	Hyperextension (pattern I)	Extension	Initial contact, terminal extension phases	Varus-external tibial rotation (recurvatum)	Sudden knee hyperextension-flexion-hyperextension even during stance. Markedly abnormal gait; retraining difficult.
Hyperextension motion (thrust)	Hyperextension (pattern II)	Extension	Entire stance phase	Varus-external tibial rotation (recurvatum)	No back-and-forth motion during stance. Gait retraining less difficult.
Varus thrust	Tibial adduction (lateral joint opening)	Adduction	Initial contact and loading response phase	Tibiofemoral compartment rotational subluxation*	Usually occurs at loading response. Gait retraining not possible. External tibial rotation may decrease thrusting; internal rotation increases thrusting. Increased external tibial rotation (lateral-posterolateral injury, medial-posteromedial injury, or both). Increased internal tibial rotation is rare, usually ACL plus lateral ligament injury.
Valgus thrust	Tibial abduction (medial joint opening)	Abduction	Initial contact and loading response phase	Tibiofemoral compartment rotational subluxation*	Increased external tibial rotation (medial-posteromedial ligament injury), with anterior subluxation of medial plateau. Increased external tibial rotation with lateral-posterolateral injury with posterior subluxation of the medial plateau.

From Noyes FR, Dunworth LA, Andriacchi TP, et al. Knee hyperextension gait abnormalities in unstable knees. Recognition and preoperative gait retraining. *Am J Sports Med.* 1996;24:35-45.
*Rotational subluxations may also occur in the absence of a varus or valgus thrust.

of the stance phase, heel strike and terminal extension (Fig. 29-3), with knee flexion noted during the loading response. Exceedingly high knee extension moments are present, along with an abnormal reversal of hip extension and ankle dorsiflexion. *Pattern II* is characterized by a prolonged knee hyperextension pattern from heel strike throughout midstance (Fig. 29-4). In these patients, the knee flexion moment is markedly below normal, with its effects incurred primarily at the knee with only a slight delay in ankle dorsiflexion.

Our clinical observations[17] on the various types of abnormal knee motions and thrusts in the sagittal, coronal, and transverse rotational planes that occur during the stance phase of gait are summarized in Table 29-1. Any abnormality in tibiofemoral alignment (varus-valgus osseous malalignment or anterior-posterior tibial slope) may affect knee-thrusting motions in the sagittal or coronal plane. The most common of these is a varus-thrusting gait abnormality caused by a varus tibiofemoral osseous malalignment. The thrusting motion

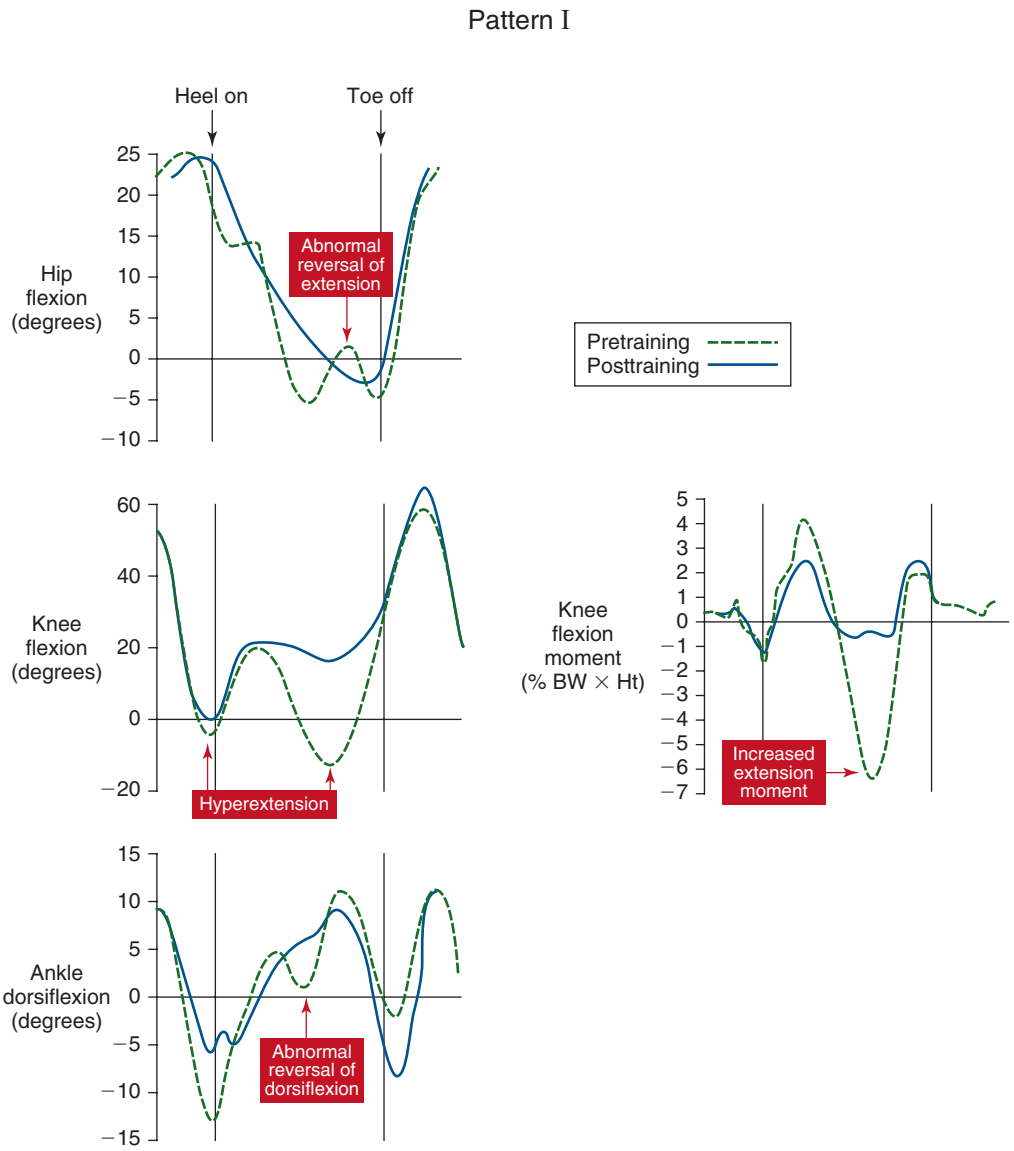


FIG 29-3 Generalized motion at the hip, knee, and ankle (in degrees), and flexion and extension moment (percentage of body weight × height) for patients showing pattern I, knee hyperextension at heel strike and midstance only. *BW*, Body weight; *Ht*, body height. (From Noyes FR, Dunworth LA, Andriacchi TP, et al. Knee hyperextension gait abnormalities in unstable knees. Recognition and preoperative gait retraining. *Am J Sports Med.* 1996;24:35-45.)

occurs with the knee near full extension immediately after heel strike, during the loading response. There may be an associated external or internal rotational subluxation with the varus thrust, depending on the presence of associated deficiency to the posterolateral structures. A less common abnormality, a valgus-thrusting gait, is usually associated with valgus lower limb malalignment. This disorder is typically accompanied by external rotation of the tibia. Knees with these osseous malalignment and associated knee ligament deficiency require surgical correction of the malalignment by osteotomy before ligament reconstructive procedures.

GAIT RETRAINING PROGRAM FOR ABNORMAL KNEE HYPEREXTENSION

A gait retraining program has been successfully used at our center[17] for knee hyperextension abnormalities since the middle of the 1980s. The program requires two to four initial clinical sessions (held preferable every week) with an experienced physical therapist to instruct the patient on the abnormal gait mechanics that occur and the adaptations required to restore a normal gait pattern (Table 29-2). The patient is instructed to practice at home for at least 2 to 4 hours daily. In addition, the patient undergoes muscle strengthening and neuromuscular coordination training as part of the comprehensive rehabilitation process. To have a successful outcome, the patient must be compliant with the time commitment and constant motivation required of this program. A family member is also taught the same instructions so he or she can observe and assist with the patient's retraining at home. It is also helpful to video the patient's abnormal and corrected gait to aid the education process. The patient may ultimately require 8 to 12 therapy sessions over 6 to 12 weeks to return to a normal asymptomatic gait pattern.

The initial focus of the retraining process is placed on the hyperextension of the knee for the patient to understand that this is the

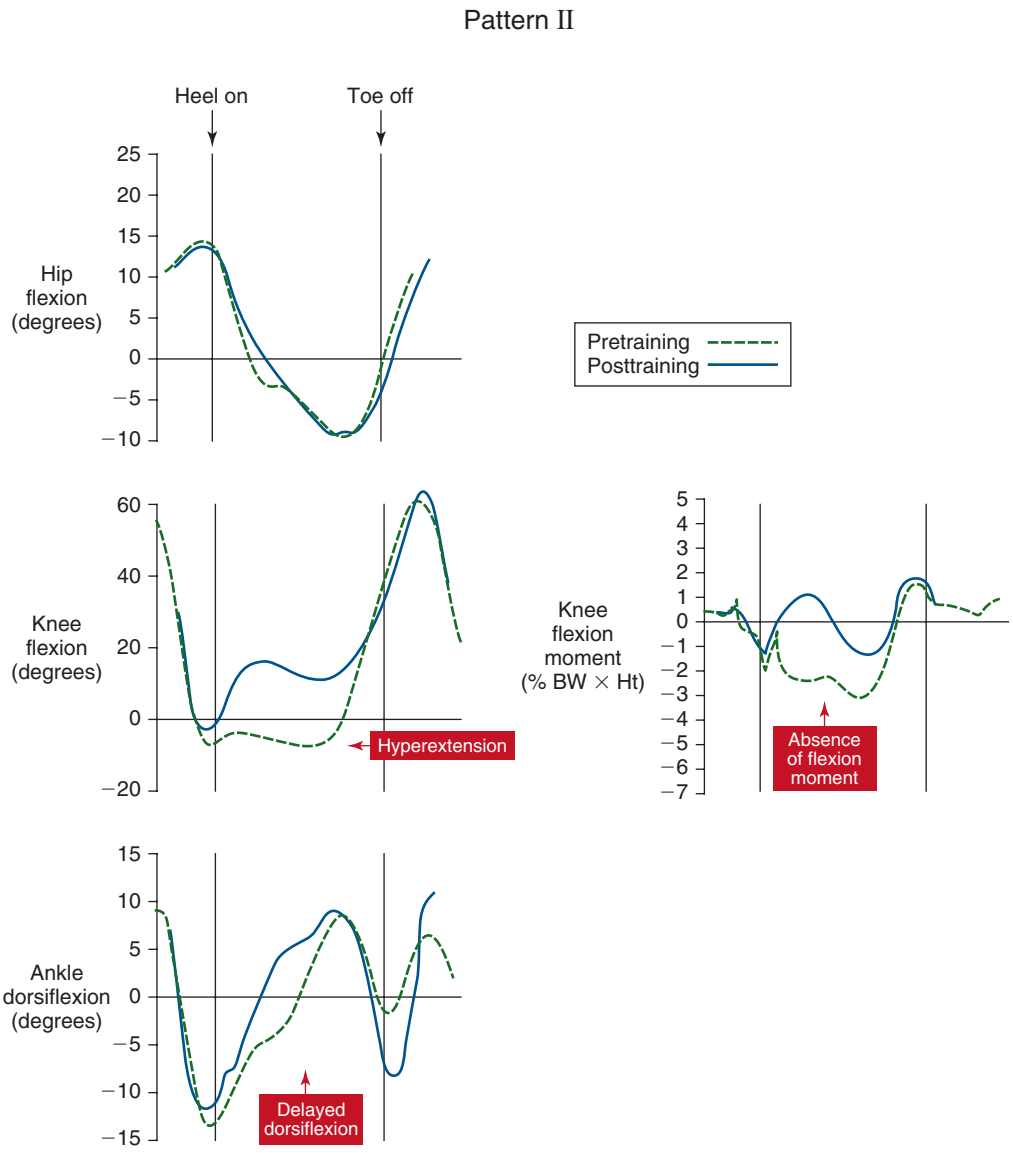


FIG 29-4 Generalized motion at the hip, knee, and ankle (in degrees), and flexion and extension moment (percentage of body weight × height) for patients showing pattern II, hyperextension of the knee throughout stance phase. *BW*, Body weight; *Ht*, body height. (From Noyes FR, Dunworth LA, Andriacchi TP, et al. Knee hyperextension gait abnormalities in unstable knees. Recognition and preoperative gait retraining. *Am J Sports Med.* 1996;24:35-45.)

primary abnormality that requires modification (Fig. 29-5). The patient is instructed to maintain 5 degrees of flexion with each step. This requires walking in a very slow and deliberate manner. A visual aid to provide to the patient is the mental image of a woman walking in high heels, which produces 5 to 8 degrees of knee flexion. In addition, a 1- to 2-inch elevated heel may be used to help maintain flexion throughout stance phase. The clinician should be aware that problems may occur during gait retraining when the patient practices the flexed knee stance. Although the flexed knee gait is advantageous in contributing to quadriceps strengthening, it may aggravate preexisting patellofemoral pain, which must be treated promptly.

The second step of the training process involves educating the patient on the abnormal ankle and foot motions that occur concurrently with knee hyperextension. The patient practices elevating the heel and pushing off with the forefoot and toes in the midstance phase to avoid knee hyperextension. The patient must limit excessive ankle plantar flexion and assume early ankle dorsiflexion to maintain forward progression of the tibia and flexion of the knee joint. It is helpful to have the patient notice and feel the pressure against the forefoot during the end of stance phase. With the first and second steps, the patient is taught to say "knee-foot" with each stance cycle as a reminder of the normal gait pattern.

When the patient is not practicing the knee-foot adaptation, he or she will revert to the abnormal knee hyperextension pattern. However, within 4 to 6 weeks, it is surprising to note that the gait pattern often returns to normal, and the patient is no longer required to perform a conscious reminder of the gait adaptation. In short, the gait pattern becomes routine.

The third step analyzes the hip and body trunk position (see Table 29-2). The fourth and final step of the retraining program determines whether an abnormal lower limb alignment (varus or valgus thrust) or an external or internal rotational knee subluxation occurs during

CRITICAL POINTS Gait Retraining Program for Abnormal Knee Hyperextension

- Program requires two to four sessions with an experienced physical therapist to instruct the patient on the abnormal gait mechanics that occur and the adaptations required to restore a normal gait pattern.
- Patient practices at home for at least 2 to 4 hours daily.
- Muscle strengthening and neuromuscular coordination training are also performed.
- Initial focus is on the knee hyperextension. Patient is instructed to maintain 5 degrees of flexion with every step, walking in a very slow and deliberate manner.
- Patient is educated on the abnormal ankle and foot motions that occur concurrently with knee hyperextension. Practices elevating the heel and pushing off with the forefoot and toes in the midstance phase to avoid knee hyperextension.
- Hip and body trunk position are analyzed.
- Clinician determines whether an abnormal lower limb alignment (varus or valgus thrust) or an external or internal rotational knee subluxation occurs during stance. Functional knee brace and additional gait retraining may be required.
- Heel wedge may be used to place the knee in slight flexion.
- Unloading brace or a lateral or medial heel wedge is used for significant varus or valgus malalignment.
- Exercises done to target specific muscles used during gait: toe raises for gastrocnemius-soleus complex, straight-leg plus raise and wall-sits for quadriceps.
- Balance and proprioception: weight shifting, tandem balance, single-leg balance (stable and unstable), rocker board (front to back and side to side), cup walking, resisted gait activity with a heavy elastic band.
- Two to three months may be required to complete the training to the point at which a normal gait pattern becomes routine on a subconscious level.

stance. This is important because a primary cause of a patient's abnormal knee hyperextension may be instability of the knee with flexion, so that coronal plane or rotational transverse plane subluxations occur. In these patients, a functional knee brace and additional gait retraining may be required.

In some cases, a heel wedge may be used to place the knee in slight flexion to minimize the midstance hyperextension that can occur with poor quadriceps control. A significant varus or valgus malalignment may require use of an unloading brace or a lateral or medial heel wedge.

There are primarily two different types of unloading braces: single-hinged and bilateral-hinged. Single-hinged braces are able to create a pulling mechanism through the affected compartment, thereby creating the unloading (e.g., when the brace has a medial hinge, the medial compartment is unloaded). With a double-upright hinged system, the brace will typically have a pushing mechanism of unloading (e.g., when attempting to unload the medial compartment, the lateral hinge mechanism will be adjusted to push through the lateral to the medial joint). In custom unloading braces, a fixed amount of unloading can also be built into the brace. The potential added advantage of double-upright unloading braces is the ability to compensate for cruciate and/ or collateral ligament instability. If a brace or heel wedge is used, the patient is reminded to actively practice the gait retraining techniques and not to solely use the brace/ wedge as a passive limit to hyperextension. These devices also assist in decreasing the medial or lateral pain complaints that can accompany either joint instability or arthritis.

TABLE 29-2 Gait Retraining Program for Abnormal Knee Stance Hyperextension

Anatomic Part	Retraining Program
Trunk-upper body	1. Maintain erect position; avoid forward loading position, which shifts body weight anteriorly to knee joint during stance phase. 2. Avoid excessive medial-lateral sway during stance phase, which induces varus-valgus moments about the knee and hip.
Hip	1. Avoid excessive hip flexion during stance phase, which encourages knee hyperextension and fatigues hip extensors. 2. For valgus lower limb alignment, avoid excessive internal femoral rotation. Encourage external femoral rotation and walking on lateral foot border. Avoid knock-knee position (important for valgus thrusts). 3. For varus lower limb alignment, avoid external femoral rotation. Encourage internal femoral rotation, knock-knee position.
Knee	1. Avoid any knee hyperextension throughout stance phase by always maintaining a knee flexion position. 2. Practice knee flexion-extension control walking in a slow manner; often begin with crutches. Initially use an excessive knee flexion position. 3. Gradually resume a more normal walking speed, after flexion-extension control and a more normal gait pattern are resumed. 4. Look for increase in patellofemoral pain. 5. Look for varus or valgus thrust with knee flexion position. 6. Look for external or internal rotational tibiofemoral subluxations when flexion position resumed.
Ankle	1. Avoid excessive plantar flexion. Maintain dorsiflexion using soleus muscle to induce early heel rise (rocker action) to encourage forward tibial progression and knee flexion. 2. Initially use excessive dorsiflexion and walking aids (elevated heel) to increase early heel off in stance phase.
Foot	1. Encourage push-off against forefoot and toes along with early heel off in stance phase to assist knee flexion during stance phase. 2. With associated varus alignment, encourage toe-out position. For valgus alignment, encourage toe-in position.

From Noyes FR, Dunworth LA, Andriacchi TP, et al. Knee hyperextension gait abnormalities in unstable knees. Recognition and preoperative gait retraining. *Am J Sports Med.* 1996;24:35-45.

Voluntary muscle control is critical to help minimize hyperextension gait mechanisms related to diminished quadriceps function. Normal gait requires adequate push-off from the gastrocnemius-soleus complex, sufficient quadriceps contraction in midstance, hip and knee flexion during swing, and an upright posture. Defects in any of these mechanisms will permit gait alterations, and, when completed with sufficient frequency, become the default gait pattern for the patient. Gait is a learned activity and eventually becomes habitual. Therefore

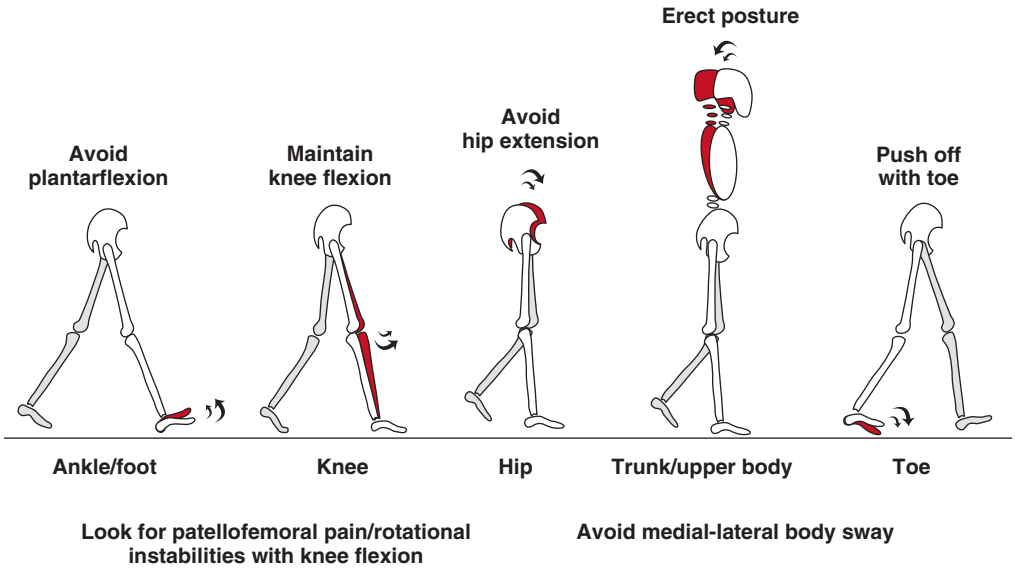


FIG 29-5 Gait abnormalities observed in patients before retraining. *Shaded structures* represent the correct, retrained positions at the trunk, upper body, hip, knee, foot, ankle, and toes. (From Noyes FR, Dunworth LA, Andriacchi TP, et al. Knee hyperextension gait abnormalities in unstable knees. Recognition and preoperative gait retraining. *Am J Sports Med.* 1996;24:35-45.)

gait retraining should include exercises to target the specific muscles during gait, pregait activities to methodically force the patient to think about using these muscles functionally, and then the act to practice the new gait pattern so it eventually becomes the learned default pattern to avoid the hyperextension gait mechanism.

In some knees with varus malalignment, there is an associated internal tibial torsion and toe-in gait. The patient may voluntarily decrease the varus thrust by purposely walking with a toe-out gait; however, when the patient is not practicing, the toe-in gait resumes. The same situation applies to a valgus knee alignment with a pronated toe-out gait. The gait retraining therefore is primarily to address knee hyperextension in which most patients will achieve a beneficial response to the program.

The following sections represent examples of how exercises may be coupled with other activities to assist with gait retraining. An important component of gait retraining is to target exercises for the specific muscles required during the gait cycle. For the gastrocnemius-soleus complex, the patient is instructed on the toe-raise exercise. This exercise can be progressed to move from using double stance to eccentric/negative repetitions (up with two legs/down with a single leg) and eventually to single-ankle plantar flexion lifting. Other options are to move from the floor to the edge of a step or to add additional weight for increasing the workload. The exercise can also be combined with traditional step-up exercises.

Quadriceps control is critical for normal gait and represents the muscle group that demands the most attention. Common exercises that have been shown to be effective in helping with quadriceps reeducation include the straight leg plus raise (Fig. 29-6), performed with the patient in the seated position. The quadriceps is contracted; the leg is lifted approximately 6 inches off the table or chair, held in the lifted position for 15 seconds, and then lowered and relaxed for 45 seconds. This 1-minute cycle is maintained and progressed in ratios (1:3, 1:2, and eventually, 1:1) and then progressed from 5 to 10 repetitions, with additional ankle weight being added to increase the difficulty of the exercise.



FIG 29-6 The straight-leg plus raise exercise.

Isometric wall sits are an excellent method of facilitating quadriceps activation. The desired angle of knee flexion is typically between 45 and 70 degrees. Patients with patellofemoral joint arthritis may need to maintain the angle of flexion between 30 and 45 degrees to decrease patellofemoral pain. Patients who do not have joint damage or pain may perform this exercise in deeper degrees of knee flexion to allow for an increase in quadriceps muscle fiber recruitment. Having the patient keep weight pressures through the heels will also decrease the potential for patellar pain complaints. This exercise is similar to a stationary leg press and is performed as two repetitions, four times a day to a maximum fatigue, experiencing a quadriceps burning sensation. The patient tries each exercise and attempts to reach a 3-minute-total duration for each wall sit repetition.

Active isometric hip adduction during the wall sit by compressing a ball between the knees may assist vastus medialis oblique recruitment. In addition to obtaining adequate quadriceps control, it is



FIG 29-7 The clamshell exercise is performed in either the long-sitting (**A** and **B**) or the side-lying (**C** and **D**) position.

important to improve hip abduction control. A heavy elastic exercise band may be placed proximal to the knee (avoiding patellar pressure) and clamshells are performed in either the hook-sitting (Fig. 29-7, *A* and *B*) or the side-lying (see Fig. 29-7, *C* and *D*) position. Three to five sets of 10 repetitions are performed. Adjustments to either knee flexion or hip flexion angles can make the exercise easier or more difficult depending on what is necessary to challenge the gluteal musculature. The single-leg squat test (Fig. 29-8) may be performed to detect poor hip strength and trunk control, discussed in detail in Chapter 13.

Normal hip abductor and external rotation strength and control of the lower limb are required to prevent the internal hip rotation-valgus lower limb position that is often observed in patients with chronic patellofemoral symptoms.

Balance and proprioception are important components of a gait-retraining program. The patient must be able to maintain single-stance control, as well as move the opposite leg through swing and be ready for the transition into the next stride. Standard progression of balance activities is typically sufficient to allow for return of a normal gait. A sample of these activities includes the following: weight shifting, tandem balance, single-leg balance (stable and unstable), rocker board (front to back and side to side), and Biodex Stabilometer (Biodex Medical Systems) for postural stability (random control and maze control). Focus of balance control is part of both the clinical treatment and home exercise programs.

To create a functional gait retraining program, a blending of the individual exercise programs must progress to include specific gait activities. Patients must overcome a variety of contributing factors including apprehension, muscle weakness, lack of range of motion,



FIG 29-8 A single-leg squat test demonstrating poor hip and knee control.

compensation, and pain. These factors must be resolved for the patient to restore a normal gait cycle. Each of the following factors contributes to a symmetric gait pattern: adequate push off, midstance quadriceps control, hip and knee flexion, and maintenance of an upright posture. Two common gait activities can be used quite successfully to assist in both the early time period after injury or surgery and in later time periods. Initially, an activity known as *cup walking* is used to encourage the patient to break down the actual gait cycle into more manageable tasks. Cups are set up in two staggered rows with symmetric stride lengths (Fig. 29-9). The patient is asked to walk or march over the cups, emphasizing each of the earlier four mentioned tasks. This activity allows the clinician to observe the gait cycle to determine where emphasis needs to be placed. Common compensatory mechanisms that patients exhibit include circumduction of the lower extremity, inadequate push off, midstance hyperextension, lack of coordinated hip and knee flexion, positive Trendelenburg sign, and forward flexed trunk. The clinician must be able to identify the deficiency to teach the patient and her or his support system how to observe the deficiency and to perform the corrective strategy. The normal automatic nature of gait now becomes a thinking activity for the patient. The patient is asked to exaggerate the gait cycle by stepping over the cups. This methodical approach allows the patient to apply a part of the gait cycle to the entire, normal gait pattern. Gait retraining activities such as this must be repeated thousands of cycles over time to create a new default gait pattern.

As time progresses from the injury or surgery, another gait activity may be used that requires the patient to wear a heavy elastic band around the distal thighs (~2 finger widths above the patella) and then produce a marching pattern to provide a resisted-gait cycle. With a central line on the floor, the patient, while marching, must maintain right foot-strike on the right side of the line and left foot-strike on the left side of the line (Fig. 29-10). This movement into swing ensures that adequate hip flexion and hip abduction musculature is used during the gait cycle. In addition, the stance limb requires adequate push off of the gastrocnemius as well as a voluntary quadriceps contraction to prevent a hyperextension episode. This resisted-gait activity can be completed in forward, backward, and lateral directions. Each direction allows the clinician to emphasize what muscle groups



FIG 29-9 Cup walking.



FIG 29-10 Elastic band gait retraining.

are used to allow for adequate voluntary muscle control. Again, these activities require voluntary thought processes to focus on recruiting the quadriceps to avoid the hyperextension mechanism from occurring.

In our experience, after approximately two to four sessions, the patient will understand the abnormal mechanics and recognize when the hyperextension patterns occur. As already discussed, mental reminders, such as "knee bent, toe push-off," are helpful in this stage. After approximately 4 to 6 weeks of training, the patient should convert to a more normal gait pattern. However, it may require 2 to 3 months to complete the training process to the point where a normal gait pattern becomes routine on a subconscious level and the patient does not resume the hyperextension gait pattern when walking quickly.

CLINICAL INVESTIGATION

Methods and Materials

Our gait retraining program[17] was studied in five patients with symptomatic knee hyperextension and deficiency of the posterolateral structures. Computerized gait analysis testing was conducted before and after the retraining program using a two-camera video-based optoelectronic digitizer for measuring motion and a multicomponent force plate for measuring ground reaction force. The force plate was camouflaged under a 10-m walkway. Patients were asked to walk at three speeds (normal, fast, slow), and measurements were obtained over these ranges to enable comparison of similar walking speeds. Data from complete cycles of stance and swing phase were obtained.

Kinematic data in the sagittal plane and kinetic data in the sagittal, coronal, and transverse planes of the hip, knee, and ankle were evaluated. Peak values during stance phase were recorded for each patient. Using a previously described mathematical model,[3,24] joint reaction loads, lateral soft tissue forces, and muscle forces were calculated. The patient data were compared with those obtained from a control group of 11 subjects matched for age and walking speed. All moments, which were expressed as external moments, were normalized to body weight and height.

Analysis of Gait Mechanics before Retraining

Statistically significant differences were found between the pretrained patients and the control subjects in the mean values for knee hyperextension during heel strike and terminal extension (Table 29-3, Fig. 29-11), with the patients demonstrating a range of 5.4 to 18.4 degrees less flexion ($P < .05$). The patients had a significantly higher mean knee midstance extension moment (127%; $P < .01$), knee adduction moment (28%; $P < .05$), and calculated medial tibiofemoral compartment loads (43%; $P < .001$) than the controls. The two knee hyperextension patterns previously discussed were identified; three patients demonstrated pattern I and two patients, pattern II.

Analysis of Gait Mechanics after Retraining

After the program of gait retraining, the patients demonstrated a statistically significant increase in the degrees of knee flexion during heel strike, terminal extension, and toe off (mean, 10 degrees). At terminal extension, an average increase of 18 degrees of flexion was measured compared with the pretraining value ($P < .01$). There were significant decreases in the knee extension moment at heel strike (23%) and terminal extension (80%). The mean adduction moment decreased to a normal value, and a significant reduction (30%) occurred in the predicted medial tibiofemoral load ($P < .05$).

There was a 36% decrease in the hip abduction moment at heel strike ($P < .01$) and an 18% decrease in hip adduction moment during midstance after gait retraining ($P < .01$). The ankle plantar flexion

TABLE 29-3 Measured and Calculated Peak Values for Control and Involved Limbs

Variable	Control Group	Study Group Pretraining	Study Group Posttraining
Knee motion (degrees):			
Heel strike	1.3 ± 1.6	–5.6 ± 2.8*	–0.2 ± 2.6†
Peak loading response	14.9 ± 5.0	6.2 ± 10.9‡	16.4 ± 4.2
Terminal extension	6.6 ± 4.0	–7.3 ± 4.4*	11.1 ± 5.8†
Toe off	35.0 ± 7.0	36.1 ± 5.3	41.8 ± 5.9§
Ankle plantar flexion motion (degrees)	11.4 ± 6.0	16.1 ± 8.5	9.4 ± 1.5†
Hip moments (% BW × Ht):			
Abduction	1.2 ± 0.9	1.1 ± 0.4	0.7 ± 0.4†
Adduction	5.1 ± 0.9	6.0 ± 1.0	4.9 ± 1.4†
Knee moments (% BW × Ht):			
Heel strike extension	2.4 ± 0.5	2.6 ± 0.7	2.0 ± 0.5§
Peak midstance extension	1.5 ± 1.0	3.4 ± 2.0‡	0.7 ± 0.7§
Adduction	3.6 ± 0.5	4.6 ± 1.4‡	3.6 ± 0.7
Ankle dorsiflexion moment (% BW × Ht)	9.0 ± 0.5	9.1 ± 0.9	8.4 ± 0.9
Predicted forces (BW):			
Flexor muscle group	1.5 ± 0.3	2.2 ± 0.7‡	1.3 ± 0.4§
Extensor muscle group	1.0 ± 0.4	1.1 ± 0.5	0.9 ± 0.4
Medial tibiofemoral load	2.1 ± 0.2	3.0 ± 0.4*	2.1 ± 0.5§

*$P < .01$ for pretraining vs. control.
†$P < .01$ for posttraining vs. pretraining.
‡$P < .05$ for pretraining vs. control.
§$P < .05$ for posttraining vs. pretraining.
BW, Body weight; *Ht,* body height.

CRITICAL POINTS Clinical Investigation

Methods

- Gait retraining program studied in five patients with symptomatic knee hyperextension and deficiency of the posterolateral structure
- Computerized gait analysis testing conducted before and after retraining measured motion and ground reaction forces
- Patient data compared with control group of 11 subjects matched for age and walking speed

Results

- Significant differences between pretrained patients and controls. Patients had:
  - Less knee hyperextension during heel strike and terminal extension
  - Greater knee midstance extension moments, knee adduction moments, calculated medial tibiofemoral compartment loads
- After retraining, patients demonstrated:
  - Significant increases in knee flexion during heel strike, terminal extension, and toe off
  - Significant decreases in the knee extension moment at heel strike and terminal extension
  - Significant decreases in the mean adduction moment to normal values
  - Decreases in the hip abduction moment at heel strike
  - Decrease in the hip adduction moment during midstance
  - Decreases in ankle plantar flexion motion

Four of five patients successfully resolved or markedly reduced hyperextension at the knee and abnormal motion patterns at the hip and ankle.

Four of five patients improved from experiencing moderate pain and instability with daily activities before retraining, to walking several hours per day without appreciable symptoms.

motion decreased by 7 degrees ($P < .01$), which was associated with an 8% decrease in the ankle dorsiflexion moment.

Four of the five patients successfully resolved or markedly reduced hyperextension at the knee and abnormal motion patterns at the hip and ankle. These individuals converted the knee flexion-extension moment to a normal biphasic pattern. One patient failed to complete the program and demonstrated continued gait abnormalities.

Effect of Retraining on Patient Symptoms

The patient symptoms before and after gait retraining were evaluated with the symptom rating scale of the Cincinnati Knee Rating System (see Chapter 41). A statistically significant improvement occurred in the pain scale (0 to 10 points) from a mean of 1.6 ± 0.9 points before training to 4.8 ± 2.3 points after training ($P < .05$) and in the partial giving-way scale from a mean of 2.4 ± 0.9 points before training to 5.2 ± 2.3 points after training ($P < .05$). Four of the five patients improved from experiencing moderate pain and instability with daily activities before retraining, to walking several hours per day without appreciable symptoms. Because of this improvement, two patients did not require ligament reconstructive surgery after retraining.

SUMMARY

In patients with chronic deficiency of the posterolateral structures, the use of gait analysis techniques and retraining can successfully change the kinetics and kinematics of the hip, knee, and ankle to more normal levels. The abnormal knee hyperextension can be significantly reduced, along with adduction and extension moments about the knee and medial tibiofemoral compartment loads. Hip abduction and adduction moments may be restored to normal levels.

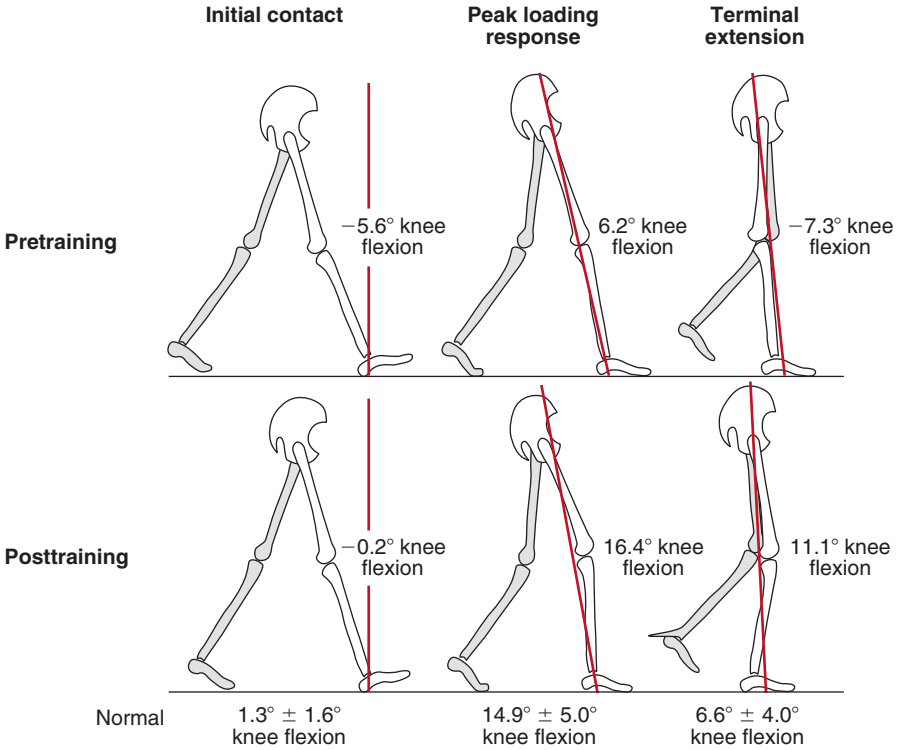


FIG 29-11 An analysis of the pretraining and posttraining knee flexion angles and how the amount of flexion relates to the ground reaction force. Hyperextension tends to place the ground reaction force anterior to the knee, requiring that the posterior structures rather than the quadriceps muscle balance the ground reaction force. (From Noyes FR, Dunworth LA, Andriacchi TP, et al. Knee hyperextension gait abnormalities in unstable knees. Recognition and preoperative gait retraining. *Am J Sports Med.* 1996;24:35-45.)

In addition, ankle plantar flexion and its counterbalancing dorsiflexion moment can be decreased. Gait retraining is indicated in knees with a hyperextension gait abnormality before any ligament reconstructive procedure and may, in some cases, eliminate the requirement for such soft tissue operations. If the gait abnormality is not corrected, cruciate and posterolateral ligament reconstructions may fail from the high tensile forces placed on the grafts postoperatively as the patient resumes an abnormal knee hyperextension gait pattern. These same principles apply to other individuals with knee hyperextension gait patterns[26] such as those that occur with quadriceps muscle weakness from a variety of knee injuries and symptomatic patellofemoral arthritis.

ILLUSTRATIVE CASES

Case 1 A 32-year-old physical therapist with chronic ACL deficiency of the left knee had given up strenuous athletics to avoid ACL reconstruction. She had no pain, swelling, or giving-way for several years. The patient participated in a light recreational volleyball game and experienced a partial giving-way episode. She presented with increasing medial joint line pain and a feeling of knee instability and believed she required ACL reconstruction. The patient had a bilateral standing physiologic varus recurvatum and walked with marked varus recurvatum thrust to the left lower extremity (Fig. 29-12). She was unaware that her gait pattern had changed, but the obvious hyperextension thrust became readily apparent to her after it was revealed under examination. The patient underwent the gait retraining program and adapted to a normal gait pattern. Within 3 weeks, her medial joint pain and instability symptoms resolved. She returned to her preinjury compensated status and had no further symptoms to warrant ACL reconstruction. Because she was a physical therapist and could understand the retraining program, she had a fast response.

Case 2 A 38-year-old woman presented 1 year after a motor vehicle accident with a diagnosis of a PCL rupture. She experienced frequent instability and shifting episodes and severe medial joint line pain. Physical examination revealed marked quadriceps atrophy, 12 mm of increased posterior tibial translation, 10 mm of increased lateral joint opening, 15 degrees of increased external tibial rotation, and a varus alignment. On standing alignment, the patient showed a varus position, but did not demonstrate a varus recurvatum. However, on walking with increased forces, a severe varus recurvatum occurred with every step (Fig. 29-13). The patient first underwent gait retraining to correct the varus thrust and rehabilitation for quadriceps muscle strengthening for 3 months. Then, an opening-wedge osteotomy was performed to correct the varus osseous malalignment, followed 6 months later with a PCL and posterolateral reconstruction.

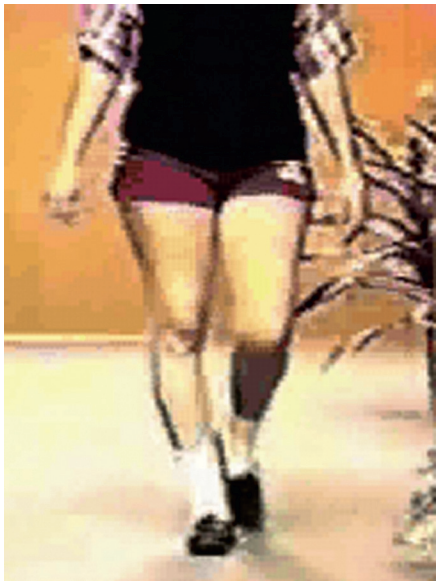


FIG 29-13 Patient who demonstrated a severe varus recurvatum with every step.



FIG 29-12 Patient with bilateral standing physiologic varus recurvatum who walked with marked varus recurvatum thrust to the left lower extremity.



FIG 29-14 Patient who presented 2 years after a motor vehicle accident with a severe gait abnormality and limp on the left lower extremity.

Case 3 A 24-year-old woman presented 2 years after a motor vehicle accident with a severe gait abnormality and limp on the left lower extremity (Fig. 29-14). She had pain throughout knee joint. Physical examination revealed complete deficiency of the PCL and posterolateral structures. The patient had seen three other orthopedic surgeons who were all reluctant to perform surgery owing to the severe gait abnormality and lower extremity muscle atrophy. She required 6 months of gait retraining. Although she was never fully able to control her knee stability, she did experience marked improvement and could consciously control the severe varus recurvatum.

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Video Content

Video 29-1

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30

Unicompartmental Knee Replacement for Varus or Valgus Malalignment

Frank R. Noyes, Sue D. Barber-Westin

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INDICATIONS

Tibiofemoral unicompartmental knee arthroplasty (UKA) is a viable option for patients in whom severe joint damage and complete loss of joint space is present in one tibiofemoral compartment. Although early reports of this procedure were disappointing, improved product materials and design, robotic technology, and a better understanding of patient indications have improved the expected outcome. The advantages of UKA over total knee arthroplasty (TKA) include lower morbidity because of less blood loss, smaller incisions, and decreased soft tissue injury; preservation of bone stock and preservation of normal (or nearly normal) knee kinematics that result in a return to higher levels of function, fewer complications, shortened hospital stays, and an overall faster recovery.[24,26,55,82,91,111,165] A study of surgical trends of UKA and TKA from U.S. Medicare beneficiaries aged 65 years or older found a sixfold increase in the number of patients who underwent UKA from 2000 to 2009, compared with a 1.7-fold increase in the number of patients who had TKA during this same time period.[24] Bicompartmental knee replacements have been described[36,61]; however, this chapter focuses on tibiofemoral UKA. Patellofemoral knee arthroplasty is described in Chapter 37.

The primary indication for UKA is symptomatic isolated painful tibiofemoral arthritis. The procedure is performed in both men and women, with multiple studies demonstrating equivalent results between genders.[85,140] Medial tibiofemoral osteoarthritis (OA) secondary to anterior cruciate ligament (ACL) deficiency is an indication in patients willing to undergo concomitant or staged ACL reconstruction, if instability is problematic.[114,119,150,162] A few investigators reported no difference in outcomes and survivorship between patients who had an intact ACL and patients who had a deficient ACL without instability symptoms.[23,41] Therefore ACL reconstruction may not be required if giving-way does not occur with activity. Lateral UKA is indicated for primary OA, such as that which develops after a lateral meniscectomy, and posttraumatic OA secondary to a tibial plateau fracture.[87,134]

Patient candidates typically have moderate to severe joint line pain and/or stiffness that limits daily activities. Pain and swelling may occur while resting, either during the day or at night. A lengthy course of nonoperative treatment, including nonsteroidal antiinflammatory drugs (NSAIDs), steroid injections, physical therapy, and weight control, fail to alleviate the pain. In our opinion, the patient should be less than 60 years of age, although consideration may be made for those older than 60 years if no contraindications exist and the other knee compartments are not arthritic or symptomatic.

Most patient candidates for UKA will have undergone prior failed surgical procedures such as chondroplasty, meniscectomy, microfracture, autologous chondrocyte implantation (ACI), or osteochondral autograft transfer. In our experience, approximately 60% of the patients who underwent UKA have undergone these types of prior failed procedures. It is important that the patient have realistic expectations regarding what this operation may and may not accomplish. At our center, most patients are able to walk without support within approximately 2 to 3 postoperative weeks, and the majority return to daily activities within 4 to 6 weeks. Light, low-impact activities such as

The senior author (Frank R. Noyes) has no conflict of interest directly or indirectly with the implant or robotic system mentioned in this chapter.

walking, swimming, golfing, light hiking, and bicycling can often be performed by 3 months. However, running and high-impact athletic or occupational activities are not advised and, in fact, should be avoided; and it is essential that the patient understand and accept these limitations. Recent studies have reported that the majority of patients who were participating in sports before UKA were able to return after surgery and that most participated in low-impact activities such as swimming, bicycling, and general fitness training.[43,55,101,125,157]

CONTRAINDICATIONS

The principal contraindication to UKA is preexisting joint arthritis in another compartment of the knee (moderate to advanced articular cartilage deterioration and/or moderate to severe joint space narrowing on standing posteroanterior [PA] radiographs) owing to the evidence that this is one of the leading causes of failure of UKA.[4,33,38,73] Anterior knee pain, without patellofemoral joint narrowing or arthritic damage, is not an absolute contraindication.[10,11,77,99] However, patellofemoral symptoms with stairs, kneeling, and light activity will persist after UKA, and most patients with these problems select TKA. Mild patellofemoral joint deterioration (Outerbridge grade 1-2) also appears not to be deleterious to short-term outcomes of UKA.[14,144]

Other contraindications include uncorrected excessive varus or valgus malalignment (>3 degrees), knee ligament instability, knee hyperextension of 10 degrees or more, inflammatory arthritis, and prior infection. Patients with complex regional pain syndrome, diabetes, knee arthrofibrosis (excessive extension or flexion contracture), chondrocalcinosis, rheumatoid arthritis, or neuromuscular disorders affecting limb control are not considered candidates.

Patients who are obese (body mass index [BMI] >32) are not considered candidates for UKA,[13] although recent reports noted no significant differences in 5- and 10-year survival rates according to BMI subcategories.[28,74,100] Osteopenia (bone mineral density T score between −1.0 and −2.5 standard deviations below normal) or osteoporosis (T score less than −2.5) are contraindications for this operation owing to the potential risk of subsidence of the implants. Other contraindications include failure to treat the patient with all possible conservative measures, noncompliance with rehabilitation, and unrealistic expectations for future activity levels. Although our experience with this operation has usually involved patients younger than 60 years, age alone is not a contraindication to the procedure, assuming no previously mentioned contraindications exist.[73,93,118,162] A few reports have shown poorer results when medial UKA was done in patients with only partial loss of tibiofemoral joint space and articular cartilage.[109,115] Ultimately, the final decision to perform UKA or TKA is made at surgery after all of the joint surfaces have been visualized. The patient should be informed and consent obtained to perform either procedure.

IMPLANT DESIGN

UKAs may be generally categorized according to the bone-cut preparation (resurfacing or inset) and bearing surface (mobile or fixed, Tables 30-1 and 30-2). Resurfacing implants require minimal bone resection, and inset implants require angular cutting similar to TKA. Bearing surfaces are usually all polyethylene or modular and include fixed bearing and mobile bearing. The initial UKA implants, such as the Marmor (Smith & Nephew) and St Georg Sled (Waldemar Link), were fixed bearing with all-polyethylene tibial inserts. Problems with these prostheses included subsidence in both the femoral condyle and tibial plateau, aseptic loosening, and wear caused by suboptimal design.[90] Subsequently, implants were redesigned to distribute loads onto the cortical rim and had a minimum thickness of the tibial insert of more than 6 mm. Metal-backed components were introduced, requiring greater bone resection. The Miller-Galante (Zimmer) is a well-known metal-backed, fixed-bearing implant with a modular polyethylene insert.

Mobil-bearing implant designs were introduced in attempts to reduce the stress exerted on the tibial surface. These implants, such as the Oxford (Biomet), have a metal femoral component that articulates with a polyethylene meniscal component and a flat metal tibial surface. A porous-coated prosthesis was developed to induce bone growth and provide better fixation. For instance, the cementless Oxford Phase 3 has a layer of porous titanium with calcium hydroxyapatite under its components. Mobile-bearing implants are subject to dislocation of the mobile insert from the tibial base.

TABLE 30-1 Modern Unicompartmental Arthroplasty Prostheses

Prosthesis	Manufacturer	Clinical Studies (References)
Oxford	Biomet UK Ltd.	8, 10, 31, 54, 56, 62, 67, 78, 126, 127, 128
Oxford Series II	Biomet	95, 130, 137, 154, 170
Oxford Series III	Biomet	1, 19, 23, 33, 38, 40, 43, 54, 65, 66, 67, 68, 70,71, 73, 74, 77, 80, 84, 89, 93, 98, 99, 100, 106, 109, 115, 117, 118, 125, 132, 144, 162, 169
Miller-Galante	Zimmer	4, 17, 18, 44, 105, 121, 123, 129, 140, 164
Preservation All-Poly	DePuy	20, 27, 41, 51, 79, 101, 102, 167
St Georg Sled (LINK SLED Unicompartmental Knee)	Waldemar Link	107, 145, 158
Unicompartmental High-Flex	Zimmer	22, 120
Restoris MSK	MAKO Surgical Corp.	32, 40, 83, 96, 97, 104, 122, 141
HLS Uni	Tornier	28, 85
Accuris System (Genesis Uni)	Smith & Nephew	39, 53
Repicci II	Biomet	48, 133
EIUS	Stryker	9
Unix	Stryker	50
UC-PLUS	Endo Plus	91
Uniglide (mobile or fixed bearing)	Corin	None
Vanguard M	Biomet	None
Journey Uni	Smith & Nephew	None
iBalance	Arthrex	None
Sigma High Performance	DePuy	None

ROBOTIC TECHNOLOGY

It is well known and documented that early UKA failures were frequently caused by inaccurate positioning of the components, which

TABLE 30-2 Modern Lateral Unicompartmental Arthroplasty Prostheses

Prosthesis	Manufacturer	Clinical Studies (References)
Oxford Domed Lateral Partial Knee	Biomet UK Ltd.	2, 92, 116, 136, 138, 146, 152, 157, 161, 163
Miller-Galante	Zimmer	5, 87, 124, 153
Preservation	Depuy	3, 45, 79, 167
HLS Evolution	Tornier	86, 87
Uniglide	Corin	7, 142
Oxford Flat Lateral Partial Knee	Biomet	152
Genesis	Smith & Nephew	53
High Flex	Zimmer	92
Repicci II	Biomet, Warsaw	12
Vanguard M	Biomet	12
Sled	Waldemar Link	7
UC-PLUS	Endo Plus	7
iBalance	Arthrex	None
Sigma High Performance	DePuy Synthes	None

led to undercorrection or overcorrection of the final limb alignment. Excessive malalignment of the tibial component (>3 degrees) or posterior tibial slope (>7 degrees) may cause component loosening, fractures, and increased bone stresses.[35,52,63,83,135] Robotic-assisted surgical navigation was introduced in the early 2000s to improve accuracy in UKA (postoperative limb alignment, component positioning, and soft tissue balancing) using less invasive techniques. There are two types of robotic surgery systems: haptic (or tactile) and autonomous. Haptic systems require active participation of the surgeon to complete the entire operation, while autonomous robotic systems complete the operation after the surgeon has performed the approach and set up the machine. Haptic systems constrain the motion of the cutting tool to only the preplanned volume or area of resection. Preoperative 3-dimensional models of the patient's knee (created with computed tomography [CT] scans) are merged with referenced bony surfaces at surgery to form a final model of the actual anatomy of the patient. The component placement and exact cutting zones are determined. As the surgeon resects these areas, the robotic arm provides auditory and tactile feedback, limiting the tip of the rotating burr to just the predefined cutting area. The MAKOplasty Partial Knee Resurfacing System that uses the Robotic Arm Interactive Orthopedic System (RIO) (Stryker) and the Acrobot system (The Acrobot Company) are examples of commercially available haptic systems.

Many studies have compared short-term outcomes between various navigation and conventional UKA techniques (Table 30-3). A systematic review by Nair and associates[103] identified 15 studies published from 2003 to 2011 in which five different navigation systems were used. Overall, the navigation methods improved component alignment and position and reduced radiographic outliers compared with conventional systems. However, there were no differences in clinical outcomes, which is not surprising considering that 14 studies had follow-up of 2 years or less, and just one study had a midterm follow-up of 7 years. A meta-analysis was conducted by Weber and colleagues[159] of 10 studies (level II and III) involving 258 medial UKAs implanted with navigation and 295 medial UKAs implanted with conventional techniques. The study reported that there were more outliers in the conventional group compared with the navigation group for all variables assessed, including mechanics axis (30% and 11%, respectively), femoral anteroposterior (AP) alignment (17% and 5%, respectively), femoral lateral alignment (41% and 18%, respectively), tibial AP alignment (14% and 8%, respectively), and tibial slope (22% and 9%, respectively).

In the largest study to date, Mofidi and coworkers[97] calculated accuracy rates by comparing intraoperative planned and postoperative radiographic measurements in 232 knees that underwent medial UKA using the MAKOplasty system. Accuracy rates of the femoral prosthesis were 2.8 ± 2.5 degrees in the coronal plane and 3.6 ± 3.3 degrees in the sagittal plane. Accuracy rates of the tibial component were 2.2 ± 1.75 degrees in the coronal plane and 2.4 ± 2 degrees in the sagittal plane. The authors concluded there was a high degree of agreement between intraoperatively planned prosthesis alignment and postoperatively measured alignment. Proper cementation technique was considered crucial in achieving accurate alignment.

CLINICAL EXAMINATION

A thorough history, including documentation of prior surgical procedures, conservative treatment measures, and all knee joint injuries, is required. Symptoms are typically experienced most often during stair climbing, walking on uneven ground, and kneeling or squatting.

The comprehensive physical examination includes a complete patellofemoral examination, discussed in detail in Chapter 35, to assess patellar tilt, subluxation, mobility, Q angle, and lower limb rotational alignment (femoral internal torsion, tibial external torsion). The patella and all surrounding tissues are palpated to localize pain. The medial and lateral joint lines are also inspected for any tenderness, indicative of tibiofemoral joint involvement.

All knee ligament tests are conducted as described in Chapters 7 and 17.

The patient's gait, range of knee motion, lower extremity and hip muscle strength, and neurovascular status are evaluated.

Radiographs taken during the initial examination include standing AP at 0 degrees, lateral at 30 degrees of knee flexion, weight-bearing PA at 45 degrees of knee flexion, and patellofemoral axial views. Double-stance full-standing radiographs of both lower extremities, from the femoral heads to the ankle joints, are obtained in knees in which varus or valgus lower extremity alignment is detected on clinical examination. Magnetic resonance imaging (MRI) is required in certain cases to determine the cartilage status of the entire knee joint, along with all other soft-tissue structures.

SURGICAL TECHNIQUE

The UKA operative technique described in this chapter uses an implant that is positioned using 3-dimensional modeling and computer-assisted robotic surgical navigation.[35] Before surgery, customized CT scans are obtained with the patient lying supine with a motion rod attached to the operative leg. Although the senior author (F.R.N.) has used various UKA prostheses, the precision obtained from the RIO UKA system for preoperative planning and surgical implantation appears to offer distinct benefits. It has been incorporated in the senior author's practice since 2008 and provides the surgical experience discussed in this chapter.

A detailed description of the surgical technique for the RIO UKA is available at www.makosurgical.com/physicians/products/rio and is not repeated in this chapter. However, there are technical and operative details that should be stressed. It is important that the surgeon and technician are thoroughly familiar with the detailed procedures and

TABLE 30-3 Accuracy of Computer Navigated Robotic Unicompartmental Knee Arthroplasty

Study	Cases (*n*)	Follow-up	CN Implant	Navigation System	Findings
Mofidi et al[97] (2014)	0/232	Immediate postoperative	NA	MAKO	Accuracy of intraoperative planned vs. postoperative measurement: Femoral component: 2.8 ± 2.5 degrees (range, 0-26 degrees) coronal plane; 3.6 ± 3.3 degrees (range, 0-17 degrees) sagittal plane Tibial component: 2.2 ± 1.75 degrees (range, 0-11 degrees) coronal plane; 2.4 ± 2 degrees (range, 0-8°) sagittal plane 102 knees mismatch in tibiofemoral contact point >1 mm
Citak et al[32] (2013)	6/6 cadaver knees	Immediate postoperative	Restoris Onlay in all	MAKO	Surgical errors in femoral component within 1.9 mm and 3.7 degrees in all directions in navigation group; 5.4 mm and 10.2 degrees in conventional group. Surgical errors in tibial component within 1.4 mm and 5.0 degrees in all directions in navigation group and 5.7 mm and 19.2 degrees in conventional group.
Dunbar et al[40] (2012)	0/20	Immediate postoperative	Unicondylar Knee System in all	MAKO	Surgical errors in femoral component within 1.6 mm and 3 degrees in all directions; in tibial component, 1.6 mm and 3 degrees in all directions. Tibial slope within 1.9 degrees of planned position. Varus error mean, 1.5 degrees; valgus error mean, 2.6 degrees.
Pearle et al[122] (2010)	0/10	Immediate postoperative	StelKast in all	MAKO	In all patients, surgical errors in tibiofemoral angle coronal plane within 1 degree.
Lonner et al[83] (2010)	27/31	Immediate postoperative	Metal-backed onlay design/ all-polyethylene inlay design	MAKO	RMS error in tibial slope 3.1 degrees in conventional group and 1.9 degrees in navigation group. Variance using conventional technique 2.6 times greater. Mean error in tibial alignment 2.7 ± 2.1 degrees greater varus conventional group, 0.2 ± 1.8 degrees in navigation group.
Weber et al[160] (2012)	20/20	Immediate postoperative	Univation in all	Orthopilot	No difference in any outcomes
Lim et al[81] (2009)	21/30	Immediate postoperative	Freedom in all	Orthopilot	No difference in mechanical axis: conventional group –2.8 ± 2.0 degrees (range, –5.8 to 3.1 degrees); navigation group –3.3 ± 2.4 degrees (range, –9.5 to 0.9 degrees)
Seon et al[139] (2009)	33/31	2-3 yr	Miller-Galante	Orthopilot	Navigation group had fewer outliers in mechanical femorotibial angle (3 vs. 11, $P = .03$); femoral component sagittal plane (6 vs. 15; $P = .04$)
Jenny et al[58] (2007)	60/60	Immediate postoperative	NA	Orthopilot	No difference in any measurement angles or outliers
Konyves et al[69] (2010)	14/10	6-10 yr	Allegretto/EIUS	EIUS	No significant difference in survivorship or radiologic alignment. Conventional group had higher variance in mechanical axis (SD, 22.5% vs. 15.1%).
Jung et al[60] (2010)	29/23	Immediate postoperative	Oxford	Stryker Navigation	Navigation group had more prostheses implanted in target range for femoral and tibial components, greater accuracy in sagittal plane for femoral and tibial components.
Rosenberger et al[133] (2008)	20/20	Immediate postoperative	Oxford	Treon plus	Navigation group had significantly higher percent in optimal implant alignment ($P = .04$), indicating malalignment was ≤3 degrees in all axes. Navigation eliminated outliers in frontal mechanical alignment and coronal orientation of the femoral component.
Keene et al[64] (2006)	20/20	6 wk	Preservation	Ci	Navigation group had higher accuracy in lower limb alignment correction (0.9 ± 1.1 degrees vs. 2.8 ± 1.4 degrees; $P < .001$); higher percentage within 2 degrees of preoperative plan (87% vs. 60%).
Cobb et al[34] (2006)	14/13	Immediate postoperative	Oxford	Acrobot	All navigation group within 2 degrees of planned position in tibiofemoral alignment in coronal plane compared with 40% in conventional group; mean of 0.65 ± 0.59 degrees and –0.84 ± 2.75 degrees, respectively; $P = .001$.

CN, Computer navigation; NA, not available; *RMS*, root mean square; *SD*, standard deviation.

follow the exact steps, including preoperative planning of the alignment and size of the tibial and femoral implant. The surgeon must perform an adequate surgical exposure, remove bone osteophytes and retained meniscus tissues, place retractors that curve around the posterior tibia to protect the neurovascular structures, perform precise registration of anatomic landmarks for the RIO software, achieve soft tissue balancing of extension and flexion gaps with appropriate adjustment of tibial and femoral implants, and perform meticulous cement fixation of implants.

The usual preoperative planning steps are taken before surgery, including a 5-day scrub with chlorhexidine. A detailed history for prior deep venous thrombosis (DVT) episodes, including personal and family history or other DVT risk factors, is undertaken. In the absence of DVT risk factors, aspirin (325 mg twice a day) is used for 21 days postoperatively. Other chemical forms of anticoagulant therapy are not required unless specific risk factors, such as prior DVT or pulmonary embolism, are present. The patient should be mobilized and active the first day after surgery and thereafter.

The operative limb is signed by the surgeon before the patient receives any medication. A time-out is performed in the operating room with the signed limb signature visible and verbal agreement of patient name, birth date, preoperative antibiotics, allergies, and operative procedure planned by surgeons and operative staff. During the operative procedure, a sequential calf pressure device is used along with antiembolism stockings on the opposite limb.

The patient positioning shown in Figure 30-1 involves the De Mayo Knee Positioner (Innovative Medical Products) to control the knee flexion position. The opposite extremity has a posterior thigh pad that, along with reflex of the hip portion of the surgical bed, maintains 10 degrees of hip flexion and decreases tension on the femoral nerve.

After appropriate draping with the knee at 45 degrees of flexion, a limited medial (or lateral) parapatellar incision is made that extends into the vastus medialis obliquus or vastus lateralis obliquus 3 to 5 cm above the patella to allow sufficient lateral or medial patella glide for exposure. An examination of the knee joint confirms the expected pathology and ensures no unexpected joint arthritis is present in the other knee compartments. There are often reactive and scarred fat pad tissues that require removal along with retained meniscus tissues of the involved compartment. Osteophytes are not removed at this point because they are helpful in identifying tibial and femoral geometry in the registration process. The tibial and femoral arrays are placed a sufficient distance from the knee joint (Fig. 30-2, *A* and *B*) not to obstruct the surgeon's view. The senior author routinely uses a headlight to completely view the interior of the knee joint. The registration process is meticulous and follows the detailed MAKOplasty Partial Knee Application User Guide 206388 Rev 01 and Surgical Technique and Planning Guide #201844 (Stryker).

After removal of osteophytes, the joint balancing step to capture data is completed, providing the tibiofemoral compartment spacing or opening at multiple knee flexion angles under a mild varus or valgus loading (Figs. 30-3 and 30-4). This allows for proper medial or lateral ligament soft tissue tension, with attention directed to prevent overstuffing of the tibiofemoral compartment, particularly at higher angles of joint flexion. The preoperative virtual positioning of the tibiofemoral components in all three planes includes fine tuning of the tibial slope, performed at this point to provide a normal soft tissue balance of extension and numerous knee flexion gaps. The planned operative bone resection is mapped and validated before commencing with the operative procedure. This includes fine tuning of the medial-lateral and internal-external position of the implant using the software to compute and verify that the femoral component tracks in a central position over the tibial component throughout the entire

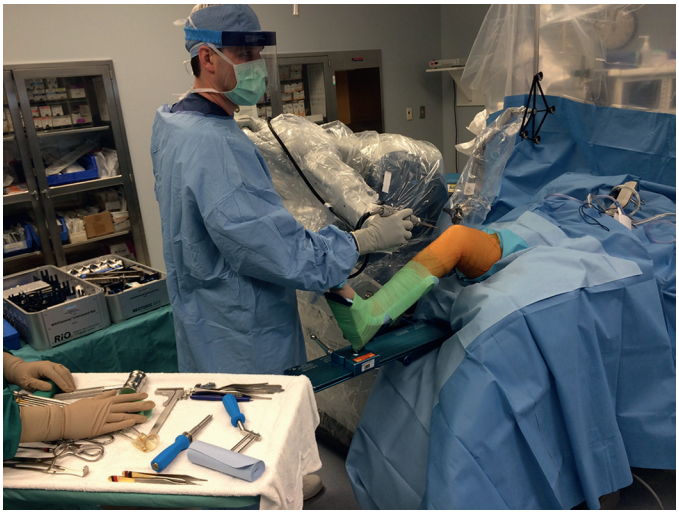


FIG 30-1 The operative positioning of the lower limb, along with the Robotic Arm Interactive Orthopedic System.



FIG 30-2 Operative view (**A**) and illustration (B) of the femoral and tibial arrays and checkpoints. (**B,** Courtesy Stryker Orthopaedics.)

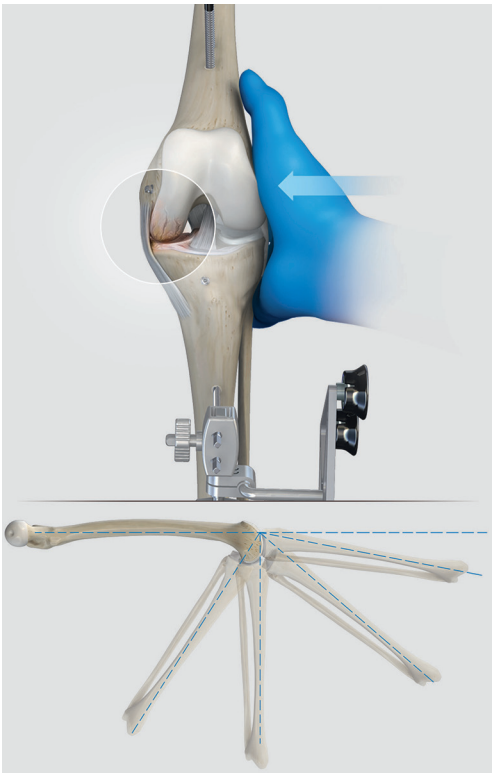


FIG 30-3 Remove overhanging medial osteophytes and then capture a minimum of four poses while applying a valgus stress to passively correct the coronal deformity. The magnitude of the valgus stress must be such that it opens up the collapsed medial compartment and tensions the medial collateral ligament to achieve the desired degree of correction and joint stability. Caution must be exercised to not overcorrect the deformity. In the case of a lateral unicompartmental knee arthroplasty, capture poses while applying a varus stress. The poses captured are in extension, mid flexion, flexion, and full flexion (or approximately 10, 45, 90, and 120 degrees). (Courtesy Stryker Orthopaedics.)

flexion-extension range of knee motion (Fig. 30-5). This step also confirms there is proper sizing of the tibial and femoral implants. The RIO is positioned in the operative field and registered (Fig. 30-6).

The operative plan starts first with the tibial bone resection, followed by femoral bone resection (Fig. 30-7). The trial components are placed with the selected tibial polyethylene trial and determination is made that there is correct anatomic prosthesis alignment during full knee flexion and extension. The surgeon ensures that the anterior femoral tip is flush with the cartilage surface and not proud. Verification of restoration of normal medial or lateral ligament stability and joint opening is performed. The cementing technique follows meticulous steps of irrigation, drying of surfaces, tibial prosthesis placement, and removal of excess cement under direct visualization. Femoral prosthesis cementing and placement of the polyethylene tibial component are done with the joint held under varus or valgus pressure at 30 degree knee flexion. After verification of the soft tissue balance at extension, mid-flexion and high-flexion knee positions, the final polyethylene implant is placed. The extensor mechanism is closed, and the medial or lateral soft tissue structures balanced as described in Chapter 37. The operative steps in closure are designed to prevent excessive medial or lateral soft tissue tension, with the goal of restoring a normal medial or lateral patella glide at 0 and 20 degree knee flexion. A femoral nerve block is commonly performed postoperatively, and the patient either stays overnight for 1 night or remains as an outpatient. The patient is seen by the surgeon and rehabilitation staff the next day to initiate the postoperative rehabilitation protocol.

POSTOPERATIVE MANAGEMENT

The postoperative rehabilitation protocol is shown in Table 30-4. Patients begin immediate knee range of motion (ROM), patellar mobilization, quadriceps strengthening, and balance training with partial weight bearing allowed. A continuous passive motion machine is not required or routinely used by us. Patients perform passive and active ROM exercises in a seated position for 10 minutes a session, approximately 6 times per day. Full passive knee extension must be obtained

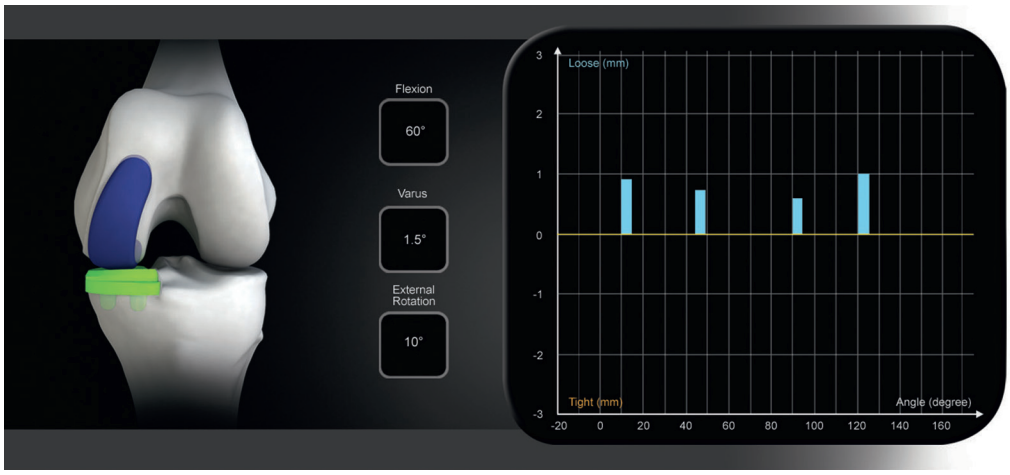


FIG 30-4 Fine tune the femoral and tibial implant placement to ensure joint gaps are 0 to 1.5 mm of looseness through range of motion and good central loading exists between the femoral and tibial components. (Courtesy Stryker Orthopaedics.)

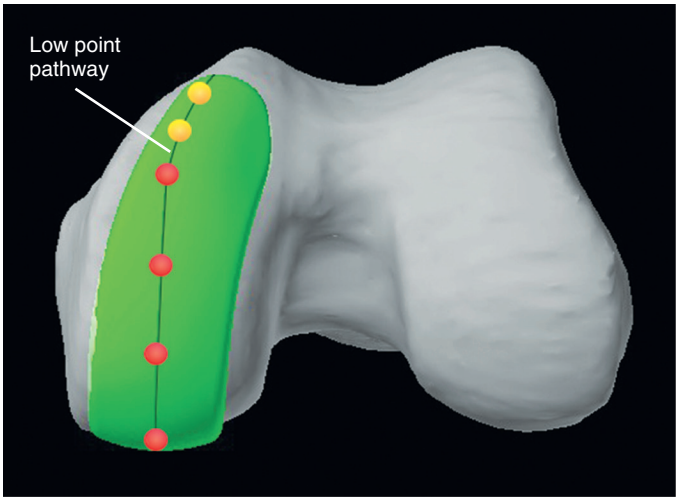


FIG 30-5 Once the joint is balanced, fine tune and medial-lateral position and internal-external rotation of the femoral component to ensure that the femoral component tracks centrally over the tibial component through the patient's range of motion. (Courtesy of Stryker Orthopaedics)

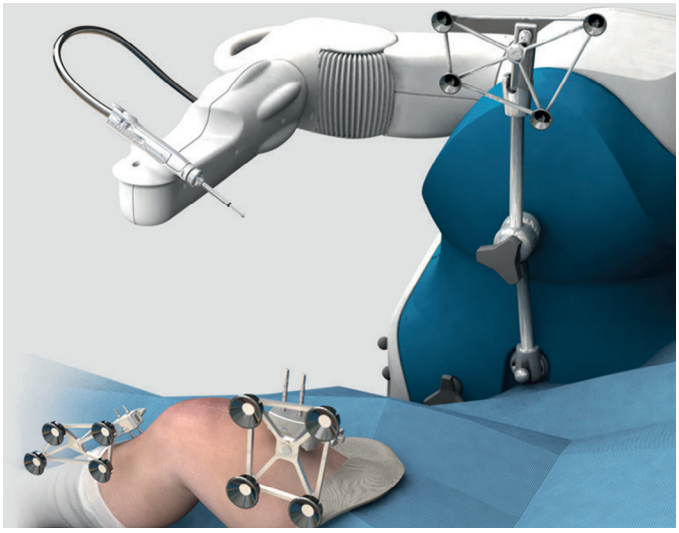


FIG 30-6 Position the RIO in the operative field and perform registration and verification of the robotic arm. (Courtesy Stryker Orthopaedics.)



FIG 30-7 Resect the femoral and tibial surfaces, then create peg holes and keels. (Courtesy Stryker Orthopaedics.)

immediately to avoid excessive scarring. Patellar mobilization is important to restore a normal medial-lateral glide and prevent contracture of soft tissue patellar retinacular structures. If the patient has difficulty regaining at least 0 degrees by the seventh postoperative day, he or she begins an overpressure program. The foot and ankle are propped on a towel or other device to elevate the hamstrings and gastrocnemius, allowing the knee to drop into full extension. This position is maintained for 10 minutes and repeated four to six times per day. A 10- to 20-lb weight may be added to the distal thigh and knee to provide overpressure to stretch the posterior capsule. Knee flexion is gradually increased to 110 degrees by the second postoperative week and 135 degrees by the third to fourth postoperative week. Passive knee flexion exercises are performed initially in the traditional seated position using the opposite lower extremity to provide overpressure. Other methods to assist in achieving flexion greater than 90 degrees include chair rolling, wall slides, knee flexion devices, and passive quadriceps stretching exercises (see Chapter 11).

Patients use a walker or crutches with 50% to 75% weight bearing allowed as tolerated. Full weight bearing is permitted when the patient demonstrates a normal gait pattern, which is usually by the third to fourth postoperative week. Balance, proprioception, and strengthening exercises are gradually increased as supervised by the therapist and shown in Table 30-4 through approximately the twelfth postoperative week. At that time, the patient is encouraged to continue the strengthening and aerobic conditioning program as desired.

COMPLICATIONS AND FACTORS LEADING TO FAILURE

Currently, the progression of tibiofemoral or patellofemoral arthritis and implant loosening are the most common causes of failure or unsatisfactory results (Table 30-5). A study of 418 failed UKAs (requiring any repeat surgery) from the French Hip and Knee Society reported that loosening was the main reason for failure (occurring in 45%) followed by progression of OA (15%) and wear (12%).[42] These findings were similar to those reported in the Swedish, Finnish,[108] and Australian registries. The operations were performed between 1978 and 2009 and included medial UKA in 88%. The majority of bearing designs were fixed (80%) and cement was used for 85% of the femoral components and 70% of the tibial components.

In a study of 1746 UKAs performed in the Kaiser Permanente National Total Joint Registry from 2002 to 2009, Bini and associates[21] reported that implant type, patient age, and yearly surgeon volume were significantly associated with revision rates. Patients younger than 55 years of age had a significantly higher revision rate of 11.7% (39 of 332) compared with those 55 to 65 years of age (4.4%; 28 of 642) and those older than 65 years (2.6%; 20 of 772; $P < .001$). The Preservation All-Poly tibial UKA had a greater risk of revision compared with the Zimmer UKA (9.5% and 1.1%, respectively; $P < .001$). The revision rates for surgeons who performed 12 or fewer UKA per year were significantly higher than those who performed more than 12 per year (6.4% and 3.2%, respectively; $P < .01$).

The incidence of thromboembolic events after UKA with use of a chemoprophylaxis and compression boot protocol is exceedingly low. Berend and associates[15] followed 1000 consecutive UKAs in 828 patients (97% medial, 3% lateral) to determine the incidence of thromboembolic complications. Patients considered to have no risk factors were prescribed aspirin (325 mg, 1-2 times/day) for 6 weeks. Moderate-risk patients received low-molecular-weight-heparin (LMWH) for 2 weeks and aspirin for 4 more weeks. High-risk patients had warfarin

Text continued on p. 894

TABLE 30-4 Noyes Knee Institute Rehabilitation for Unicompartmental Arthroplasty

	POSTOPERATIVE WEEKS				
	1-2	3-4	5-6	7-8	9-12*
ROM minimum goals:					
0-110 degrees	X				
0-135 degrees		X			
Weight bearing:					
50%-75% body weight	X				
100% body weight		X			
Patella mobilization	X	X	X	X	
Modalities:					
EMS	X	X	X		
Pain/edema management (cryotherapy)	X	X	X	X	
Stretching: hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X
Strengthening:					
Quadriceps isometrics, straight-leg raises	X	X	X	X	X
Closed-chain: gait retraining, toe-raises, wall-sits, minisquats	X	X	X	X	X
Knee flexion hamstring curls (90 degrees)		X	X	X	X
Knee extension quadriceps (90-30 degrees)		X	X	X	X
Hip abduction-adduction, multi hip		X	X	X	X
Leg press (70-10 degrees)		X	X	X	X
Balance/proprioceptive training:					
Weight shifting, minitrampoline, BAPS, BBS	X	X	X	X	X
Conditioning:					
UBC	X	X	X	X	X
Bike (stationary)		X	X	X	X
Aquatic program			X	X	X
Swimming (kicking)				X	X
Walking				X	X
Stair-climbing machine				X	X
Ski machine				X	X
Elliptical machine				X	X
Upper body weight training			X	X	X
Core training			X	X	X

PHASE 1: WEEKS 1 TO 2

General Observation

50%-75% weight bearing with crutches/walker when:
- Pain is controlled
- Hemarthrosis is controlled
- Voluntary quadriceps contraction is achieved

Goals

ROM 0-110 degrees
Adequate quadriceps contraction
Control inflammation, effusion

Factors Evaluated

Pain (controlled)
Hemarthrosis (mild)
Patellar mobility (good)
ROM (minimum 0-110 degrees)
Quadriceps contraction and patella migration (good)
Soft tissue contracture (none)

Continued

TABLE 30-4 Noyes Knee Institute Rehabilitation for Unicompartmental Arthroplasty—cont'd

PHASE 1: WEEKS 1 TO 2

	Frequency	Duration
Range of Motion		
0-110 degrees, hang 10-20 lb of weight if <0 degrees	6 ×/day, 10 min	
Patella mobilization	3 ×/day	
Ankle pumps (plantar flexion with resistance band)	15 min	
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion, extension, abduction, adduction)		3 sets × 10 reps
Active quadriceps isometrics		10 reps
Knee extension quadriceps, active/active-assisted (range as tolerated)		3 sets × 10 reps
Multi-hip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Weight shift side-side and forward-backward		5 sets × 10 reps
Balance board/two-legged		5 sets × 10 reps
Cup walking		5 sets × 10 reps
Single-leg stance		5 sets × 10 reps
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

PHASE 2: WEEKS 3 TO 4

General Observation	Full weight bearing (weeks 2-3) when gait pattern is normal and: • Pain is controlled • Hemarthrosis is controlled • Voluntary quadriceps contraction, full extension, is achieved	
Goals	ROM 0-135 degrees Control inflammation, effusion Muscle control	
Factors Evaluated	Pain (controlled) Effusion (mild) Patellar mobility (good) ROM (minimum 0-135 degrees) Quadriceps contraction and patella migration (good) Soft tissue contracture (none)	
	Frequency	**Duration**
Range of Motion		
Passive (0-135 degrees), hang 10-20 lb weight if <0 degrees; flexion overpressure: stool rolls, wall-slides if <90 degrees	3 ×/day, 15 min	
Patella mobilization	3 ×/day, 15 min	
Ankle pumps (plantar flexion with resistance band)	3 ×/day, 15 min	
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec

TABLE 30-4 Noyes Knee Institute Rehabilitation for Unicompartmental Arthroplasty—cont'd

	Frequency	Duration
PHASE 2: WEEKS 3 TO 4		
Strengthening	2-3 ×/day, 20 min	
Straight-leg raises (flexion, extension, abduction, adduction)		3 sets × 10 reps
Isometric training: multiangle (0 and 60 degrees)		1 set × 10 reps
Knee extension quadriceps (resistance, 90-30 degrees)		3 sets × 10 reps
Closed-chain: wall-sits (0-45 degrees)		30-60 sec × 5
Knee flexion hamstring curls (0-90 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Weight shift side-side and forward-backward		5 sets × 10 reps
Balance board/two-legged		
Cup walking		
Single-leg stance		5 reps
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Stationary bicycling (high seat, low resistance)		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
PHASE 3: WEEKS 5 TO 6		
General Observation	Full weight bearing when: • Pain is controlled without narcotics • Hemarthrosis is controlled • ROM 0-135 degrees • Muscle control throughout ROM	
Goals	ROM 0-135 degrees Control inflammation, effusion Muscle control Early recognition of complications (motion, RSD, patellofemoral) Full weight bearing	
Factors Evaluated	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (minimum 0-135 degrees) Muscle control (3+/5) Inflammatory response (none)	
	Frequency	**Duration**
Range of Motion		
Passive (0-135 degrees), continue overpressure program if <0-100 degrees	3 ×/day, 10 min	6 ×/day
Patella mobilization	3 ×/day, 10 min	
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (ankle weight 2.5-10 lb)		3 sets × 10 reps
Heel raise/toe raise		3 sets × 20 reps
Knee extension (resistance, 90-30 degrees)		3 sets × 10 reps
Knee flexion (active, 0-90 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps

Continued

TABLE 30-4 Noyes Knee Institute Rehabilitation for Unicompartmental Arthroplasty—cont'd

PHASE 3: WEEKS 5 TO 6

	Frequency	Duration
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Closed-chain: wall-sits (0-45 degrees)		5 reps
Balance Training	2 ×/day, 5 min	
Balance board, two legged		
Cup walking		
Single-leg stance		5 reps
Aerobic Conditioning	1-2 ×/day, 10 min	
UBC		
Stationary bicycling (high seat, low resistance)		
Water walking (water depth at thigh or waist)		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min

PHASE 4: WEEKS 7 TO 8

General Observation	Independent ambulation ROM 0-135 degrees Can stand and walk for 30 min	
Goals	Full weight bearing Muscle control Control of inflammation, effusion ROM 0-135 degrees	
Factors Evaluated	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-135 degrees) Muscle control (4/5) Inflammatory response (none)	
	Frequency	**Duration**
Range of Motion	2 ×/day, 20 min	
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (flexion, extension, abduction, adduction) with weights or rubber tubing		3 sets × 10 reps
Closed-chain:		
Wall-sits		5 reps
Minisquats (rubber tubing, 0-30 degrees)		3 sets × 20 reps
Forward step-ups (2- to 4-inch block)		3 sets × 10 reps
Hamstring curls (resistance, 0-90 degrees)		3 sets × 10 reps
Knee extension (resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Balance Training	2 ×/day, 5 min	
Balance board, single legged (stable vs. unstable surface)		
Single-leg stance		5 reps

TABLE 30-4 Noyes Knee Institute Rehabilitation for Unicompartmental Arthroplasty—cont'd

PHASE 4: WEEKS 7 TO 8

	Frequency	Duration
Aerobic Conditioning	1-2 ×/day, 10-15 min	
UBC		
Water walking		
Swimming (straight-leg kicking)		
Stationary bicycling		
Stair machine (low resistance, low stroke)		
Ski machine (short stride and level, low resistance)		
Modalities	As required	
Cryotherapy		20 min

PHASE 5: WEEKS 9 TO 12

General Observation	Independent ambulation ROM 0-135 degrees	
Goals	Increase strength and endurance Increase balance and coordination ROM 0-135 degrees	
Factors Evaluated	Pain (minimal/no CRPS) Swelling (minimal) Manual muscle test (hamstrings, quadriceps, hip abductors/adductors/flexors/extensors; 4+/5) Patellar mobility (good) Gait (symmetrical)	
	Frequency	**Duration**
Range of Motion	2-3 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	1-2 ×/day, 20 min	
Straight-leg raises		3 sets × 10 reps
Straight-leg raises with weights or rubber tubing		3 sets × 30 reps
Hamstring curls (resistance, 0-90 degrees)		3 sets × 10 reps
Knee extension (resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue ×3
Minisquats (with rubber tubing, 0-40 degrees)		3 sets × 20 reps
Lateral step-ups (2- to 4-inch block)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Balance Training	2 ×/day, 5 min	
Balance board, single legged (stable vs. unstable surface)		
Single-leg stance		5 reps
Aerobic Conditioning	1-2 ×/day, 15 min	
Water walking		
Swimming (straight-leg kicking)		
Stationary bicycling		
Walking		
Stair machine (low resistance, low stroke)		
Ski machine (short stride and level, low resistance)		
Modalities	As required	
Cryotherapy		20 min

*After postoperative week 12, patient continues strengthening and conditioning program as desired.
BAPS, Biomechanical Ankle Platform System (Patterson Medical); *BBS*, Biodex Balance System (Biodex Medical Systems); *CRPS*, complex regional pain syndrome; *EMS*, electrical muscle stimulation; *ITB*, iliotibial band; *UBC*, upper body cycle; *ROM*, range of motion.

TABLE 30-5 Effect of Various Factors on Failure of Unicompartmental Knee Arthroplasty

Factor	Studies Associated With Failure (References)	Studies Not Associated With Failure (References)
Progressive arthritis (any compartment)	4, 18, 42, 51, 73, 118, 127, 145, 164	
Component loosening	3, 19, 27, 42, 51, 73, 95, 127, 137, 164, 169	
Bearing dislocation	31, 68, 80, 169	
Polyethylene wear	121	
Tibiofemoral angle 4-6 degrees valgus	66	
Prior HTO	154	
Partial loss medial joint space on x-ray	109	
Patellofemoral joint osteoarthritis (x-ray or arthroscopy)	11, 74	10, 11 (except lateral patellar damage), 118, 144
Body mass index	13, 51, 71	28, 38, 74, 100, 123
Age	74 (<60 yr), 7 (<55 yr)	38, 51, 71, 73, 93, 118, 123, 148, 154
Gender		38, 51, 53, 73, 74, 93
Type tibial implant (full poly, cemented, uncemented metal back)		53, 123
ACL deficiency		23
Concomitant ACL reconstruction		72, 114, 150, 162

ACL, Anterior cruciate ligament; *HTO*, high tibial osteotomy.

supplemented by LMWH. All patients received intermittent pneumatic compression devices and antithrombotic stockings throughout their hospital stays and began full weight bearing and ROM exercises the day of surgery. Only one DVT (0.1%) was reported, and no pulmonary embolism or deaths occurred.

Prosthesis-related bone loss (postoperative decrease in bone mineral density [BMD]) reported after TKA[76,143] has been believed to be related to strain shielding. Strain shielding may promote reduction of bone density and bone resorption, whereas overload promotes excessive formation of bone that causes an increase in bone density and may induce fatigue damage.[46] Loss of bone may lead to periprosthetic fracture or weakening of the implant fixation, resulting in loosening and implant failure.[94,143] To date, only one clinical study assessed BMD after UKA. Richmond and associates[131] followed 50 medial UKAs (Oxford or Genesis) with CT osteodensitometry 1 and 2 years postoperatively. These authors reported mean cancellous BMD decreased only 1.9% on the medial side and 1.1% on the lateral side. Mean cortical BMD decreased 0.4% on the medial side and 0.5% on the lateral side. There were no differences among the implant designs in early BMD changes.

CLINICAL STUDIES

Medial Unicompartmental Knee Arthroplasty

The survivorship rates reported after medial UKA are shown in Table 30-6, and the clinical outcomes are shown in Table 30-7. The rating systems most commonly used to determine clinical outcome to date have been the American Knee Society (AKS) and Oxford Knee Score (OKS), described in detail in Chapter 45. The AKS Function and Knee scores reported in these studies represent the original version of this system because the extensive update was published in 2012.

The Oxford UKA has been the most widely studied of all medial UKA prostheses. Labek and coworkers[75] conducted a systematic review of the literature describing outcomes of the Oxford UKA of articles published from 1988 to 2008. The investigators found that the average results published by the inventor team were significantly better with regard to revision rates than those published by independent studies or worldwide registries. The revision rate from the developing team was 2.7 times lower than the rates published in independent studies and 4.4 times lower than registry data from Sweden and Denmark. These authors cautioned that "the average surgeon should be aware of the fact that the outcome published by the inventing center appears to be hardly reproducible in average patient care and other institutions."[75] The data shown in Table 30-7 represent studies on the Oxford UKA published from 2011 to 2014; only 3 of the 17 studies were from the inventor team. Ten-year survival rates from independent studies ranged from 75% to 95%, although rates from the inventor team ranged from 93% to 95%.

The question of whether individuals with bilateral severe medial OA should undergo simultaneous or staged UKA has been addressed in three studies.[16,29,30] Chen and coworkers[30] followed a group of 171 patients for 2 postoperative years. The patients were invited to choose between the two options, and the majority (72.5%) elected a simultaneous procedure. There were no differences in complications or short-term outcomes with regard to AKS or Oxford scores. The cumulative operating time and length of hospital stay were shorter for simultaneous procedures, and the overall cost for this option was lower. There were no serious complications in either group; all patients received enoxaparin 40 mg once daily and pneumatic calf pumps for prophylaxis of venous thromboembolic events. Chan and associates[29] reported significant differences in major complications between 318 simultaneous and 160 staged medial UKA knees. There were 13 such complications in the simultaneous group and none in the staged group; however, no chemoprophylaxis was used for thromboembolic events that accounted for 10 of the 13 complications. Berend and colleagues[16] reported no major complications in 70 knees that underwent simultaneous UKA and 282 knees that had staged bilateral UKAs. These investigators used chemoprophylaxis (discretion of the medical management providers) and mechanical compression boots to prevent thromboembolic events. The simultaneous group had a shorter cumulative operating room time and hospital stay and a higher AKS function score a mean of 19.4 months postoperatively. There was a selection bias in that patients who received simultaneous procedures were younger and less obese.

Unicompartmental Knee Arthroplasty versus High Tibial Osteotomy

The outcomes of modern UKA and HTO have been compared in several investigations, with most finding little to no differences in postoperative knee function between these operations (Table 30-8).[47]

In 2014, Nwachukwu and associates[112] compared UKA and HTO practice patterns in a large U.S. private payer insurance database that

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TABLE 30-6 Survival Rates of Medial Unicompartmental Arthroplasty

Study	Prosthesis	No. Knees/ Patients	Mean Follow-up (yr)	Survival End Points	SURVIVAL RATES					
					2-3 yr	5 yr	7 yr	10 yr	15 yr	20 yr
Baker et al[7] (2012)	Mixed	30,795/NA	NA	Revision	96%	93%	91%	—	—	—
Choy et al[31] (2011)	Oxford Phase 1	188/166	6.6 (range, 4.7-8.6)	Revision	—	6.6 yr: 90%	—	—	—	—
Schroer et al[137] (2013)	Oxford Phase 2	83/77	3.6 (range, 0.3-7.1)	Revision or aseptic loosening	—	86%	—	—	—	—
Zermaten & Munzunger[170] (2012)	Oxford Phase 2	48/42	10	Revision	88%	85%	83%	78%	—	—
Mercier et al[95] (2010)	Oxford Phase 2	43/40	14.9 (range, 13-17)	Revision	—	91%	—	75%	70%	—
Vorlat et al[154] (2006)	Oxford Phase 2	149/140	10.5 (range, 5.2-14.5)	Revision or exchange of implant	96%	92%	90%	82%	—	—
Rajasekhar et al[130] (2004)	Oxford Phase 2	135/124	5.8 (range, 2-12)	Revision	98%	97%	97%	94%	—	—
Bergeson et al[19] (2013)	Oxford Phase 3	839/688; mean age, 63 yr (range, 29-91 yr)	3.7 (0.9-6.5)	Revision	95%	—	—	—	—	—
Boissonneault et al[23] (2013)	Oxford Phase 3	92/84; mean age, 65 yr	4.9	Revision	—	94%	—	—	—	—
Kristensen et al[73] (2013)	Oxford Phase 3	659/579	4.6 (range, 0.1-10.7)	Removal or exchange of implant	—	—	—	85%	—	—
Murray et al[100] (2013)*	Oxford Phase 3	2438/2438	4.6 (range, 1-12)	Removal or exchange of implant	—	BMI†: 95%, 97%, 95%, 94%, 95%, 100%	—	BMI†: 95%, 93%, 95%, 94%, NA, NA	—	—
Yoshida et al[169] (2013)	Oxford Phase 3	1251/990	5.2 (range, 1-10.5)	Revision	98%	98%	98%	95%	—	—
Kim et al[66] (2012)	Oxford Phase 3	246/246	7.4	Revision or exchange of implant	—	—	8-yr: 92%	—	—	—
Clement et al[33] (2012)	Oxford Phase 3	49/49	7.2	Revision	91%	91%	91%	—	—	—
Matharu et al[93] (2012)	Oxford Phase 3	459/392	4.4 (range, 0.5-11.2)	Conversion TKA	99%	94%	93%	—	—	—
Weston-Simmons et al[162] (2012)	Oxford Phase 3	52/52, all ACL reconstructed	5 (range, 1-10)	Revision or exchange of implant	96%	93%	93%	93%	—	—
Pandit et al[117] (2011)*	Oxford Phase 3	1000/818	5.6 (range, 1-10)	Revision or exchange of implant	99%	99%	97%	95%	—	—
Price & Svard[127] (2011)*	Oxford Phase 1, 2, 3	682/543	0.5-22	Revision or exchange of implant	97%	96%	94%	94%	92%	91%
Argenson et al[4] (2013)	Miller-Galante	160/147	20	Revision	—	—	—	94%	83%	74%
Rachha et al[129] (2013)	Miller-Galante	56/52 (5 lateral UKA)	10.7 (range, 5-18)	Revision	—	—	—	95%	—	—

Continued

TABLE 30-6 Survival Rates of Medial Unicompartmental Arthroplasty—cont'd

Study	Prosthesis	No. Knees/ Patients	Mean Follow-up (yr)	Survival End Points	SURVIVAL RATES					
					2-3 yr	5 yr	7 yr	10 yr	15 yr	20 yr
Foran et al[44] (2013)	Miller-Galante	62/51	19 (range, 15-21)	Revision	—	—	—	—	93%	90%
Parratte et al[121] (2009)	Miller-Galante	35/31	9.7 (range, 5-16)	Revision	—	—	—	12-yr: 81%	16-yr: 70%	—
Berger et al[18] (2004)	Miller-Galante	59/48	13 (range, 11-15)	Revision	—	—	—	98%	96%	—
Naudie et al[105] (2004)	Miller-Galante	113/84	10 (range, 3-14)	Revision or x-ray evidence of loosening	—	93%	—	86%	—	—
Pennington et al[123] (2003)	Miller-Galante	46/41	11 (range, 5.6-13.8)	Revision	—	—	—	11-yr: 92%	—	—
Hamilton et al[51] (2014)	Preservation	517/416	4.9	Revision	97%	6-yr: 92%	—	—	—	—
Bruni et al[27] (2013)	Preservation	33/33	8	Revision	—	—	8-yr: 83%	—	—	—
Liebs et al[79] (2013)	Preservation	430/430	6 (range, 2.1-9.8)	Revision	95%	93%	90%	9-yr: 90%	—	—
Bhattacharya et al[20] (2012)	Preservation	97/85	3.7 (range, 2-6.2)	Revision or waiting for revision	—	6-yr: 91%	—	—	—	—
Newman et al[107] (2009)	St. Georg Sled	48/46	15	Revision, Bristol score <60, loosening	—	—	—	—	90%	—
Steele et al[145] (2006)	St. Georg Sled	203/174	14.8 (range, 10-29.4)	Revision	—	—	—	97%	92%	80%
Biswas et al[22] (2014)	Zimmer Uni Knee	88/NA	4 (range, 2-12)	Revision or x-ray evidence of loosening	—	—	—	96%	—	—
Barnes et al[9] (2013)	EIUS	34/28; mean age, 79 yr (range, 64-98)	8	Revision	—	85%	8-yr: 70%	—	—	—
Heyse et al[53] (2012)	Genesis	223/223; mean age, 54 yr (range, 30-60 yr)	10.8 (range, 5-18)	Revision or exchange of implant	—	—	—	91%	85%	—
Hall et al[50] (2013)	Unix	85/76	10 (range, 8-13)	Revision	—	—	8-yr: 99%	10-yr: 92%, 12-yr: 76%	—	—
Cavaignac et al[28] (2013)	HLS Uni	270 (55 lateral)	11.6 (range, 7-22)	Revision	—	—	—	93%	—	—
Whittaker et al[164] (2010)	Miller Galante or Oxford	229/229	Miller Galante, 8.1; Oxford, 3.6	Revision	—	MG 95% Oxford 89%	—	—	—	—

*From the inventor team of the Oxford medial unicompartmental arthroplasty prosthesis.
†Body mass index (BMI) subgroups (in order): <25 ($n = 378$), 25 to <30 ($n = 856$), 30 to <35 (712), 35 to <40 (286), 40 to <45 ($n = 126$), ≥45 ($n = 80$).
ACL, Anterior cruciate ligament; *NA*, not available; *TKA*, total knee arthroplasty; *UKA*, unicompartmental knee arthroplasty.

TABLE 30-7 Clinical Outcomes of Modern Medial Unicompartmental Arthroplasty

Study	Prosthesis	No. Knees	Mean Age (yr)	Mean Follow-up (yr)	No. Knees With Outcome Data	Knee Rating Outcome Scores	Other Outcomes
Choy et al[31] (2011)	Oxford Phase 1	188	65 (range, 44-82)	6.6 (range, 4.7-8.6)	188	HSS = 90 (range, 85-100)	80% could squat; 92% could sit cross-legged; 5% revised
Schroer et al[137] (2013)	Oxford Phase 2	83	57 (range, 40-76)	3.6 (range, 0.3-7.1)	72	AKS Knee = 87 (range, 41-100); Function = 77 (range, 10-100); Oxford = 20 (range, 12-51)	Satisfaction: 51% excellent, 7% very good, 29% good, 13% fair/poor; 13% revised
Rajasekhar et al[130] (2004)	Oxford Phase 2	135	53-88	5.8 (range, 2-12)	96	AKS Knee = 92 (range, 51-100); Function = 76 (range, 20-100)	57% no pain, 33% mild pain, 10% moderate pain; 92% fully satisfied
Akran et al[1] (2013)	Oxford Phase 3	263	64 (range, 35-84)	3 (range, 2-4.3)	263	OKS range = 29-47; AKS Knee range = 71-100; Function range = 68-100	7% cemented group revised, 5% uncemented group revised; no differences in short-term follow-up between cemented and uncemented
Boissonneault et al[23] (2013)	Oxford Phase 3	92	4.9		92	AKS Objective in ACL deficient = 88, ACL intact = 85; Functional in ACL deficient = 100, ACL intact = 73	No significant differences in clinical scores or failures between ACL-deficient and ACL-intact knees
Kristensen et al[73] (2013)	Oxford Phase 3	659	64 (30-94)	1 and 6	1 yr: 547 6 yr: 110	NA	94% satisfied at 1 year; 7% revised, most for either progression of OA or aseptic loosening
Pietschmann et al[125] (2013)	Oxford Phase 3	181	65 (range, 44-83)	4.2 (range, 1-10)	131	OKS = 38.6; AKS Overall = 90 in active patients, 82 in inactive patients; Function = 87 in active, 78 in inactive; WOMAC Pain = 93 in active, 84 in inactive	80% active patients (before surgery) returned to sports, mostly low impact; 93% self-reported excellent/good result; 3% revised
Kim et al[66] (2012)	Oxford Phase 3	246	62 (range, 45-84)	7.4	246	AKS Knee = 86 (range, 10-100); Function = 82 (range, 60-100); no relationship between scores and postoperative tibiofemoral angle	7% failed; survival rate associated with tibiofemoral angle; highest in 4-6 degrees valgus group, lowest in ≥10 degrees valgus group
Clement et al[33] (2012)	Oxford Phase 3	49	68	7.2	43	Oxford Function = 16; Pain = 22; total = 38	86% satisfied, 8% revised
Weston-Simmons et al[162] (2012)	Oxford Phase 3	52	51 (range, 36-67)	5 (range, 1-10)	51	AKS Overall = 76 (range 25-95); Function = 95 (range, 45-100); OKS = 41 (range, 17-48)	All ACL reconstructed, no instability at follow-up; no effect of age, gender, concomitant or staged ACL reconstruction
Pandit et al[118] (2011)	Oxford Phase 3	1000	66 (range, 32-88)	5.6 (range, 1-10)	895	OKS = 41; AKS Objective = 86; Function = 86	3% revised; no effect of weight, age, activity level, patellofemoral joint damage on outcome
Price et al[126] (2005)	Oxford Phase 1, 2, 3	564	70 (range, 34-94)	NA	512 ≥60 yr age, 52 <60 yr age	HSS = 94 in younger group, 86 in older group	4.3% revised; 10-yr survival rates: 96% age >60 yr, 91% age <60 yr

Continued

TABLE 30-7 **Clinical Outcomes of Modern Medial Unicompartmental Arthroplasty—cont'd**

Study	Prosthesis	No. Knees	Mean Age (yr)	Mean Follow-up (yr)	No. Knees With Outcome Data	Knee Rating Outcome Scores	Other Outcomes
Argenson et al[4] (2013)	Miller-Galante	147	66 (range, 35-88)	20	70	AKS Overall = 91 (range, 50-100); Function = 88 (range, 45-100)	NA
Rachha et al[129] (2013)	Miller-Galante	74	64 (range, 47-80)	10.7 (range, 5-18)	56 (5 lateral UKA)	AKS Overall = 80 (range, 51-95); Function = 75 (range, 45-90)	54% no pain, 27% mild pain, 11% moderate pain, 8% severe pain
Parratte et al[121] (2009)	Miller-Galante	35	46 (range, 41-49)	9.7 (range, 5-16)	35	AKS Knee = 97 (range, 85-100); Function = 89 (range, 80-100)	65% enthusiastic, 26% satisfied, 3% no change, 6% not satisfied; 17% revised, mostly for wear
Berger et al[18] (2004)	Miller-Galante	59	67 (range, 51-84)	13 (range, 11-15)	59	HSS = 90 (range, 60-100)	57% no pain, 33% slight pain, 5% moderate pain, 5% severe pain
Pennington et al[123] (2003)	Miller-Galante	46	54 (range, 35-60)	11 (range, 5.6-13.8)	44	HSS = 94 (range, 72-100); UCLA = 6.5 (range, 4-10)	No effect of age, weight, BMI, polyethylene height, change in HSS score on revision rate
Bruni et al[27] (2013)	Preservation	33	54 (range, 42-59)	8	26	AKS Overall = 87; Function = 84; Oxford = 40; WOMAC = 85	15% revised
Liebs et al[79] (2013)	Preservation	430	74 (range, 44-91)	6 (range, 2.1-9.8)	NA	WOMAC Function = 23.4; Pain = 21.3; Stiffness = 21.9; SF-36 Physical Component = 41.4, Mental Component = 49.5	7% revised
Naal et al[101] (2007)	Preservation	83	65 (range, 47-83)	1.5 (range, 1-2.3)	83	SF-36 scores for all domains significantly higher than matched reference population	93% returned to sports, recreational activities (mostly low impact) after surgery; no effect of age or gender on return to activities
Biswas et al[22] (2014)	Zimmer Uni Knee	88	49 (range, 33-55)	4 (range, 2-12)	88	AKS Overall = 95 (range, 48-100); UCLA activity = 7.5 (range, 5-9)	3% revised
Panni et al[120] (2012)	Zimmer Uni Knee	80	68 (range, 55-84)	4.5 (range, 3-6)	77	IKS Knee = 82 (range, 76-94); Function = 94 (range, 88-98)	0% revised; no difference in IKS scores between patient >60 yr age and <60 yr age; survivor rates NA
Heyse et al[53] (2012)	Genesis	173	54 (range, 30-60)	10.8 (range, 5-18)	173	AKS Overall = 97; Function = 97	71% of patients who were active before surgery returned to athletics; 7% revised
Cavaignac et al[28] (2013)	HLS Uni	270 (55 lateral)	66 (range, 39-92)	11.6 (range, 7-22)	270	AKS Knee = 80 (range, 64-96); Function = 79 (range, 50-100)	No effect of BMI AKS scores, survivorship rate; 5% revised
Whittaker et al[164] (2010)	Miller- Galante or Oxford	229	45-87	Miller Galante, 8.1; Oxford, 3.6	185	No difference between groups for AKS, WOMAC, SF12 scores	15% Miller-Galante and 9% Oxford revised

ACL, Anterior cruciate ligament; *ADL*, activities of daily living; *AKS*, American Knee Society; *BMI*, body mass index; *HSS*, Hospital for Special Surgery; *IKS*, International Knee Society; *KOOS*, Knee Osteoarthritis Outcome Survey; *NA*, not available; *OA*, osteoarthritis; *OKS*, Oxford Knee Score; *TKA*, total knee arthroplasty; *UKA*, unicompartmental knee arthroplasty; *VAS*, visual analogue scale; *WOMAC*, Western Ontario and McMaster Universities Arthritis Index.

TABLE 30-8 Studies Comparing Medial Unicompartmental Arthroplasty with High Tibial Osteotomy

Study	Type HTO UKA Prosthesis	No. Knees/ Patients	Mean Age (yr)	Mean Follow-up (yr)	AMERICAN KNEE SOCIETY SCORES Knee	Function	Other Outcomes	Failure Rates
Yim et al[168] (2013)	Opening wedge Miller-Galante	58/50	58 (range, 43-65) 60 (range, 47-63)	3.6 (3-4) 3.7 (3-4)	NA	NA	Lysholm: HTO = 90 ± 9, UKA = 90 ± 8 Return to sports: HTO = 67%, UKA = 60%	5% 6%
W-Dahl et al[155] (2010)	Hemicallotasis Unknown	450/479	30-64 30-64	10 10	NA	NA	NA	17% 17%
Dettoni et al[39] (2013)	Opening wedge Accuris	54/56	55 65	2-4 2-4	76 93	91 84	NA	NA
Takeuchi et al[149] (2010)	Opening wedge Compartment Uni-Knee	27/30	67 (54-78) 77 (69-86)	5.1 6.9	89 88	95 79, ($P < .01$)	Return to sports: HTO = 18%, UKA = 0%	0% 10%
Borjesson et al[25] (2005)	Closing wedge Brigham	18/22	63 ± 4 63 ± 4	5 5	NA	NA	British Orthopedic Association score: HTO = 38, UKA = 37. Patient rating: all patients except 1 UKA rated knee as improved. No difference in gait walking speed, step frequency at 1 and 5 yr.	NA

HTO, High tibial osteotomy; *NA*, not available; *UKA*, unicompartmental knee arthroplasty.

represented 10% of the U.S. population. Between 2007 and 2011, a total of 15,354 UKA and 1047 HTO procedures were performed. The ratio of UKA:HTO was 12:09 in 2007 and increased every year to 17:02 in 2011. Using the age of 30 years as a reference, the likelihood of receiving UKA over HTO became significant when patients reached 50 years of age.

In a unique study, Valenzuela and colleagues[151] compared the outcomes of 22 patients who underwent UKR (Miller-Galante) after a failed closing-wedge HTO with 18 patients who underwent primary UKR (Miller-Galante). The mean ages for the groups were similar (65 and 67 years, respectively), and the follow-up time periods were also similar (6.5 and 7.3 years, respectively). There were no significant differences in AKS Knee and Function scores or in Oxford knee scores between the groups. The authors suggested that a prior HTO did not influence the clinical outcome of a subsequent UKR.

Unicompartmental Knee Arthroplasty versus Total Knee Arthroplasty

Many studies have compared outcomes of UKA with TKA (Table 30-9) even though a direct comparison between these procedures is most likely not realistic because of different implant designs, indications for surgery, duration of follow-up, patient age and postoperative activity levels, and surgeon experience and volume.[55,82,88,108,111,166] In addition, few have matched UKA and TKA cohorts before surgery for age, gender, BMI, and knee function as determined from validated rating scales. Many were retrospective in design.[82,88,147,166]

Many studies have been conducted with national knee joint registry data from outside the United States. For example, Niinimaki and associates[108] reported survivorship data from the Finnish registry on 4713 UKAs and 83,511 TKAs followed a mean of 6 years postoperatively. The majority of UKA prostheses were Oxford Phase III, but 37 different prostheses were used in the TKA patients. The study found that UKA had inferior survivorship rates, even when adjusted for age greater or less than 65 years and gender. Aseptic loosening was the most common cause of failure of both procedures, but it occurred more frequently in UKA. Similar survivorship results have been reported from knee arthroplasty registry data from Australia,[6] the United Kingdom,[110] New Zealand,[113] and Sweden.[156] However, Goodfellow and associates[49] criticized the use of revision rates as outcome measures for national knee joint registry data. In analyzing data from the New Zealand registry, these authors found that the sensitivity of revision rates to clinical failure was different between UKA and TKA. The UKA group had higher Oxford knee scores but nearly three times the revision rate as TKA. In knees with very poor scores (<20 points), only 12% of TKAs were revised compared with 63% of UKRs with similar scores. The conclusion was reached that UKA may be revised more frequently because it is a less invasive intervention and may be converted to TKA without difficulty, whereas revision TKA is a more complicated procedure. This is especially valid in patients with nonspecific knee pain without obvious failure of the implant.

Noticewala and colleagues[111] reported superior knee function outcomes (as determined by Western Ontario and McMaster Universities Osteoarthritis Index [WOMAC] and Short Form [SF]-12 scores) after UKA compared with TKA a mean of 3 years after surgery. Multivariate linear regression analysis that controlled for age, gender, Charlson

TABLE 30-9 Unicompartmental Knee Arthroplasty vs. Total Knee Arthroplasty

	TKA				UKA						
Citation	No. Knees	Mean Age (yr)	Mean Follow-up (yr)	Prostheses	No. Knees	Mean Age (yr)	Follow-up (yr)	Prostheses	Functional Scores	Survivorship	Factors Affecting Survival
Niinimaki et al[108] (2014)	83,511	69 (range, 23-96)	6.4 (range, 0-27)	37 different designs	4713	63 (range, 35-91)	6.0 (range, 0-24)	Oxford, 87%; 3 others, 13%	NA	5-yr: UKA 89%, TKA 96%; 10-yr: UKA 81%, TKA 93%; 15-yr: UKA 70%, TKA 89%	Aseptic loosening in both; age <65 yr TKA; UKR (adjusted for age and gender).
Noticewala et al[111] (2012)	128	67 (range, 46-88)	3 (range, 2-8.5)	NA	70	67 (range, 40-87)	3 (range, 2-6.5)	NA	UKA superior scores SF-12 physical, mental; WOMAC pain, stiffness, physical function. UKA larger improvement in all scores compared with preoperative status.	NA	NA
Lyons et al[88] (2012)	5606	68 ± 9	6.5 (range, 2-33)	NA	279	66 ± 8	7 (range, 2-23)	NA	UKA higher scores at follow up, WOMAC function, SF-12 physical, AKS function, total. No difference in change in scores from preop between UKA and TKA.	5-yr: UKA 95%, TKA 98%, 10-yr: UKA 90%, TKA 95%	Wear, loosening in both; osteoarthritis progression in UKA.
Lombardi et al[82] (2009)	115	62 (range, 41-85)	2.7 (range, .2-4.3)	Oxford Phase III, Vanguard (Biomet)	115	61 (range, 40-85)	2.5 (range, 0.1-4.3)	Oxford Phase III	UKA higher Lower extremity activity scale scores. No difference AKS or Oxford scores.	NA	NA
Willis-Owen et al[166] (2009)	20	NA	NA	NA	40 (20 medial, 20 lateral)	NA	NA	NA	UKA higher Total Knee Questionnaire scores compared with TKA. UKA scores not significantly different from age- and gender-matched healthy controls.	NA	NA
Hopper & Leach[55] (2008)	76	62 (range, 35-75)	1.8 (range, 1.1-3.5)	PFC (DePuy)	34	61 (range, 43-75)	1.9 (range, 1-3.7)	Oxford	Low- impact sports: TKA 72% before surgery, 46% after surgery; UKA 88% before surgery, 85% after surgery. UKA group participated in greater number of sport sessions and for greater amount of time.	NA	NA

AKS, American Knee Society; *SF-12*, Short Form 12; *TKA*, total knee arthroplasty; *UKA*, unicompartmental knee arthroplasty; *WOMAC*, Western Ontario and McMaster Universities Arthritis Index.

Comorbidity Index, diagnosis, and preoperative WOMAC and SF-12 scores found that UKA was significantly associated with higher SF-12 and WOMAC scores than TKA. In addition, the improvements in these scores compared with the preoperative condition were significantly greater in UKA patients.

Wiik and colleagues[165] studied walking speed 1 year after UKA or TKA in 23 and 23 patients, all of whom had high Oxford knee scores (mean, 44 ± 3 and 40 ± 8, respectively) and who were matched for age, gender, height, and BMI. The UKA group was able to walk significantly faster, achieving a mean of 7.0 km/h compared with the TKA group mean of 6.2 km/hr ($P < .05$). The authors attributed the findings to significantly reduced step length, increased stance time, and lower cadence in the TKA group.

Lateral Unicompartmental Knee Arthroplasty

The survivorship rates reported after modern lateral UKA are shown in Table 30-10, and the clinical outcomes are shown in Table 30-11. The largest series reported at the time of writing, from Baker and colleagues,[7] compared survivorship rates between 2052 lateral UKA and 30,795 medial UKA from the National Joint Registry of England and Wales. The 7-year rates were comparable (93% for lateral and 91% for medial) and only age (younger than 55 years) significantly affected the results. Several studies[5,53,79,86,87,124,163] reported 10-year survival rates from 83% to 100%, and three investigations[5,53,87] produced 15-year rates that ranged from 80% to 92%.

In a unique analysis of athletic activity levels before and after surgery, Walker and colleagues[157] reported that 98% of 45 patients were able to return to sports activities a mean of 3 years after undergoing an Oxford Domed (Biomet) UKA. The majority were participating in low-impact activities. There were no significant differences in SF-36 scores between the patients and a matched healthy control population. The remainder of clinical studies used scales that rated activities of daily living and in all but one the cohorts' average age at surgery was 60 years or greater.

Clinical outcomes have been mixed regarding lateral UKA performed for posttraumatic OA secondary to tibial plateau fracture.[87,134] Lustig and associates[87] reported survivorship rates of 100% at 10 years and 80% at 15 years in a small series of 13 patients followed a mean of 10.2 years postoperatively. The mean AKS knee score improved from 51 points before surgery to 88 points at follow-up, with similar improvements noted in the mean AKS function score. However, Sah and Scott[134] found inferior outcomes in AKS scores in 10 patients treated for posttraumatic OA compared with 38 patients who underwent lateral UKA for primary OA. Although none of the knees had been revised a mean of 5.2 years postoperatively (range, 2-15 years), 5 of the 10 patients in the posttraumatic OA group reported only fair satisfaction with their outcome. All 38 patients in the primary OA group reported excellent satisfaction.

As of the time of writing, no study had compared outcomes between lateral UKA and femoral osteotomy or TKA.

TABLE 30-10 Survival Rates of Lateral Unicompartmental Arthroplasty

Study	Prosthesis	No. Knees	No. Patients	Mean Follow-up (yr)	Survival End Points	SURVIVAL RATES				
						2-3 yr	5 yr	7 yr	10 yr	15 yr
Baker et al[7] (2012)	Multiple, 66% mobile bearing	2052	NA	NA	Revision	96%	93%	93%	—	—
Weston-Simmons et al[163] (2014)*	Oxford Domed	265	258	4.1 (range, 0.5-8.3)	Revision	97%	94%	92%	8-9 yr: 92%	—
Streit et al[146] (2012)	Oxford Domed	50	50	2.9 (range, 2-4.2)	Revision	94%	—	—	—	—
Liebs & Herzberg[79] (2013)	Preservation Mobile bearing	128	128	6 (range, 2.1-9.8)	Revision	93%	92%	83%	9 yr: 83%	—
Xing et al[167] (2012)	Preservation Fixed bearing	31	31	4.5 (range, 2-6.4)	Revision	100%	—	—	—	—
Arastu et al[3] (2009)	Preservation Mobile bearing	43	39	3.1 (range, 0.8-4.4)	Revision	79%	—	—	—	—
Smith et al[142] (2014)	AMC Uniglide Fixed bearing	101	100	4.5	Revision	99%	95%	91%	—	—
Heyse et al[53] (2012)	Genesis (Accuris)	50	50	10.8 (range, 5-16)	Revision	—	—	—	92%	92%
Lustig et al[86] (2011)	HLS Evolution Fixed bearing	54	52	8.4 (range, 5-16)	Revision, implant removal, complete loss medial joint space	—	—	—	91%	—
Pennington et al[124] (2006)	Miller-Galante	29	24	12.4 (3.1-15.6)	Revision	100%	100%	100%	100%	—
Lustig et al[87] (2012)	HLS Evolution, Miller-Galante	13	13	10.2 (range, 3-22.1)	Revision	100%	100%	100%	100%	80%
Argenson et al[5] (2008)	Mixed	40	39	12.6 (range, 3-23)	Revision or loosening	—	—	—	92%	16 yr: 84%

*From the inventor team of the Oxford lateral unicompartmental knee arthroplasty prosthesis.

TABLE 30-11 Clinical Outcomes of Modern Lateral Unicompartmental Arthroplasty

Citation	Prosthesis	No. Knees	Mean Age (yr)	Mean Follow-up (yr)	No. Knees Outcome Data	Knee Rating Outcome Scores	Other Outcomes
Walker et al[157] (2014)	Oxford Domed	50	60 (range, 36-81)	3 (range, 2-4.3)	45	OKS preoperative 30 ± 7, F/U 43 ± 5 AKS Objective preoperative 50 ± 15, F/U 91 ± 14 Function preoperative 67 ± 21, F/U 90 ± 17 UCLA ≥7 in 66% SF-36 scores same as matched healthy control group, significantly higher than OA group	93% active in sports before surgery, 98% active after surgery
Weston-Simmons et al[163] (2014)*	Oxford Domed	265	64 (range, 32-90)	4.1 (range, 0.5-8.3)	257	AKS Objective preoperative 48 (range, 2-95), F/U 86 (range, 27-100) Function preoperative 68 (range, 10-100), F/U 83 (range, 10 to 100) OKS preoperative 24 (range, 5-46), F/U 40 (range, 9-48)	12 revisions (5%); dislocation <1%
Altuntas et al[2] (2013)	Oxford Domed	64	71 (range, 44-92)	3.2 (range, 2-5.1)	50	OKS preoperative 24 (range, 9-36); F/U 42 (range, 23-48)	2 revisions (3%)
Streit et al[146] (2012)	Oxford Domed	50	60 (range, 36-81)	2.9 (range, 2-4.2)	46	OKS 43 ± 5.3 AKS Objective 91 ± 13.9, Function 90 ± 17.5	3 revisions (6%); dislocation 6.2%; 96% satisfied with outcome
Liebs & Herzberg[79] (2013)	Preservation mobile bearing	128	74 (range, 44-91)	6 (range, 2.1-9.8)	128	WOMAC function 34 ± 29; pain 34 ± 31; stiffness 23 ± 27 SF-36 physical component 38 ± 11; mental component 48 ± 12	14 revisions (11%)
Xing et al[167] (2012)	Preservation fixed bearing	31	67 (range, 36-90)	4.5 (range, 2-6.4)	31	AKS preoperative 69, F/U 96	No revisions or failures
Forster et al[45] (2007)	Preservation: 13 mobile bearing, 17 fixed bearing	30	67 (range, 36-93)	2	30	AKS Knee 95; Function 95-100 OKS 13-15	No difference in function outcome between fixed-bearing and mobile-bearing implants; 3 (23%) revised in mobile-bearing group

TABLE 30-11 Clinical Outcomes of Modern Lateral Unicompartmental Arthroplasty—cont'd

Citation	Prosthesis	No. Knees	Mean Age (yr)	Mean Follow-up (yr)	No. Knees Outcome Data	Knee Rating Outcome Scores	Other Outcomes
Smith et al[142] (2014)	AMC Uniglide fixed bearing	101	65 (range, 36-91)	5.4	33	AKS Pain preoperative 10 (range, 0-45), F/U 42 (range, 0-50) Knee preoperative 44 (range, 0-86), F/U 82 (range, 33-100) Function preoperative 56 (range, 0-100), F/U 77 (range, 35-100) OKS preoperative 20 (range, 5-45), F/U 37 (range, 9-48) WOMAC pain preoperative 15 (range, 7-23), F/U 8.8 (range, 5-20) Function preoperative 21 (range, 8-31), F/U 13.4 (range, 7-30) Total preoperative 36 (range, 15-53), F/U 22.2 (range, 12-48)	4 revisions (4%)
Heyse et al[53] (2012)	Genesis (Accuris)	50	54 (range, 30-60)	10.8 (range, 5-16)	50	AKS Knee 97 Function 96.5-98.6 (female, male respectively)	3 revisions (6%)
Lustig et al[86] (2011)	HLS Evolution fixed bearing	54	72 (range, 25-88)	8.4 (range, 5-16)	45	IKS Knee preoperative 68 (range, 35-92), F/U 95 (range, 70-100) Function preoperative 69 (range 0-100), F/U 82 (range, 25-100)	77% very satisfied, 19% satisfied; No/occasional pain, 85%; 17% limping with walking, 11% used cane; 4 revisions (7%)
Volpi et al[153] (2007)	Miller-Galante	28	73 (range, 65-82)	1-5	25	HSS preoperative 60 (range, 48-68); F/U 88 (range, 71-95)	No revisions
Pennington et al[124] (2006)	Miller-Galante	29	68 (range, 52-86)	12.4 (3.1-15.6)	29	HSS preoperative 60 (range, 42-79); F/U 93 (range, 82-100)	No revisions
Argenson et al[5] (2008)	Mixed	40	61 (range, 34-79)	12.6 (range, 3-23)	38	AKS Knee preoperative 57 (range, 35-75), F/U 88 (range, 40-100) Function preoperative 46 (range, 10-89), F/U 78 (range, 20-100)	5 revisions (12.5%)

*From the inventor team of the Oxford lateral UKA prosthesis.
AKS, American Knee Society; *F/U*, follow-up; *HSS*, Hospital for Special Surgery; *IKS*, International Knee Society; *OKS*, Oxford Knee Score; *WOMAC*, Western Ontario and McMaster Universities Arthritis Index.

ILLUSTRATIVE CASES

Case 1. A 52-year-old man presented with chronic left knee pain in the medial tibiofemoral compartment that occurred with all daily activities and prevented any light recreational sports. He previously underwent a medial meniscectomy and then failed a course of conservative treatment of physical therapy and nonsteroidal antiinflammatory drugs. The physical examination showed an absence of clinical findings related to the patellofemoral and lateral tibiofemoral compartments. Standing 45-degree posteroanterior radiographs showed loss of the medial tibiofemoral compartment space (Fig. 30-8, *A*). The patient underwent a MAKO medial unicompartmental knee arthroplasty, with correction of the varus angulation to neutral. The preoperative planning of the procedure is shown in Figure 30-8, *B* to *D*. An important part of the procedure was the determination of the amount of medial joint opening that allowed the appropriate adjustment of the tibiofemoral gap, avoiding undue compartment loads and balancing the medial soft tissue restraints (Fig. 30-8, *E*). The postoperative radiographs are shown in Figs. 30-8, *F* and *G*.

Case 2. A 46-year-old woman presented with right lateral knee pain and lateral tibiofemoral arthritis. She had a 20-minute walking tolerance. She previously underwent a lateral meniscus transplant that was successful in alleviating her knee pain for 6 years. The patient elected to undergo lateral UKA after the transplant failed and a 45-degree radiograph showed loss of the lateral tibiofemoral compartment space (Fig. 30-9, *A*). A lateral UKA using the MAKOplasty technique was performed. The preoperative planning and placement of the prosthesis are shown in Figure 30-9, *B* to *D*. The postoperative radiographs are shown in Figure 30-9, *E* to *F*.

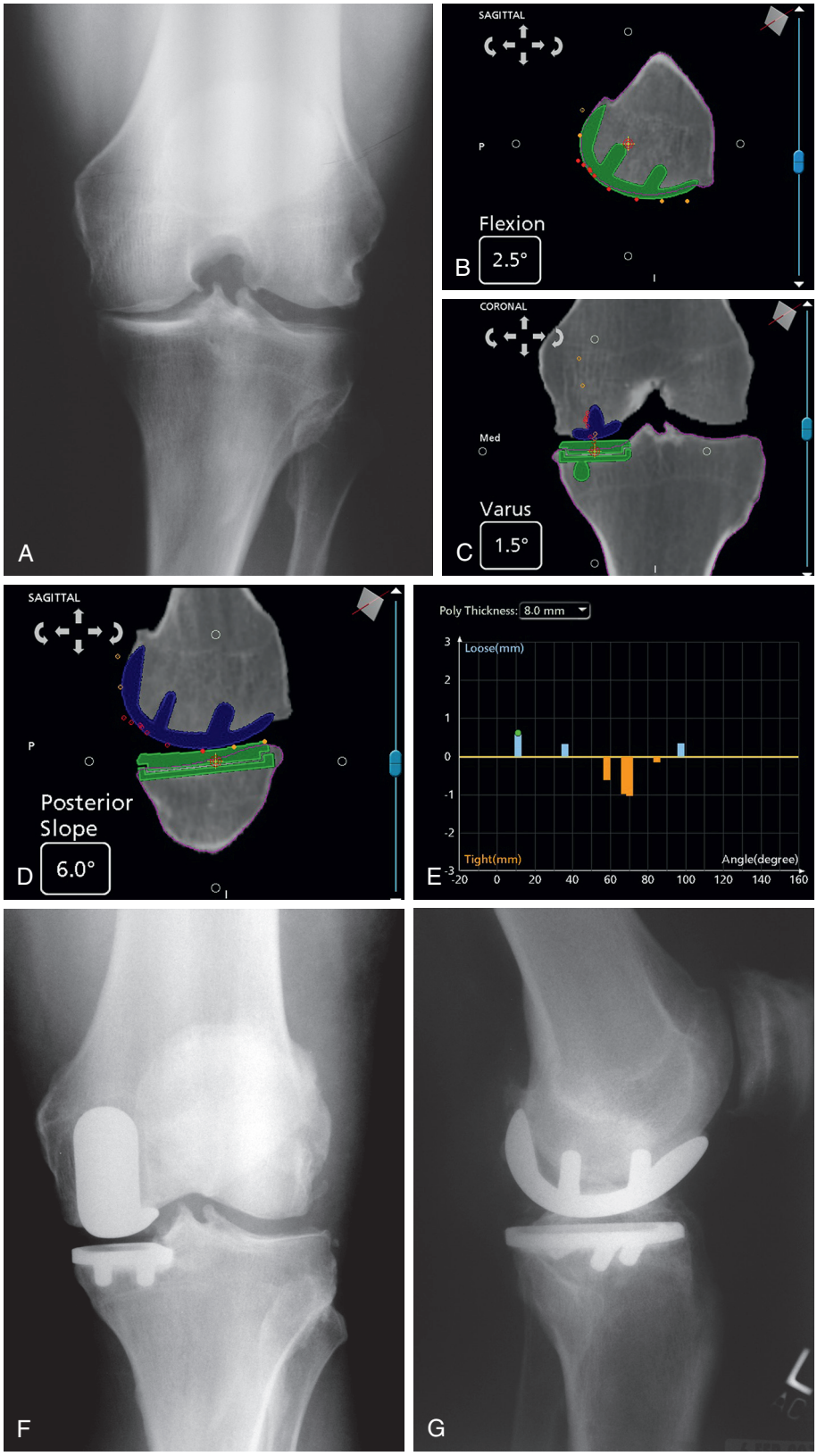


FIG 30-8 Case 1.

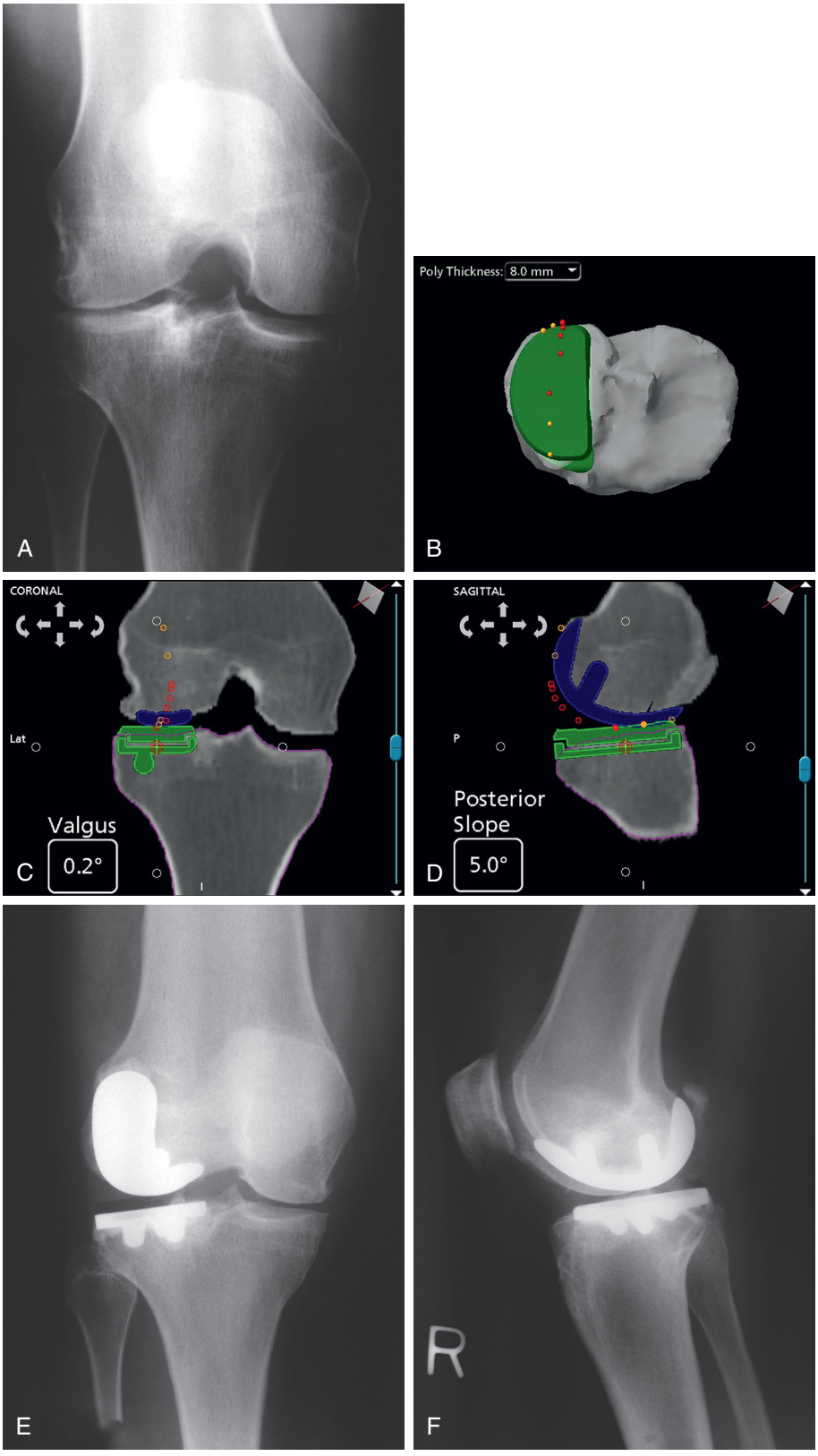


FIG 30-9 Case 2.

Video Content

Video 26-3
Video 30-1
Video 30-2

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31

Knee Articular Cartilage Restoration Procedures

Joshua D. Harris, Brian J. Cole

OUTLINE

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INDICATIONS

Management of symptomatic focal chondral and osteochondral defects in the knee is complex and multifactorial. The most salient principle in evaluation of the clinical presentation of patients with focal chondral defects of the knee should focus on "treating the patient" and not the defect. This means avoiding linear reasoning in the presence of a known defect that lacks an inexorable nexus with a patient's clinical presentation. The existence of a lesion on magnetic resonance imaging (MRI) or arthroscopic image should not automatically indicate surgery. It is well known that chondral defects are highly prevalent in both symptomatic and asymptomatic patients (Table 31-1). The incompletely understood natural history of articular cartilage lesions and the predictability of their surgical outcome mandate ensuring that the defect is clinically relevant and a competent source of the patient's symptoms.

Ascribing symptoms to a lesion warrants determination of the exact location of the defect that is tender on exam, if this location of pain is exacerbated by weight bearing, if biologic activity is present via detection of an effusion, and if there is a reduction of pain with intraarticular injection. Articular cartilage is an aneural tissue. Thus, the presence of a defect does not necessarily produce pain. However, patients with full-thickness lesions may demonstrate clinically important limitations in pain, function, sports and recreation, and quality of life as measured by Knee injury and Osteoarthritis Outcome Score (KOOS) subscores.[31] These limitations are not significantly different than those experienced by subjects with arthritis enrolled for osteotomy or arthroplasty and may be worse than those with anterior cruciate ligament (ACL) deficiency.[31] The exact mechanism accounting for pain caused by pathology in an aneural tissue is not completely understood. Stimulation of periarteriolar nociceptive fibers in the subchondral bone is one theory.[38] In addition, the intraarticular biologic inflammatory milieu likely plays a large role with reduced anabolic factors and increased catabolic and nociceptive factors. This leads to synovitis, effusion, capsular distention, and pain.

Once the determination that a defect is symptomatic has been made, conservative treatment options may commence. These include, but are not limited to, rest, activity modification (typically reduction in load, including reductions in body mass index [BMI]), oral antiinflammatory medications, glucosamine, chondroitin, methylsulfonylmethane, injection therapies (steroid [methylprednisolone, triamcinolone, betamethasone], nonsteroid [ketorolac], hyaluronate viscosupplementation, platelet-rich plasma [PRP]), and physical therapy with modalities. Despite the therapeutic effect of injections, the diagnostic effect of added local anesthetic may provide more clinically useful information in determining the severity of symptomatology and may hint at the responsiveness to subsequent treatment.

In the situation of failed conservative treatment, surgical decision making is predicated on the patient's informed consent. This includes recognition of and addressing the patient's preoperative expectations. Complete disclosure of the surgical algorithm (Figs. 31-1 and 31-2) and each technique's advantages, disadvantages, risks, benefits, alternatives, expected outcomes, and postoperative rehabilitation is warranted. The algorithm for selection of the optimal technique is based on multiple patient factors (age, gender, activity level, BMI, symptom duration), limb- and knee-related factors (meniscus, cruciate and collateral ligaments, alignment), and defect-specific factors (location, size, depth, subchondral bone). There are three general categories for surgical procedures designed to address articular cartilage pathology in the knee: (1) palliative (chondroplasty, debridement, lavage, meniscectomy), (2) repair (microfracture, drilling, abrasion, augmented scaffold-supported marrow-stimulation techniques), and (3) restoration (osteochondral autograft, osteochondral allograft, autologous chondrocyte implantation [ACI], and other chondrocyte- and mesenchymal stem cell-based therapies).

In addition to the treatment of the defect, concomitant limb and knee pathology must be addressed in either simultaneously or staged fashion. These entities include meniscal preservation (repair or transplantation),[27] alignment correction (varus or valgus malalignment treatment with proximal tibial or distal femoral unloading osteotomies, respectively, and patellofemoral malalignment treatment with

TABLE 31-1 Prevalence of Chondral Defects in the Knee Based on Unique Subject Populations

Subject Population	Prevalence (%)
All ages: all defect locations, sizes, depths	60-63[5,9,33,45]
All ages: all defect locations, sizes, only full-thickness defects	16[2,9,33,45]
All defect locations: age <40 yr, only full-thickness defects	5-7[9,33,45]
Concomitant anterior cruciate ligament tear	16-46[6]
All locations: amateur and professional athletes, only full-thickness defects	36[15]
All locations: asymptomatic professional basketball players, runners	59-77[15,35,44]

From Harris JD, Brophy RH, Jia G, et al. Sensitivity of magnetic resonance imaging for detection of patellofemoral articular cartilage defects. *Arthroscopy*. 2012;28(11):1728-1737.

CRITICAL POINTS Indications and Contraindications

Indications

- Symptomatic full-thickness chondral defect
- Symptoms such as direct tenderness at lesion, activity-related weight-bearing pain, effusion, and response to injection
- Treat concomitant pathology (meniscus, alignment, ligament)
- Patient selection and addressing expectations are critical

Contraindications

- Asymptomatic
- Patients unwilling or unable to comply with postoperative rehabilitation
- Uncorrected concomitant pathology (meniscus, alignment, ligament)
- Osteoarthritis

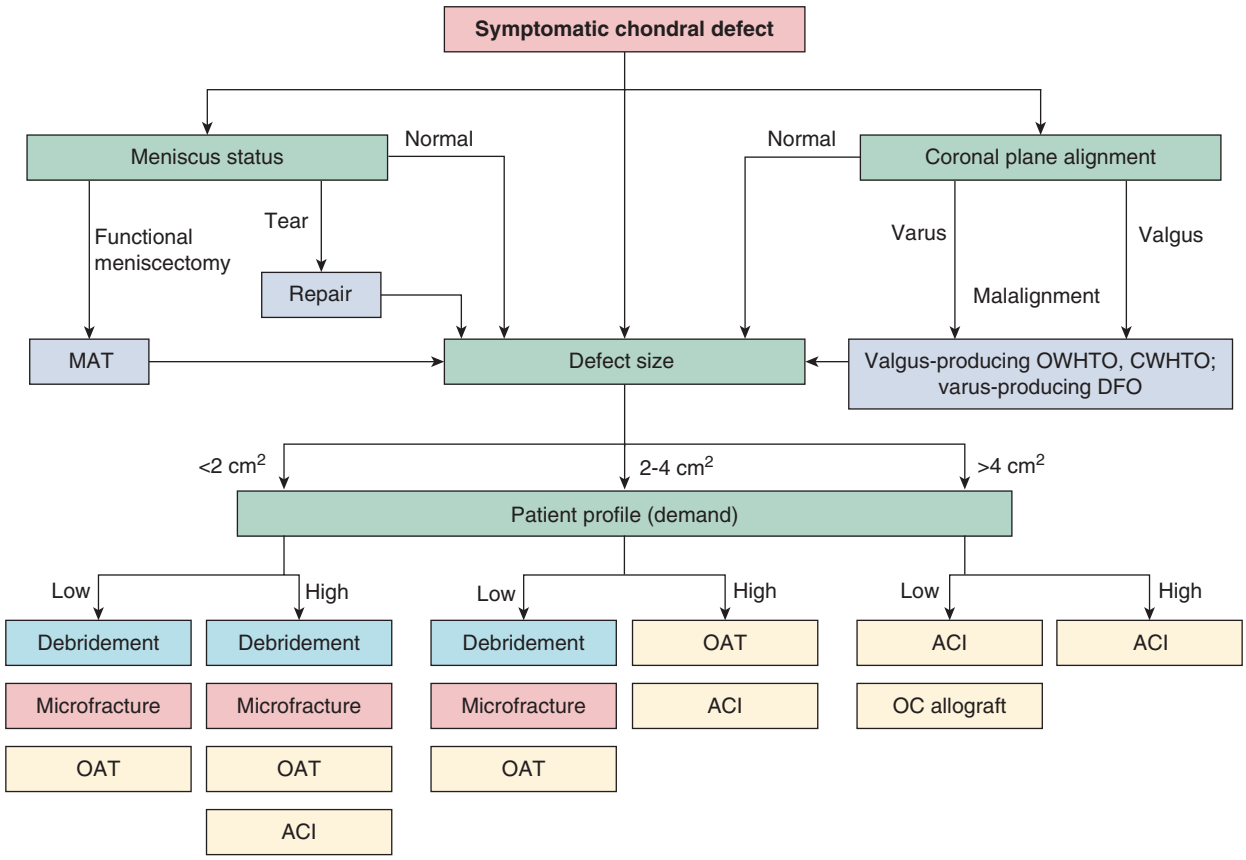


FIG 31-1 Management of symptomatic chondral defect in the tibiofemoral compartment (medial or lateral femoral condyle and/or tibial plateau). Concomitant pathology, such as meniscal deficiency and/or coronal plane malalignment should be addressed simultaneously or in a staged fashion. The most important defect-specific parameter dictating treatment choice is size (cm^2). Yellow shading denotes cartilage restoration, red shading denotes cartilage repair, and purple shading denotes cartilage palliation. *ACI*, Autologous chondrocyte implantation; *CWHTO*, closing-wedge high tibial osteotomy; *DFO*, distal femoral osteotomy; *HTO*, high tibial osteotomy; *MAT*, meniscal allograft transplantation; *OAT*, osteochondral autograft transplantation; *OC*, osteochondral allograft *OWHTO*, opening-wedge high tibial osteotomy.

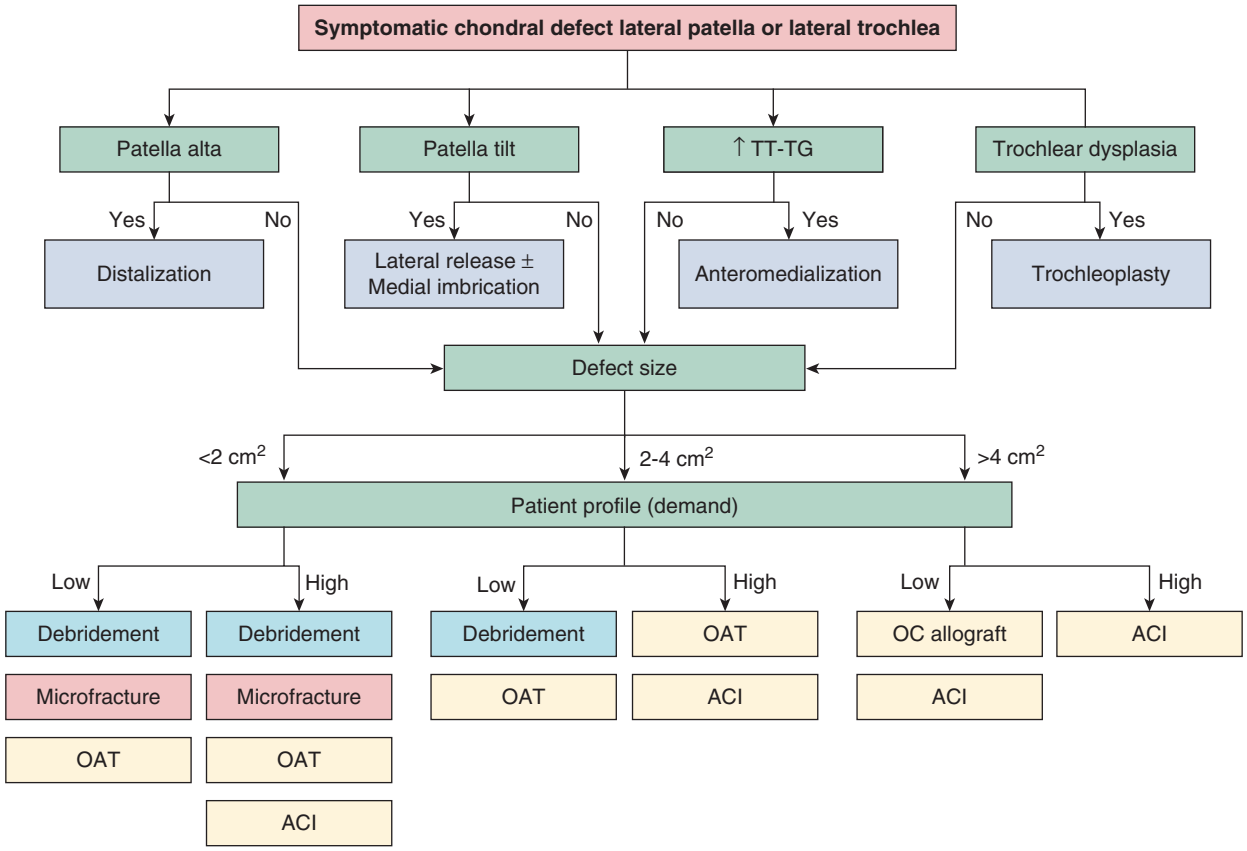


FIG 31-2 Management of symptomatic chondral defect in the patellofemoral compartment (trochlea, patella). Concomitant issues such as patella tilt, alta, increased tibial tubercle-trochlear groove (TT-TG), and trochlear dysplasia should be addressed simultaneously or in a staged manner. Centrally or medially located defects warrant different unloading osteotomy techniques. Medial patellofemoral cartilage pathology is a contraindication to medialization osteotomy. The most important defect-specific parameter dictating treatment choice is size (cm^2). Yellow shading denotes cartilage restoration, red shading denotes cartilage repair, purple shading denotes cartilage palliation. *ACI*, Autologous chondrocyte implantation; *OAT*, osteochondral autograft transplantation; *OC*, osteochondral allograft.

anteromedialization Fulkerson-type tibial tubercle osteotomy),[24,43] and knee ligament reconstruction.[6] The time commitment, intensity, and duration of the postoperative rehabilitation must not be overlooked or underestimated. The time to return to impact activities and return to sport must be discussed. Furthermore, in the setting of competitive athletes, the following factors play a significant role: timing of surgery (in or off season, stage of career); level of sport (high school, collegiate, elite amateur, professional); scholarship, contract, or bonus status; and opinions of stakeholders in the athlete's care (owners, managers, coaches, trainers, agents, teammates, family, friends, spouses). Given the prevalence with which chondral pathology is identified in professional athletes' knees,[15,35,44] the length of time required to rehabilitate following surgery,[22] and the subsequent implications (time lost to team, financial), it is critical to carefully and appropriately select the correct surgical technique in this patient population. As a general consideration, if there is an extraarticular treatment (e.g., osteotomy) that can predictably relieve or improve an athlete's symptoms, strong consideration for delaying an intraarticular procedure (e.g., articular cartilage transplantation) until his or her career is over is a reasonable option.

CONTRAINDICATIONS

There are several groups of subjects that are not candidates for articular cartilage restorative techniques in the knee. There is currently no role for prophylactic cartilage restoration in asymptomatic subjects. However, two exceptions to this contraindication exist: large surface area osteochondritis dissecans lesions and post-lateral meniscectomy in active females with valgus lower extremity alignment. In general, low-level symptoms should drive most early decision making rather than the theoretical risk of progression. There are no clear data showing that neglect leads to inexorable progression or, conversely, that treatment may halt or attenuate progression. Patients with osteoarthritis have an irreversible process illustrated via diffuse degenerative changes of subchondral bone sclerosis, subchondral cyst formation, osteophytes, and joint space narrowing. Patients not willing or unable to comply with the postoperative guidelines and rehabilitation protocols are contraindicated. Other contraindications include uncorrected comorbidities (meniscal deficiency, malalignment, ligamentous insufficiency), malignancy, and infection. Relative contraindications include elevated BMI, tobacco use,[3,4,34] and inflammatory arthritides such as rheumatoid arthritis, psoriatic arthritis, gout, and pseudogout.

CLINICAL BIOMECHANICS

The knee is subjected to high loads during simple tasks such as gait and squatting and even higher forces during sports involving sprinting and jumping.[16,41] These result from external (ground reaction force,

perturbation) and internal (muscle forces, joint reaction force) sources.[40] Small alterations in the direction or angle of a force acting on the knee can significantly influence the magnitude of forces observed.[42] This effect is demonstrated with both ACL injury and focal chondral defects in the knee.

ACL injury leads to translational and rotational disturbances in the knee. These kinematic shifts lead to altered articular cartilage stress in that regions of articular cartilage that were unloaded preinjury are now loaded, and regions of articular cartilage that were loaded preinjury are now unloaded. Because of the mechanosensitivity of chondrocytes and their low level of adaptability and reparability, the knee is susceptible to cartilage degeneration and progression with activity, especially in the setting of previous surgery or excessive BMI. In the presence of a focal chondral defect, the rim of the lesion may bear the load from the opposing articular surface, similar to a car driving over a pothole (Fig. 31-3). This stress concentration has been observed in several biomechanic models. Guettler and associates[21] showed that, for defects larger than 10 mm in diameter, stress concentration occurs around the rim (at 2.2 mm from the rim medially and 3.2 mm from the rim laterally). Eventually, the size (diameter) enlarges enough so that the opposing articular surface contacts and transmits stress to the exposed subchondral bone within the full-thickness defect. This depends on the defect size, location, and shape.

Flanigan and colleagues[14] showed that there were condyle-specific thresholds for contact on exposed subchondral bone within circular defects and stress concentration around the defect at defect sizes greater than 1.61 and 1.99 cm^2, respectively. In a separate investigation, Flanigan and coworkers[13] demonstrated that there were both shape-dependent and condyle-specific thresholds for contact on exposed subchondral bone within oval-shaped defects. Oval-shaped defects with the long axis in the coronal plane (medial to lateral) on the lateral condyle had the lowest size threshold for exposed subchondral bone contact (0.73 cm^2), and oval-shaped defects with the long axis in the sagittal plane (anterior to posterior) on the medial condyle actually had no size threshold (contact not observed). Stress concentration around the defect rim was observed in all defects, regardless of shape, size, or location. The stress dissipated with increasing radius away from the center of the lesion. Harris and associates[26] have also shown that the defect wall geometry (vertical vs. 45-degree beveled; see Fig. 31-3) may play a large role in rim stress concentration, exposed intralesional subchondral bone contact, and subsequent defect progression. These mechanics are all based on condylar/meniscal/plateau geometry, especially coronal and sagittal plane radii of curvature.

The preferential greater lateral-biased defect loading mechanics is based on the unique geometries of the lateral and medial femoral condyles and their interaction with menisci and tibial plateaus. The mean sagittal and coronal plane radii of curvature for the lateral condyle are smaller than the medial condyle. Furthermore, the sagittal radius differs from the coronal radius. This, in effect, creates more "point loading" on the more "convex-on-convex" lateral compartment versus the more congruent "convex-on-concave" medial compartment. Clinically, this may translate to significantly greater risk of subchondral bone changes in full-thickness defects on the lateral condyle, as well as speak to the incrementally greater vulnerability that the lateral compartment has following meniscectomy. This "bone boss" "intralesional osteophyte" effect has been observed in subjects undergoing ACI by Henderson and associates.[32] Patients with a bone boss had a longer duration of symptoms (greater time of subchondral bone experiencing opposing articular surface contact, more microcracks and microfractures).[32] Additionally, Alford and colleagues[1] demonstrated that lateral compartment lesions progress more rapidly than medial and are likely to become symptomatic at smaller sizes. These findings suggest that not only should tibiofemoral lesions be surgically treated differently than patellofemoral, but also lateral femoral condyle lesions should be treated differently than medial condylar lesions. Earlier intervention for lateral lesions may be desirable. The intervention type (entire osteochondral unit [osteochondral autograft, allograft] vs. surface [chondral] treatments) likely also matters.

CRITICAL POINTS Clinical Biomechanics

- Stress concentration occurs around the rim of full-thickness articular cartilage defects in the knee.
- Defects may progress based on several defect specific factors: size, shape, compartment, location.
- Lateral lesions may progress more rapidly than medial because of convex-on-convex mechanics (vs. convex-on-concave medially) between the femoral condyle and tibial plateau.
- With vertical walled lesions, although there is a lower volume of cartilage in the defect and on the exposed subchondral bone by the opposing surface, the stress concentration around the defect rim is greater.

CLINICAL EVALUATION

History

Patients with symptomatic focal chondral defects of the knee experience pain that is reproducibly located at the site of the defect, is primarily activity related (especially with axial load and weight bearing with tibiofemoral lesions, and especially with stairs or prolonged knee flexion with patellofemoral lesions), is associated with effusions (indicative of a biologically active synovitis process and capsular distention), and is often associated with a temporary relief of symptoms with intraarticular local anesthetic injection. Although single-dose intraarticular local anesthetic and corticosteroid injection is effective in significantly reducing pain, we recommend caution with certain anesthetic and corticosteroid injection combinations because of potential articular cartilage chondrotoxicity. These include betamethasone sodium phosphate, betamethasone acetate, triamcinolone acetonide, 0.5% bupivacaine, 1% lidocaine or 0.25% bupivacaine combined with betamethasone acetate or sodium phosphate, and 1% lidocaine combined with methylprednisolone acetate or triamcinolone acetonide.[5,8,10] Because of this potential iatrogenic damage, we recommend 1%

CRITICAL POINTS Clinical Evaluation

- Pain reproducibly located at the site of the defect.
- Pain primarily activity-related (weight bearing with tibiofemoral and stairs or prolonged knee flexion with patellofemoral).
- Associated with intermittent effusions.
- Temporary relief with intraarticular local anesthetic injection.
- Focus on not only the exact location of tenderness (at the defect) but also concomitant pathology, including alignment, meniscal status, ligamentous sufficiency.
- Gait evaluation, proximal and distal musculature (i.e., atrophy), extremity rotational profile, and pedal arch.
- Weight-bearing plain radiographs, including long-leg alignment view, are initial diagnostic evaluation of choice.
- Noncontrast MRI can detail the status of articular cartilage, subchondral bone, effusion, and concomitant pathology.
- Advanced MRI sequences (e.g., dGEMRIC) may characterize collagen and proteoglycan content better than conventional MRI.

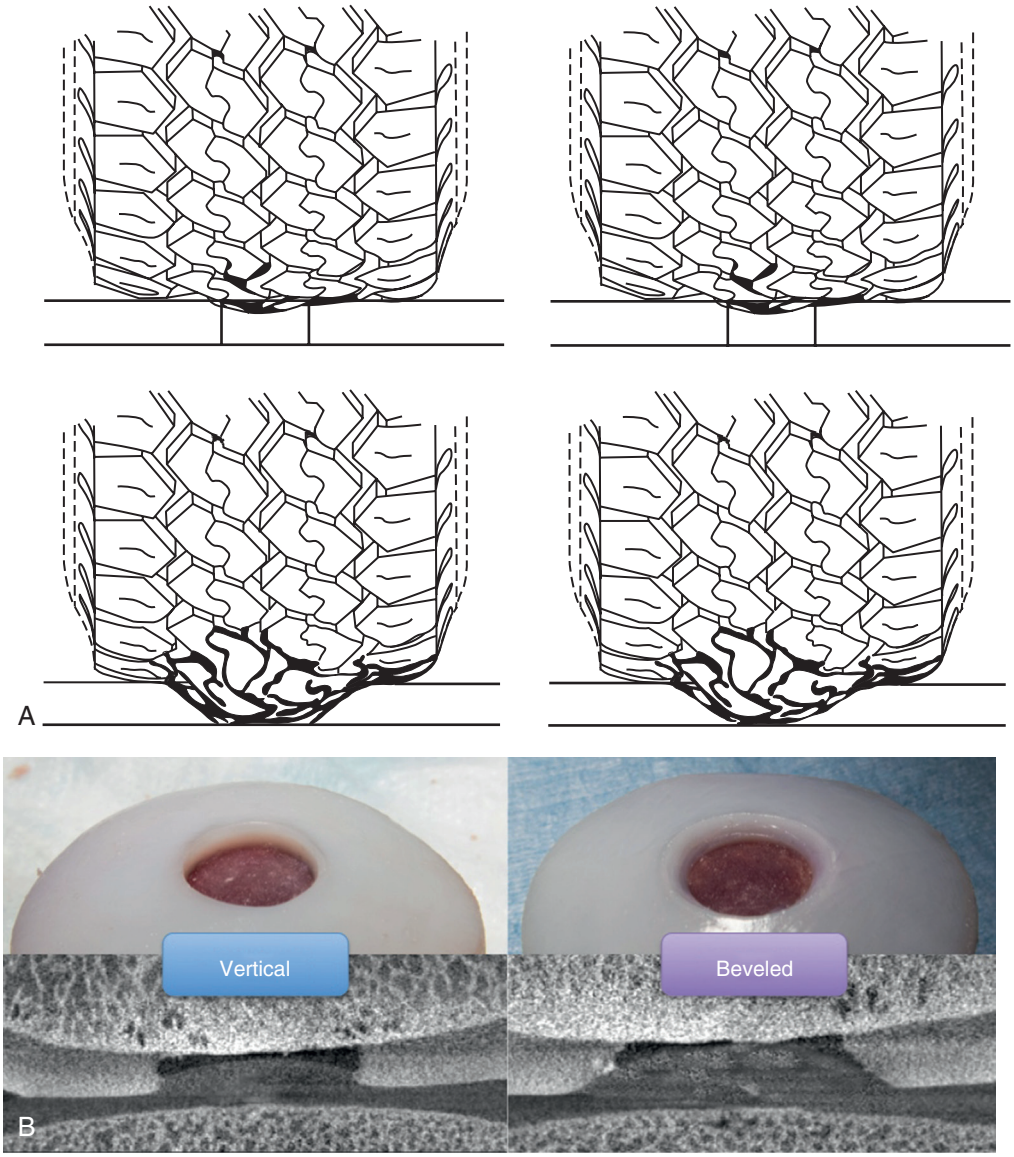


FIG 31-3 **A,** The top images illustrate a full-thickness chondral defect with vertical walls. Although there is greater stress concentration around the rim of the defect, the exposed subchondral bone is more protected. The presence of a defect increases the pressure on the rim of the defect (Pressure = Force/Surface area) because of a smaller surface area of articulating contact areas. The bottom right image illustrates enlargement of the lesion diameter with maintenance of vertical walls so that the exposed intralesional subchondral bone is contacted by the opposing articular surface. The bottom left image illustrates beveling of the lesion so that the exposed subchondral bone is contacted by the opposing articular surface. However, in addition, there is greater surface area of articular cartilage contact distribution with subsequent reduction in stress. We recommend vertical over beveled walls for cartilage repair surgery because it better contains the new cartilage tissue within the defect. **B,** The top two images are vertical and beveled lesions in cadaveric bovine femoral condyles. Upon axial load at the defect by the opposing intact tibial articular surface, visualized on microcomputed tomography, the stress concentration around the defect rim is greater, although there is a lower volume of cartilage in the defect and on the exposed subchondral bone by the opposing surface with the vertical wall lesion.

lidocaine for short- and 0.5% ropivacaine for long-term anesthesia, and dexamethasone as the corticosteroid of choice because these medications have not demonstrated chondrotoxicity in combination in the literature. Preoperative duration of symptoms is highly variable. The mean preoperative duration of symptoms can range from as few as 6 months to more than 15 years, and the number of prior preoperative surgeries can range from none to 30.[22,27,30,43]

Physical Examination

The physical examination of subjects with symptomatic chondral defects should focus not only on the defect itself but also on concomitant pathology. Initial assessment should focus on gait observation. Antalgic patterns indicate pain in the extremity, Trendelenburg gait indicates a contribution of hip abductor weakness to knee pain,

quadriceps avoidance patterns are observed with patellofemoral lesions, and knee flexion contractures are seen with hamstring tightness (from multiple spine, pelvis, hip, and lower extremity sources; patella baja; and patellofemoral pain). Coronal plane alignment should be evaluated during double- and single-leg stance and gait for evaluation of static and dynamic alignment and assessment of thrust.

Lower extremity rotational profiles may be grossly evaluated via inspection for femoral version and tibial torsion via in-toeing or out-toeing. Foot observation examination should be performed during standing and ambulating, and double- and single-heel rises should be done for arch assessment.

Inspection for muscle atrophy at all muscle groups should be performed (this can be quantitatively evaluated with both circumference measurements, manual muscle testing, and isokinetic testing). Palpation is a critical component of the examination, especially focusing on tenderness at the site of the lesion. Although detection of large effusions is straightforward in most subjects, smaller effusions may require milking and ballottement of the patella to detect. Wilson's test may be used to diagnose a classical location osteochondritis dissecans (OCD) lesion on the lateral aspect of the medial femoral condyle. This maneuver is performed by internally rotating the tibia with the knee in a flexed position and then extending the knee while maintaining internal rotation. Pain will reproducibly occur at 30 degrees of flexion as the tibial spine contacts the defect. External tibial rotation will alleviate the pain. The sensitivity and specificity of the physical examination for diagnosis of OCD is 91% and specificity 69%, respectively, which is greater than MRI.[37] In addition to the defect itself, cruciate and collateral ligament stability should be assessed via Lachman, anterior and posterior drawer, sag, and quadriceps active tests and varus/valgus stress tests at 0 and 30 degrees of knee flexion. Posterolateral corner structures may be evaluated via external rotation recurvatum and dial testing, posterolateral drawer, and reverse pivot shift tests.

Diagnostic Tests

Plain radiographs of the knee and full-length alignment radiographs are the initial diagnostic evaluation of choice for evaluation of patients with chondral defects in the knee. Our preferred series includes a weight-bearing anteroposterior view, weight-bearing 45-degree flexion posteroanterior (AP) view, weight-bearing lateral view in 30 degrees of flexion, and patellofemoral view (Merchant or sunrise). A full-length hip-to-ankle weight-bearing AP view allows for determination of the mechanical axis of the lower extremity. All plain radiographs should use a spherical radiographic magnification marker of known size to permit calculation of meniscal or osteochondral allograft sizes (or both).

Noncontrast MRI is useful for evaluation of the articular cartilage, underlying subchondral bone, menisci, ligaments, tendons, and joint fluid. Proton density-weighted, intermediate-weighted, and T2-weighted images provide the best contrast resolution for articular cartilage evaluation. Fluid-sensitive sequences, such as T2 weighted and short-tau inversion recovery (STIR), are able to best differentiate the hyperintense synovial fluid-articular cartilage interface. Thus surface lesions are best evaluated with these sequences. Although fluid-sensitive sequences help to identify subchondral edema, they make it difficult to evaluate the articular cartilage-subchondral bone junction. Acquisitions without fat suppression help to clearly delineate the latter. MRI may be particularly useful in the evaluation of stable delamination injury in which the articular cartilage surface is intact but the underlying cartilage or subchondral bone is damaged. These injury types may be missed by the gold standard articular cartilage evaluation, arthroscopy, because the surface is not breached. Although some types of cartilage lesions are difficult to completely characterize via MRI, this is usually because of the lesion thickness, its orientation and shape, the magnet strength (signal-to-noise ratio spatial resolution), and the imaging plane orientation relative to the defect. Regions of cartilage softening and superficial fibrillation or fissures may be missed by conventional MRI sequences. Advanced sequences, such as T2 mapping, T2*, T1ρ, sodium imaging, and dGEMRIC (delayed gadolinium-enhanced MRI of cartilage) may be useful to evaluate early articular cartilage damage via ultrastructural details of collagen and proteoglycan pathology.

PREOPERATIVE PLANNING

Based on the patient's clinical history, physical examination, imaging work-up, and preoperative discussion with informed consent, a surgical treatment may be recommended. Prior records (operative report and arthroscopic photographs) are an important component of the decision-making algorithm (see Figs. 31-1 and 31-2) because they give the treating surgeon information regarding defect size, defect peripheral walls, subchondral bone appearance, meniscal and ligamentous status, and opposing articular surface ("kissing" lesions). It is critical to recognize and appreciate all patient-, limb-, knee-, and defect-specific factors (Table 31-2) that may influence the surgical outcome.

Each patient and his or her cartilage defect should be approached individually and not always according to a cookbook algorithm. In other words, "treat the patient, not the defect." Algorithms are general guidelines that use various patient and defect factors to help the surgeon and patient select a certain type of surgery. For patients with symptomatic chondral defects in the knee, a prerequisite to cartilage

CRITICAL POINTS Preoperative Planning

- Thorough history and physical examination ("treat the patient, and not the defect"), including prior record review (operative reports, arthroscopic photographs).
- Preoperative informed consent includes a discussion of the intensity, frequency, and duration of postoperative rehabilitation and the patient's ability to comply with it.
- Evaluate and treat all concomitant pathology (meniscus, alignment, ligament) either simultaneously or in a staged fashion.
- Specific surgical techniques are based on patient-, limb-, knee-, and defect-specific factors.
- Defect-specific factors include size, location, depth, shape, and walls.

TABLE 31-2 Patient-, Limb-, Knee-, and Defect-Specific Factors That Influence Outcome of Articular Cartilage Surgery in the Knee

Patient	Limb	Knee	Defect
Age	Coronal alignment	Meniscal status	Size
Body mass index	Patellofemoral "alignment"	Ligament status	Location
Smoking status	Muscle atrophy	Prior surgeries	Depth
Duration symptoms	Contracture	Effusion	Shape
Goals			Subchondral bone
Rehab compliance			Walls
			Single vs. multiple

repair or restoration is the ability to comply with the postoperative protocol in frequency, intensity, and duration. In the tibiofemoral compartment, small lesions (<2 cm^2) are frequently treated with debridement chondroplasty in both low- and high-demand subjects. However, in certain high-demand subjects and subjects who have failed a prior chondroplasty, both microfracture and osteochondral autograft are reliable options. If the subchondral bone plate is disrupted, then osteochondral autograft may be preferred because of the restoration of the entire osteochondral unit. There are several surgical options for medium (between 2 and 4 cm^2) and large (>4 cm^2) lesions. In low-demand subjects, debridement chondroplasty, microfracture, and ACI are viable surface treatment options. The ability to obtain vertical walls (for both microfracture and ACI) is sometimes difficult because of peripheral defect location. This precludes containment of the mesenchymal clot in microfracture or chondrocyte containment in ACI. In the situation of poor lesion containment, osteochondral allograft may be the best surgical choice. In the situation of subchondral bone loss, osteochondral allograft and ACI ("sandwich technique" with bone graft) are both viable options. Failed surface treatments (e.g., microfracture, ACI) may be revised with osteochondral allograft.

In the patellofemoral compartment, the geometry of the articulating surfaces is very different from that of the femoral condyles. In addition to compressive load, a large amount of shear stress is placed on both native and repaired articular cartilage. Thus most articular cartilage repair and restoration procedures are performed in conjunction with a tibial tubercle osteotomy. In the presence of patella alta, a distalization is recommended. If the tibial tubercle to trochlear groove (TT-TG) distance is elevated (>20 mm), then an anteromedialization (Fulkerson-type) osteotomy is recommended. A caveat to anteromedialization is the proximal and/or medial patellar or trochlear lesion, because this defect location would be overloaded with the osteotomy. In the setting of concomitant lateral patellar instability and an incompetent medial patellofemoral ligament (MPFL), an MPFL reconstruction is warranted. As with the tibiofemoral compartment, small (<2 cm^2) defects may be successfully addressed with debridement chondroplasty in both low- and high-demand patients. In certain high-demand subjects and in subjects that have failed a prior debridement, microfracture and osteochondral autograft may be useful for small trochlear lesions. However, in the patella, osteochondral graft (both autograft and allograft) may be difficult because of size, angle, and cartilage thickness mismatch limitations. For medium and large defects on the patella, the only technique able to successfully match the patellar articulating surface geometry is ACI. For medium and large trochlear lesions, both ACI and osteochondral allograft may be used. In the presence of subchondral bone loss, osteochondral allograft is appropriate. Following surface treatment (e.g., microfracture, ACI) failure, just as in the tibiofemoral compartment, lesions may be revised with osteochondral allograft.

In preparation for cartilage palliation techniques (chondroplasty, debridement, lavage, meniscectomy), standard knee arthroscopy equipment should be available. These include arthroscope, video tower, cannula(s), shavers, curettes, gouges, biters, graspers, and radiofrequency devices.

In preparation for cartilage repair (microfracture, drilling, abrasion, augmented scaffold-supported marrow-stimulation techniques), additional equipment should include microfracture awls of various angles, Kirschner wires, small-bore drill bits, other proprietary drills (PowerPick and PowerPick XL [Arthrex], which provides 1.5 mm-diameter drill, with 4- or 6-mm depth, at 30 or 45 degrees angle options, and NanoFx [Arthrosurface], which provides 1 mm-diameter drill, with 9-mm depth), and arthroscopic burs of various sizes. Additional matrix scaffold augmentation may be added to standard marrow-stimulation techniques to stabilize the mesenchymal clot and potentially improve cell differentiation into a more hyaline-like cartilage repair. These include autologous matrix-induced chondrogenesis (AMIC), BioCartilage, and BST-CarGel. AMIC uses a porcine collagen (type I/III) matrix (Chondro-Gide, Geistlich Pharma) with conventional microfracture and fibrin glue. BioCartilage (Arthrex) is a homologous mixture of 1 mL of the patient's PRP and 1 mL of BioCartilage, a dehydrated micronized allograft articular cartilage extracellular matrix, placed on a microfractured defect. BST-CarGel (Primal Healthcare) is a chitosan-based biopolymer mixture of the patient's whole blood and a glycerophosphate buffer placed on a microfractured defect.

Currently, BioCartilage and DeNovo NT (Zimmer) are the only minced articular cartilage technologies commercially available for use in the United States. BioCartilage is an augmented marrow stimulation technique that relies upon the patient's subchondral bone mesenchymal stem cells and PRP, in addition to the dehydrated minced juvenile allograft articular cartilage, to form the cartilage repair tissue. DeNovo NT is different from BioCartilage in that it intentionally does not violate the subchondral bone. DeNovo NT is a chondroconductive, chondroinductive, and chondrogenic product composed of 1 mm^3 fragments of juvenile (<13 years) articular cartilage embedded in fibrin adhesive at the time of implantation. Similar to BioCartilage, DeNovo NT is "minimally manipulated" and thus does not require U.S. Food and Drug Administration (FDA) premarket approval. Also similarly, both BioCartilage and DeNovo NT take advantage of the greater migration and proliferation capacity of juvenile cells (vs. adult cells) without immunogenicity.

In preparation for cartilage restoration (osteochondral autograft, osteochondral allograft, ACI, other chondrocyte and mesenchymal stem cell–based therapies), additional equipment should include instruments and equipment for the open arthrotomy, including defect sizing tools, retractors, scissors, forceps, rongeurs, and scalpel blades. For osteochondral grafts, various sizes of osteochondral graft donor and recipient reamers and cannulated sizing blocks, osteochondral graft preparation back-table workstations, small oscillating saws, and saline pulse lavage are necessary. For ACI and other cell-based therapies, epinephrine-soaked neuropatties, thrombin, fibrin glue, mineral oil, glycerin, small (e.g., 6-0) absorbable suture, tuberculin syringe, 18-gauge plastic Angiocath, type I-III collagen membrane or periosteum, and cells are required.

For all cartilage repair or restoration techniques, the postoperative rehabilitation begins immediately following surgery. This requires preoperative acquisition of the postoperative equipment. These include continuous passive motion (CPM) machines, crutches, brace, ice cryotherapy and/or compression devices, and mechanical thromboembolic disease socks (e.g., thromboembolic hose, compression stockings).

INTRAOPERATIVE EVALUATION AND OPERATIVE TECHNIQUE

Tourniquets are frequently used in knee arthroscopy and arthrotomy. Their use in articular cartilage repair and restoration requires cognizance of their inflation status during surgery. If inflated during marrow-stimulation techniques, the tourniquet should be deflated and the arthroscopic pump turned off to visualize subchondral marrow content (fat and blood) exude to verify sufficient depth of penetration of awl, drill, or wire. In ACI, it is critical to ensure the tourniquet is deflated during defect preparation so that complete hemostasis may be achieved before chondrocyte implantation.

Evaluation of the defect via arthroscopy or arthrotomy is standardized and should include assessment and recording of size (measured

CRITICAL POINTS Intraoperative Evaluation and Operative Technique

- Deflate tourniquet during marrow-stimulation techniques to observe subchondral marrow contents (fat and blood) exuding to ensure sufficient depth of penetration of awl, drill, pick, or wire.
- Deflate tourniquet during autologous chondrocyte implantation during defect preparation so that complete hemostasis can be achieved before chondrocyte implantation.
- Assess and record defect size, depth, location, shape, number, and wall status.
- Ensure complete removal of abnormal, unstable, damaged articular cartilage back to stable rim with vertical walls.
- If unable to obtain vertical walls because of reaching peripheral articular cartilage edge, it is better to leave some damaged cartilage to form a wall for cartilage fill rather than removing it so that no wall would be able to contain cartilage fill.
- Removal of the calcified cartilage zone is important in both microfracture and autologous chondrocyte implantation.
- Avoid excessive subchondral bone removal, as this may stimulate overgrowth and intralesional osteophyte formation.

in anterior to posterior plane and medial to lateral plane), depth (partial thickness, full thickness without subchondral bone loss, full thickness with bone loss), location (femoral condyle, trochlea, patella, tibial plateau), number (single vs. multiple, "kissing" bipolar lesions), shape (defect shape in relation to condyle shape), and wall status (lesion with contained vertical walls or uncontained peripheral lesions). Defect preparation should include sharp removal of unstable loose damaged articular cartilage back to intact healthy articular cartilage with full-thickness vertical walls. In both microfracture and ACI, removal of the zone of calcified cartilage improves repair tissue integration with the underlying subchondral bone. Violation of the subchondral bone should be avoided, especially with ACI, because this causes bleeding and greater proportions of fibrocartilage repair. Excessive removal of subchondral bone also may stimulate subchondral bone overgrowth, intralesional osteophyte formation, and eventual repair breakdown.

Osteochondral allograft is an open single-stage articular cartilage restoration procedure in the knee. The surgical approach and technique vary based on lesion location, with either a medial or lateral parapatellar miniarthrotomy used for exposure. Defect preparation involves recipient site sizing and assurance that the surrounding normal osteochondral unit is stable, with sufficient walls to support the donor plug. The recipient site is reamed to a depth with a healthy subchondral bone bed (typically 6-9 mm). The recipient site articular cartilage thickness is measured at multiple clock-face references (typically 12, 3, 6, and 9 o'clock). The donor allograft is obtained from a qualified tissue bank, with the graft stored at 4° C and used between 14 and 28 days following harvest. It is opened and soaked in cold saline to avoid dramatic temperature changes, which may be chondrotoxic. A surface area– and depth-matched donor plug is then prepared. Before implantation, the donor plug is washed with sterile saline pulse lavage to remove any potential immunogenic subchondral bone marrow elements. The plug is then manually press fit into the recipient site with gentle finger pressure. It is critical to ensure flush placement of the donor plug in the recipient site because proud or recessed plug placement has been shown to significantly increase contact pressure and subsequent articular cartilage degeneration.[11] If secure graft fixation is questionable, then a recessed bioabsorbable screw may be placed in the center of the graft.

ACI is a two-stage cartilage restoration procedure in the knee. Stage one involves a knee arthroscopy, defect assessment, and cartilage biopsy, followed by a chondrocyte culture expansion in vitro. The biopsy may be obtained from multiple locations. However, it is usually taken from the superior lateral (or medial) edge of the intercondylar notch. The biopsy is taken with a sharp curette or gouge, approximately 5 mm wide, 10 to 14 mm long, and is 200 to 300 milligrams and contains approximately 200,000 to 300,000 chondrocytes. This can yield up to four vials of 12 million chondrocytes per vial. The cells are cryopreserved for up to 2 years. After the surgical date is selected, the cells are thawed and cultured for 4 weeks. Upon delivery the day (or the day before) of surgery, the cells expire within 48 hours.

The second stage of ACI involves either a medial or lateral parapatellar miniarthrotomy for exposure. Defect preparation involves removal of all unstable, loose, degenerated articular cartilage with creation of stable normal vertical walls. The calcified cartilage zone should be removed. However, do not be too aggressive in removal of this layer because it will stimulate subchondral bleeding and subsequent fibrocartilage formation. If bleeding is encountered (with the tourniquet down), epinephrine- or thrombin-soaked neuropatties should be used to obtain complete hemostasis. The risk of periosteal hypertrophy precludes use of periosteum for a graft cover.[29] Currently, most surgeons use a type I-III porcine collagen membrane (considered off-label use) for the chondrocyte cover. The porous side of the membrane may or may not (surgeon preference) be seeded with chondrocytes before suturing into the defect. Absorbable 6-0 suture is used (with mineral oil lubrication) in simple interrupted fashion, spaced 2 to 3 mm apart. The needle is initially passed on the patch side then through the articular cartilage. The needle should exit the articular cartilage approximately 3 mm from the edge of the lesion. The suture knot should be placed on the patch side, relatively recessed in relation to the surface of the surrounding articular cartilage. The final one or two suture locations should be at the most superior aspect of the defect, so that none of the chondrocyte solution may leak out (following a watertightness test). The suture line may be reinforced for water tightness with fibrin glue. An 18-gauge Angiocath and a tuberculin syringe are used to aspirate the resuspended cell solution. The solution is injected under the patch, the patch sutured closed, and then fibrin glued. Intraarticular drains should not be used postoperatively to avoid iatrogenic damage to the patch, cells, or both.

Postoperative rehabilitation is similar for both osteochondral allograft and ACI. Defect location (tibiofemoral vs. patellofemoral) dictates the weight bearing and motion restrictions following surgery. For tibiofemoral lesions, a brief (6 weeks) non–weight-bearing period commences following surgery (contrary to patellofemoral, in which weight bearing can begin as long as the knee is locked in extension in a brace). CPM is important in the early postoperative period (first 6 weeks) because the biological properties of articular cartilage and range of motion are significantly improved with CPM.[36] Weight bearing progresses from 6 through 12 weeks, while full symmetric pain-free motion is concurrently achieved. Core and lower extremity strengthening continues beyond 3 months, and functional sport-specific training may begin between 3 and 6 months. However, return to sport is restricted to beyond 9 to 12 months. Concurrent meniscal allograft transplantation or osteotomy may alter weight-bearing and motion limitations in the first 6 to 8 weeks after surgery.

CLINICAL OUTCOMES

Several synthetic systematic reviews and metaanalyses have been published that report on clinical, radiographic, and histologic outcomes after articular cartilage surgery in the knee. Overall, early clinical

reports were small, retrospective case series of levels III and IV evidence. Later publication dates have increasingly yielded larger, high-quality, level I evidence randomized comparative trials. Overall, with time, the level of evidence and methodological quality of knee articular cartilage surgery publications have significantly improved.[28] The rapid proliferation of the number of original research and synthetic review publications prompted the development of a valid and reliable knee articular cartilage condition-specific study methodological quality score.[23]

A systematic review of level I and II evidence studies on clinical outcomes after microfracture identified 15 studies (6 long term and 9 short term) for analysis.[19] These investigations compared microfracture to either ACI or osteochondral graft (autograft or allograft). At short-term follow-up in younger subjects, low-demand subjects, and those with smaller lesion size, microfracture demonstrated good clinical outcomes. However, beyond 5 years after surgery, treatment failures and osteoarthritis were observed, regardless of lesion size. This review parallels the findings of other systematic reviews and meta-analyses. A level IV evidence meta-analysis of articular cartilage repair in athletes revealed that microfracture outcomes deteriorated with time.[22] Significantly better clinical outcomes were observed with either ACI or osteochondral autograft. Results after microfracture were significantly worse with larger defect size (>4 cm^2). Rate of return to sport was significantly lower after microfracture versus ACI or osteochondral autograft. A separate but similar systematic review identified age, level of play, preoperative duration of symptoms, defect size, and repair tissue morphology as significant predictors of return to sport in athletes after microfracture.[39] A significant limitation of these reviews with regard to microfracture is that many fail to address or discuss concomitant pathology.[25] Several investigations compare "cartilage restoration" techniques, such as ACI or osteochondral autograft (which often have simultaneous correction of alignment and meniscus) with microfracture (which is frequently performed in isolation). Thus, this bias remains unaddressed and is a current limitation of the articular cartilage literature.

Just as in microfracture, several systematic reviews and meta-analyses of ACI exist, analyzing short- to long-term outcomes and comparing with osteochondral graft and marrow stimulation procedures. Within these investigations, several compare different generations of ACI, with identification of optimal outcomes and avoidance of complications. A level I and II evidence systematic review demonstrated that a collagen membrane base was significantly better than periosteal cover ACI.[17] Furthermore, matrix-associated had similar outcomes to collagen membrane-based ACI. However, the strength of the evidence in the latter review was weak because of short duration of follow-up, small numbers of subjects, medium-sized lesions, and younger ages of subjects. A separate but similar systematic review of level I and II evidence studies compared ACI with microfracture and osteochondral autograft.[30] Microfracture outcomes deteriorated after 18 to 24 months. ACI and osteochondral autograft demonstrated similar improvements in short-term outcomes. Younger subjects and those with shorter preoperative duration of symptoms and fewer prior surgical interventions had the best outcomes after both microfracture and ACI. Defect size greater than 4 cm^2 was predictive of significantly improved outcomes versus microfracture or osteochondral autograft.

A systematic review of 82 studies (more than 5000 subjects and 6000 defects) analyzed the rate of failures, complications, and reoperations after all generations of ACI.[29] The failure rate was low (1.5%-7.7%) across all generations. Failure rate (7.7%) and unplanned reoperation rate (27%) were highest after periosteal cover ACI. Graft hypertrophy and delamination was most commonly observed after periosteal cover ACI. Arthrofibrosis was most common after arthrotomy-based ACI (vs. all-arthroscopic implantation).

A systematic review of level I and II evidence clinical outcomes after osteochondral cylinder techniques analyzed eight studies (in comparison with microfracture and ACI).[18] Superior clinical outcomes and earlier return to sport was demonstrated after osteochondral autograft versus microfracture. Although mean lesion size was small (<3 cm^2), there was no significant observed difference between osteochondral autograft and ACI. Histologic examination consistently demonstrated hyaline cartilage in the transplanted plugs but no hyaline cartilage between the plugs.

No level I or II evidence exists regarding osteochondral allograft use in the knee. However, for focal and diffuse single-compartment chondral or osteochondral lesions, osteochondral allograft predictably and significantly improves patient-reported outcomes and results in high patient satisfaction.[7] At 5-year follow-up, overall satisfaction approaches 90% and 65% of patients have little or no radiographic osteoarthritis. Short-term complications are infrequent (<3%). Failures, although variably defined (repeat surgery, revision cartilage surgery, osteotomy, or conversion to arthroplasty), are uncommon (<18%). Survival rates decline with time: 91% to 95% at 5 years,[12,20] 76% to 85% at 10 years,[12,20] and 74% to 76% at 15 years.[12,20] Prognostic factors that may negatively influence clinical outcomes include diagnosis of spontaneous osteonecrosis of the knee, bipolar lesions, age greater than 50 years, patellofemoral lesions, Workers' Compensation status, preoperative duration of symptoms greater than 12 months, and failure to address malalignment or meniscal deficiency.[7]

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32

Osteochondral Grafts: Diagnosis, Operative Techniques, and Clinical Outcomes

Simon Görtz, Guilherme C. Gracitelli, William D. Bugbee

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INTRODUCTION

Hyaline articular cartilage is an avascular and insensate tissue that allows low-friction transmission of physiologic loads in diarthrodial joints. Its functional structure ideally is maintained in homeostasis over the lifetime of an individual but remains incapable of mounting an effective repair response when injured in a skeletally mature adult.[9,44] The treatment threshold for surgical intervention is not unequivocal, but patients with symptomatic lesions are generally considered candidates for cartilage restoration procedures.[2]

The use of osteochondral grafts of autologous or allogeneic origin is well supported on a basic science level and has a long successful clinical history as a means of biologic resurfacing.[7,15] Both modalities rely on transplanting mature hyaline cartilage containing viable chondrocytes attached to subchondral bone to restore the architecture and characteristics of native tissue in acquired osteoarticular defects. By transplanting structurally complete osteochondral units with an intact tidemark, the fixation issue is mostly relegated to that of osseous ingrowth.[37] Although both graft sources represent a common cartilage organ transplantation paradigm and are complementary, each has its unique, reciprocal challenges with regard to tissue availability and safety that must be weighed, managed, and communicated whenever the use of osteochondral grafts is being considered.

INDICATIONS

Autografts

Autologous osteochondral grafts are best used to address relatively small, yet symptomatic, focal articular lesions of the femoral condyles, especially if these grafts present with associated subchondral abnormalities such as a bone cyst or an intralesional osteophyte. Autologous plugs are also a potential salvage option as in situ fixation for a delaminating osteochondritis dissecans (OCD) lesion (International Cartilage Repair Society [ICRS] grades II-IV; see Chapter 44).[19,52]

Advantages of autologous grafts are immediate availability, relatively low costs, and their nonantigenic and osteogenic behavior that routinely lead to reliable osteointegration.[10] The possibility of arthroscopic delivery of these smaller grafts is appealing, albeit technically challenging.

One obvious disadvantage of autologous graft sources is that the maximum graft surface area is self-limited by the donor area available to be harvested for small and most medium-sized lesions. This is especially true in the previously injured or operated knee, in which suitability regarding tissue quality and overall joint topography has to be critically assessed. In addition, donor site morbidity can significantly add to the disease burden during intraarticular transfer.[7]

Allografts

Osteochondral allografts are suitable to treat medium to large chondral and osteochondral lesions.[24] In particular, osteochondral allografting may be considered the most appropriate treatment for large and high-grade (ICRS grades III-IV) OCD in the knee. Other specific conditions amenable to allografting include osteonecrosis and posttraumatic defects, such as after periarticular fractures. Further indications for allografting of the knee include treatment of patellofemoral chondrosis or arthrosis and for highly select cases of multifocal or bipolar posttraumatic or degenerative lesions. In a case in which meniscus replacement is also necessary, a composite tibial plateau with attached meniscus can be transplanted. Allografts are also increasingly employed in the salvage of knees that have failed other cartilage resurfacing procedures. Primary treatment may be considered in large chondral defects whose size presents a relative contraindication for other treatments and for which the surgeon believes other procedures may be inadequate.

Osteochondral allografting is the only treatment option that restores mature orthotopic hyaline cartilage and that reproduces the site-appropriate anatomy of the native joint both macroscopically and microscopically, without the risk of inducing donor site morbidity.[25] Osteochondral allografts are versatile when addressing even very large, complex, or multiple lesions in topographically challenging environments, especially if they involve an osseous component.

Obvious drawbacks to the allograft paradigm are the relative scarcity of donor tissue, financial and logistical issues of graft procurement, and residual risk of infection, a discussion that is an essential part of the informed consent process.[24] Although rare allograft-associated bacterial infections have been reported,[69] there are no available published data quantifying this risk or that of viral transmission. Patients are counseled that the risk for disease transmission from a fresh osteochondral allograft is comparable with that associated with banked blood transfusion. In a 35-year experience at our institution using more than 800 fresh allografts, no cases of transmission of disease from donor to recipient have been documented.

Fresh, cold-stored osteochondral allografts have shown to maintain viable chondrocytes and mechanical properties of the matrix many years after transplantation.[2,13-15,36,47,72] These findings have generally supported the use of tissue for small osteochondral allografts in the setting of reconstruction of chondral and osteochondral defects. Chondrocyte viability and structural integrity of the matrix are preserved during hypothermal storage in nutritive culture medium containing human serum, with cell density, viability, and metabolic activity remaining essentially unchanged from baseline for as many as 14 days before deteriorating significantly after 28 days, although the hyaline matrix remains relatively intact.[4,60,63,70,71] The clinical consequences of these storage-induced graft changes have yet to be determined, but 28 days is generally considered the threshold of graft utility in present clinical practice.

CONTRAINDICATIONS

Some of the contraindications to allograft transplantation are uncorrected ligamentous instability, meniscal deficiency, or axial malalignment of the lower extremity, as well as the presence of inflammatory or crystal-induced arthropathy or any unexplained global synovitis of the knee.

Autologous plugs are not advised in lesions presenting with a lack of containment or substantial subchondral bone loss, which might lead to loss of fixation and graft failure. Whereas "kissing" lesions are also widely considered unsuitable for autologous grafting, bipolar and multicompartmental allografting has been modestly successful in the younger individual.[50] However, advanced multicompartmental arthrosis is a relative contraindication to the allografting procedure, and neither osteochondral grafting technique should be considered an alternative to prosthetic arthroplasty in an individual with symptoms and acceptable age and activity level for prosthetic replacement.

CLINICAL EVALUATION

A careful and focused history and a physical examination are essential to determine candidacy for any cartilage restoration procedure. Because articular cartilage itself is insensate, it is important to identify contributory pain generators and to distinguish them from mechanical symptoms. Tools such as the International Cartilage Repair Society (ICRS) Cartilage Injury Evaluation Package,[33] which incorporates several validated outcome measures, can be helpful in systematically documenting the anatomic condition and functional envelope of the knee and in establishing a baseline for therapy.

The clinician should elucidate the location and quality of pain, onset (acute vs. chronic) and duration of symptoms, alleviating and exacerbating events or measures, prior treatment and surgical history (if any), as well as activity at the time of injury and expected future level of occupational and recreational performance. Significant medical factors potentially relating to knee pathology should be sought such as prior trauma, collagen-vascular/inflammatory disorders, or corticosteroid use. It should be noted that the time from the initial cartilage injury and pending disability compensation claims is universally recognized as inversely related to outcome. The onset and character of symptoms are worth noting in an effort to distinguish pain at rest (indicative of an underlying, more advanced degenerative process) from activity-related pain or mechanical symptoms such as catching or locking that suggest meniscal injury, loose bodies, or cartilage flaps associated with acute injury or early degenerative disease.

The physical examination should begin with a visual inspection of the patient's gait and limb alignment. With the patient placed supine, the examiner can commence with a closer inspection of the knee joint and comparison with the uninjured side, focusing on the area of the chief complaint. Range of motion (ROM) and ligamentous stability should be noted using standard maneuvers. Presence of effusion should be noted, and the patellofemoral joint should be assessed for alignment, baja or alta position, mobility, grind, tracking, tilt, and signs of apprehension. It is particularly useful to palpate the femoral condyles and other accessible articular surfaces because focal tenderness at the site of cartilage lesions is an important physical finding. Symptomatic trochlear or patellar lesions can be stressed with a bounce test or by applying prepatellar pressure during the grind test, whereas condylar lesions often become painful when loaded with a valgus or varus stress test or during a McMurray maneuver. Accordingly, joint line pain and other complaints caused by meniscal or synovial symptoms or originating from extraarticular structures such as bursae or the iliotibial band should be distinguished from chondral pathology.

Patients who are considered for an osteochondral grafting procedure should optimally be fully imaged, including a complete radiologic series and magnetic resonance imaging (MRI) studies with cartilage-specific sequencing, if available. Depending on the type and location of cartilage injury being suspected, this should include at least standing anteroposterior (AP) weight-bearing and flexed knee lateral radiographs. Many chondral lesions and their subchondral sequelae are detectable on the AP views (Fig. 32-1), which also give an indication of possible secondary changes such as joint space narrowing and osteophytes. Imaging both knees side by side allows for a built-in comparison view. Of note, OCD presents with bilateral lesions in about a third of the cases that are often easily detected on an x-ray in their typical location on the lateral aspect of the medial femoral condyle toward the intercondylar notch. The lateral flexed view is an important supplementary tool to help assess lesion size, triangulate locations, and identify patient's morphology such as patella alta or baja and trochlear groove topography. Additional views that can be obtained include standing posteroanterior 45-degree flexed knee (Rosenberg) views and supine flexed knee (Merchant) views. The Rosenberg view brings the posterior condyles into view, which helps assess the posterior joint space during loading. Merchant views are standard for the evaluation of the patellofemoral articulation. Long-leg (hip to ankle) standing AP weight-bearing radiographs should be obtained if axial alignment is deemed contributory to the patient's symptomatology and are essential for preoperative planning if a realignment procedure is being considered.

MRI remains as an import tool for assessing the status of the articular cartilage and associated structures of the knee (Fig. 32-2).[61] The

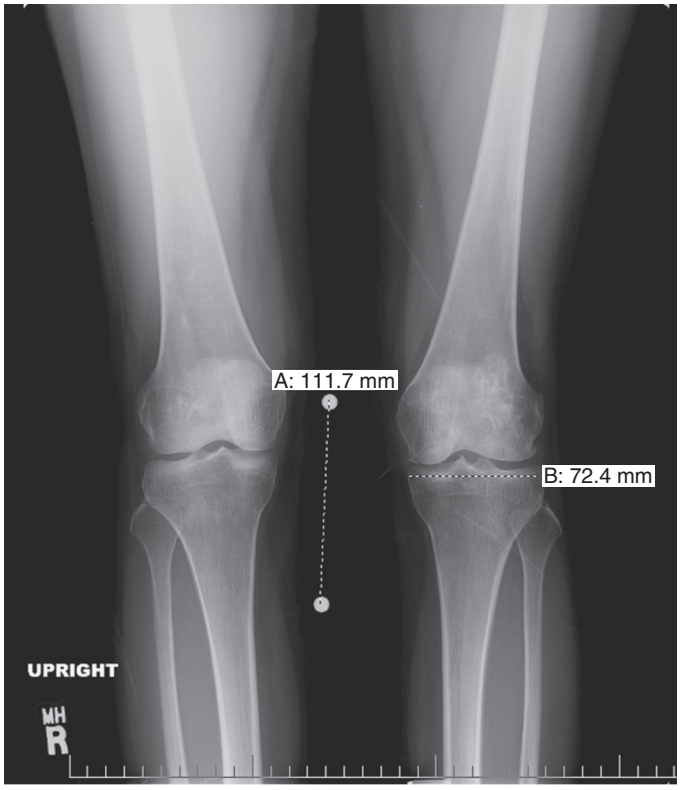


FIG 32-1 Anteroposterior radiograph of bilateral knees in a 44-year-old patient with osteonecrotic changes to her left lateral femoral condyle, displaying a tibial measurement and a radiographic magnification marker for allograft sizing.



FIG 32-2 T2 sequence magnetic resonance imaging of the left knee of an 18-year-old woman demonstrates an osteochondritis dissecans lesion in typical location on the lateral aspect of the left medial femoral condyle.

most common MRI sequences for cartilage assessment of cartilage repair require cartilage that are fat-suppressed 3-dimensional gradient echo (3D-GRE) and proton-density (PD) and T2-weighted (dual) fast spin echo (FSE) techniques with or without fat suppression. In general, 3D-GRE sequences with fat suppression allow analysis of the thickness and surface of cartilage, whereas dual FSE sequences outline the internal structure of hyaline cartilage.[7,8,31,34] Although not widely used on clinical scanners, recent advancements in specific sequences of MRI such as delayed gadolinium enhanced MRI of cartilage (dGEMRIC), T1 rho, T2 mapping and diffusion weighted imaging can assess biochemical details of cartilage tissue.[68] Additionally, with the widespread deployment and subsequent validation of novel qualitative and quantitative MRI sequences, imaging may play a larger role in the postoperative evaluation of cartilage repair techniques. This includes ultrashort echo time sequences that allow qualitative and quantitative evaluation of the calcified layer of cartilage, which play an important role in the overall function of the osteochondral unit. In an exploratory subgroup analysis, preserving the calcified cartilage layer was particularly useful in predicting biomechanic properties of osteochondral allografts.

Early degenerative ICRS grade I or II changes (softening, fibrillation) and associated surface irregularities often present as subtle alterations in contour morphology and thickness on MRI. Decreases in thickness can indicate cartilage volume loss, although increases in thickness can signal intrasubstance collagen degeneration and free water accumulation. Advanced degenerative grade III or IV lesions are usually more overt on MRI, manifesting as poorly marginated substance defects often associated with corresponding signal-intensive subchondral edema or cysts, apposing joint surface changes, localized synovitis, or general joint effusion. In contrast, acute, traumatic defects routinely present as focal chondral or osteochondral lesions with distinct margins, often with underlying bone signal changes.

PREOPERATIVE PLANNING

If the patient has had prior surgery, the corresponding operative reports and arthroscopic photographs (if available) are usually helpful not only in assessing the index lesion but also in gauging the overall disease burden and suitability for autologous graft harvest, if applicable. Obviously, results of any modalities and examinations described previously will also factor into the decision and any surgical planning.

Common to all fresh allografting procedures is matching the donor with the recipient. It should be noted that in current practice, small-fragment fresh osteochondral allografts are not human leukocyte antigen (HLA) or blood type matched between donor and recipient and that no immunosuppression is used. The allografts are matched to recipients on size alone. In the knee, an AP radiograph with a magnification marker is used (see Fig. 32-1), and a measurement of the mediolateral dimension of the tibia, just below the joint surface, is made and corrected for magnification of the radiograph. This corrected measurement is used, and the tissue bank makes a direct measurement on the donor tibial plateau. Alternatively, a measurement of the affected condyle can be performed. A match is considered acceptable at ±2 mm; however, it should be noted that there is a significant variability in anatomy, which is not reflected in size measurements. In particular, in treating OCD, the pathologic condyle is typically larger, wider, and flatter; therefore a larger donor generally should be used.

Lastly, when considering realigning osteotomy on the same articulating side of an osteochondral graft, staging the procedure is advised to not jeopardize the microvascularity of the recipient bone bed.

INTRAOPERATIVE PLANNING

The patient is positioned in a supine fashion to allow for full flexion of the knee. A tourniquet is recommended to assist with intraoperative visualization. A leg or foot holder can help to position and maintain the leg between 70 and 100 degrees of flexion during open procedures.

Autografting

Historically, the intercondylar notch and lateral trochlea were presumed to be non–load bearing and thus recommended as donor sites for autologous osteochondral grafting. More recent reports have demonstrated that these areas do bear significant weight, which can theoretically contribute to increased donor site morbidity. The lateral trochlea appears to be the most involved in loading followed by the intercondylar notch and the distal medial trochlea.[1] Because the lateral trochlea is wider than the medial side, the medial trochlea may best be suited for smaller donor plugs (<5 mm).[20] Larger plugs can be taken from the lateral trochlea, starting proximal to the sulcus terminalis, where the lowest contact pressures of the lateral trochlea were measured. Owing to its load-bearing demands, the lateral trochlea appears to have thicker articular cartilage, making it the favorite graft source of most surgeons. Plugs taken from the far medial and lateral margins of the femoral trochlea, just proximal to the sulcus terminalis, also appear to provide the most accurate reconstruction of the surface anatomy of central lesions in the weight-bearing portion of either femoral condyle.[5]

Smaller grafts (4 or 6 mm) from the lateral intercondylar notch can also provide precise matches to similar lesions; however, significant inaccuracies are noted when the lateral intercondylar notch grafts are increased in size (8 mm). Although all traditional donor sites have less cartilage thickness than common recipient sites, this discrepancy is most profound between the lateral intercondylar notch and the weight-bearing portion of the femoral condyles.[67] In addition, the concave central intercondylar notch grafts do not match the topography of the convex femoral condyles,[1] and their harvest jeopardizes the integrity of the trochlear subchondral bone, which might be responsible for the increased incidence of anterior knee pain in some studies.

In general, matching articular geometry becomes more difficult, and the potential for donor site morbidity increases with larger dowels.

Allografting

Usually, patients have undergone prior surgery or are at least fully imaged; otherwise, a diagnostic arthroscopy is performed before the allografting procedure to confirm the extent of the lesion and thus adequacy of the available graft. It is the surgeon's responsibility to inspect the graft and to confirm the adequacy of the size match and quality of the tissue before surgery.

OPERATIVE TECHNIQUE

Autografting

The technique can be performed through a standard arthrotomy, miniarthrotomy, or arthroscopically. Even in arthroscopic approaches, graft harvest from the trochlea almost always necessitates a mini-incision, and the surgeon should be prepared to convert to a standard arthrotomy because certain locations (e.g., the posterior femoral condyle) may be difficult to access with less invasive approaches and perpendicularity in graft harvest, and placement might be difficult to achieve.

After the entire knee joint has been inspected and tissue adequacy of the potential donor sites validated, the lesion to treat is accessed, probed, and measured, and a corresponding graft match is established. In current practice, available donor plug sizes vary from 4 to 10 mm depending on the technique and instrumentation system used and on the size of the chondral lesion treated. For reasons outlined previously, we advocate medium-sized trochlear plugs, optimally harvested through the same ipsilateral incision. The procedure should begin with the graft harvest to ensure availability of a suitable graft before creating a recipient tunnel or to at least have a fallback option available, such as bone void filler.

Proprietary instrument systems generally use a hollow-core instrument for the graft harvest. An appropriately sized T-handled recipient harvester is tapped perpendicular to the articular surface of the far ipsilateral margin of the trochlea, just proximal to the sulcus terminalis. The depth should be a minimum of 8 mm or more, depending on subchondral involvement of the lesion to treat. It is paramount to check the perpendicularity of the harvesting device from several angles after introduction and before advancing it further. Once tapped, the harvester chisel is then removed by rotating the driver to amputate the graft. The functional length of the graft is measured, and efforts should be made to fashion the recipient socket so that it provides a secure press-fit circumferentially and has enough depth to accommodate the plug easily lengthwise.

Biomechanic studies have confirmed that optimally sized, level-seated plugs face nearly normal joint contact pressures in situ.[40] Results also show that slightly countersunk grafts and angled grafts with the highest edge placed flush to neighboring cartilage demonstrate fairly normal contact pressures. Conversely, elevated angled grafts increase contact pressures as much as 40%, making them biomechanically disadvantageous.[39] The consensus is that it is more favorable to leave a graft slightly countersunk than elevated with respect to the neighboring cartilage.[55] Therefore we advise slightly lengthening the recipient tunnel to avoid leaving the graft proud or subjecting it to undue insertion forces in an effort to bury an oversized graft.

Depending on the instrument systems, the recipient socket can be prepared using either a core or a drill. The traditional osteochondral autograft system uses a tubular coring device. Using the same technique described previously with a slightly smaller circumference T-handled harvester and maintaining strict perpendicularity, the recipient socket is created. Again, it is advisable to not oversize the recipient tunnel; rather, it should be of equal or greater depth than the donor plug's length. Drilling the recipient site might produce a more precise socket depth. In either event, the recipient socket should be measured for accuracy. The bony portion of the plug can be rasped down to the desired depth measurement, if necessary. After the donor graft's length is verified, it is then transplanted into the recipient site using the donor insertion guide, which dilates the cartilage layer with its beveled edge creating a tight press fit. The last 1 mm of impaction should be performed by lightly tapping a bone tamp over the cartilaginous cap. The bone tamp should be oversized or placed offset to avoid countersinking a slightly shorter graft.

If required, the process can be repeated until a reasonable tissue fill is achieved in the lesion, but careful spacing of the plugs is essential. A 2-mm bone bridge between recipient sockets is recommended to help achieve and maintain a secure press fit. The resulting margins on the articular surface should fill with fibrocartilage. To avoid premature amputation of the graft, the osseous portions should not intersect with one another. This can be most problematic with longer grafts obtained in areas of the knee where there is high curvature, such as the posterior femoral condyle. Finally, to prevent recipient tunnel wall fracture, each plug transfer should be completed before proceeding with additional recipient sockets.

The surgeon may choose to retrofill the created defects to minimize donor site morbidity. Using the plugs removed from the recipient

sockets carries the risk of displacement owing to their undersized nature relative to the donor voids. However, osteobiologic plugs that correspond to the diameters of commercial coring devices are available for this purpose and are optional. After the graft process, surface congruity is confirmed, and the joint is put through a ROM to ensure graft stability and lack of impingement. The knee is closed in a standard fashion over a drain after irrigation of the joint and inspection for loose bodies.

Allografting

The technique of fresh osteochondral allografting generally relies on an open arthrotomy of variable size, depending on the position and dimension of the lesion. For most femoral condyle lesions, eversion of the patella is not necessary. A standard midline incision is made from the center of the patella to the tip of the tibial tubercle and elevated subcutaneously. Depending on the location of the lesion (either medial or lateral), the joint is entered by incising the fat pad, taking care not to disrupt the anterior horn of the meniscus or to damage the articular surface. In some cases in which the lesion is posterior or very large, the ipsilateral meniscus must be detached and reflected. Generally, this can be done safely, leaving a small cuff of tissue adjacent to the anterior insertion of the meniscus for reattachment during closure. Once the joint capsule and synovium have been incised and retractors carefully placed, the knee is brought to a degree of flexion that presents the lesion into the arthrotomy site. The lesion is then inspected and palpated with a probe to determine the extent, stable margins, and maximum size.

The two commonly used techniques for the preparation and implantation of osteochondral allografts include the press-fit plug technique and the shell-graft technique. Each technique has advantages and disadvantages. The press-fit plug technique is similar in principle to the autologous osteochondral transfer systems described previously. This technique is optimal for contained condylar lesions between 15 and 35 mm in diameter (Fig. 32-3). Fixation is generally not required owing to the stability achieved with the press fit unless the lesion falls into the intercondylar notch. Disadvantages include the fact that very posterior femoral and trochlear lesions are not conducive to the use of a circular coring system and may be more amenable to shell allografts. In addition, the more ovoid shape of a lesion, the greater amount of normal cartilage that needs to be sacrificed at the recipient site to accommodate the circular donor plug. Shell grafts are technically more difficult to perform and typically require fixation. However, depending on the technique employed, less native host cartilage may need to be sacrificed.

Dowel Allograft

As with autologous dowels, several proprietary instrumentation systems are currently available (Fig. 32-4) for the preparation and implantation of press-fit dowel allografts up to 35 mm in diameter, and surgical techniques are similar.

After a size determination is made, a guidewire is driven into the center of the lesion, perpendicular to the curvature of the articular surface. The size of the graft is then determined using sizing dowels, remembering that overlapping dowels (in a "master card" or "snowman" configuration) can possibly deliver the best area fit. The remaining articular cartilage is scored to subchondral bone, and a core reamer is used to remove the articular cartilage remnants and at least 3 to 4 mm of subchondral bone (Fig. 32-5). Because it merely serves as an osteoconductive scaffold for healing to the host by creeping substitution,

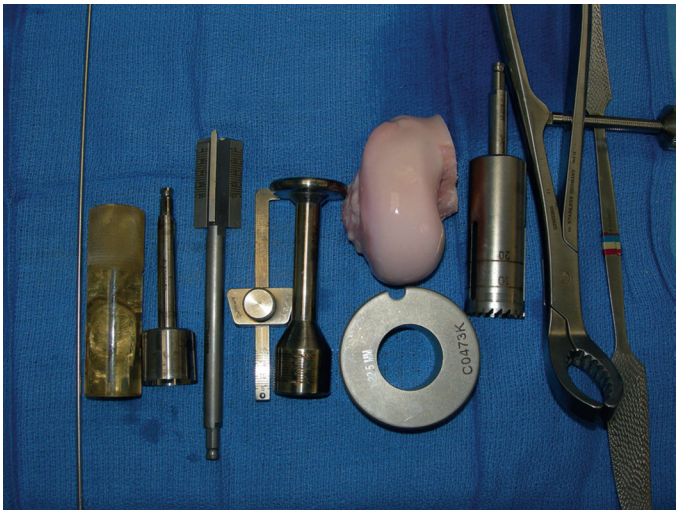


FIG 32-4 Common proprietary instrumentation used for dowel allograft preparation.

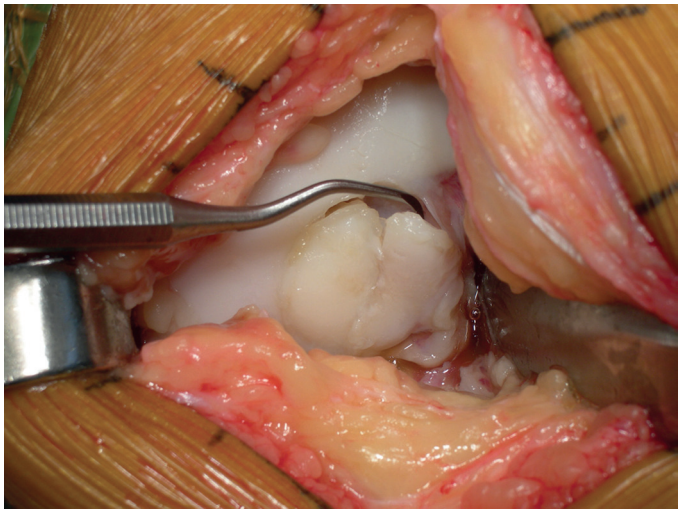


FIG 32-3 Intraoperative appearance of an osteochondritis dissecans lesion in the typical location on the left medial femoral condyle of an 18-year-old woman. (Same patient as shown in Figure 32-2.)

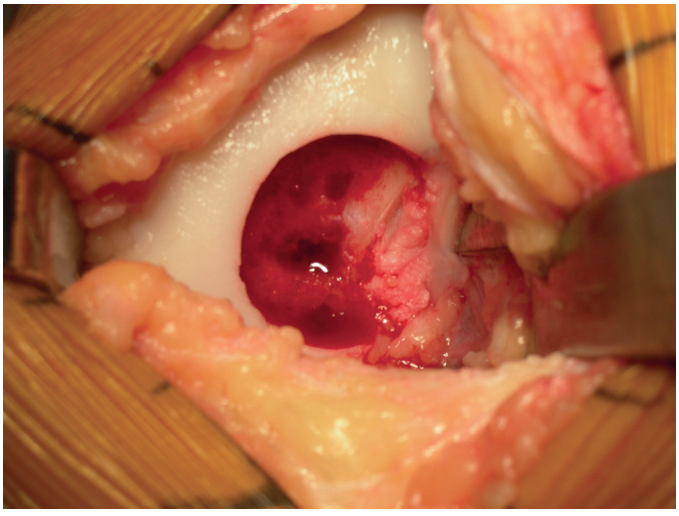


FIG 32-5 Intraoperative view after preparation of the graft bed via core reaming of the osteochondral defect and debridement down to bleeding bone.

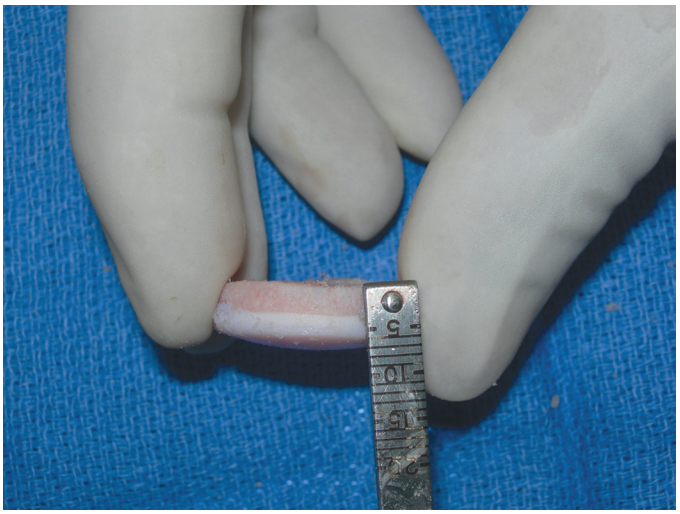


FIG 32-6 Side view of prepared dowel allograft before implantation displays the thickness of the articular cartilage in relationship to the subchondral bone portion.



FIG 32-7 Subchondral portion of the allograft dowel is being thoroughly pulse lavaged to remove potentially antigenic marrow elements and debris.

which is a rate-limited process, the portion of transplanted bone should be minimized wherever possible, without compromising the stability of the graft as warranted by the clinical situation (Fig. 32-6). This will also minimize the potential antigenic burden of marrow elements possibly remaining in the transplanted spongiosa.[18] In deeper lesions, fibrous and sclerotic bone is removed to a healthy, bleeding osseous base that does not exceed 10 mm in depth. Lesions below this depth should be curetted manually, and packed morselized autologous bone graft should be used to fill any deeper or more extensive osseous defects. Circumferential depth measurements are made of the prepared recipient site after the guide pin has been removed.

The graft is then placed into a graft holder or held manually with bone-holding forceps. The correspondent anatomic location is identified on the graft, and after a circular saw guide has been placed in the position, again perpendicular to the articular surface, an appropriate-sized tube saw is used to core out the graft. Recently, we reported an excellent OCA surface match with medial femoral condyle (MFC) donors or lateral femoral condyle (LFC) donor graft into the common MFC recipient site, suggesting that nonorthotopic LFC OCAs are also acceptable graft options for MFC defects.[53] Before removing the graft from the condyle, identifying marks are made to ensure proper orientation. Once the dowel is removed, the recipient's depth measurements are transferred to the graft. This graft is then cut with an oscillating saw and is trimmed with a rasp to the precise thickness in all four quadrants. The deep edges of the bone plug can be further chamfered with a rongeur and bone rasp to ease insertion.

The graft is then irrigated copiously with a high-pressure lavage (Fig. 32-7) to remove all marrow elements possible, and the recipient site is dilated using a slightly oversized tamp. This may ease the insertion of the graft to prevent excessive impact loading of the articular surface when the graft is inserted, while compacting the subchondral bone to prevent subsidence of the graft. At this time, any remaining osseous defects are bone grafted to a level base. The allograft is then inserted by hand in the appropriate rotation and is gently tamped into place until it is flush, again minimizing mechanical insult to the articular surface of both the graft and the surrounding native tissue. Alternatively, the graft can be seated by gently ranging the knee using the apposing joint surface as a fulcrum.

After the graft is seated, additional fixation with absorbable polydioxanone pins may be added, if necessary, particularly if the graft is large or has an exposed edge within the notch (Fig. 32-8). The knee is then brought through a complete ROM to confirm that the graft is stable and that no catching or soft tissue obstruction is noted. The wound is then copiously irrigated, and routine closure is performed.

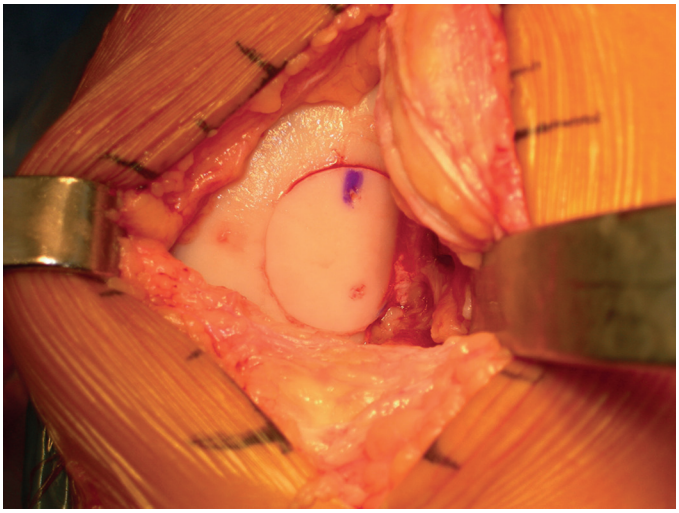


FIG 32-8 Osteochondral dowel plug in place and secured by several absorbable polydioxanone pins. Note the flush fit with the surrounding joint surface and the ink marks ensuring orthotopic orientation of the graft.

Shell Allograft

The defect is identified through the previously described arthrotomy, and the dimensions of the lesion are marked with a surgical pen. Minimizing the sacrifice of normal cartilage, a geometric shape is created that is amenable to handcrafting a shell graft (Figs. 32-9 and 32-10). A No. 15 scalpel blade is used to demarcate the lesion, and sharp ring curettes are used to remove all tissue inside this mark. Using motorized burrs and sharp curettes, the lesion is debrided down to a depth of 4 to 5 mm (Fig. 32-11). The shape is transferred to the graft, which is molded in a freehand fashion (Fig. 32-12), initially slightly oversizing the graft and carefully removing excess bone and cartilage from the template as necessary through multiple trial fittings. If there is deeper

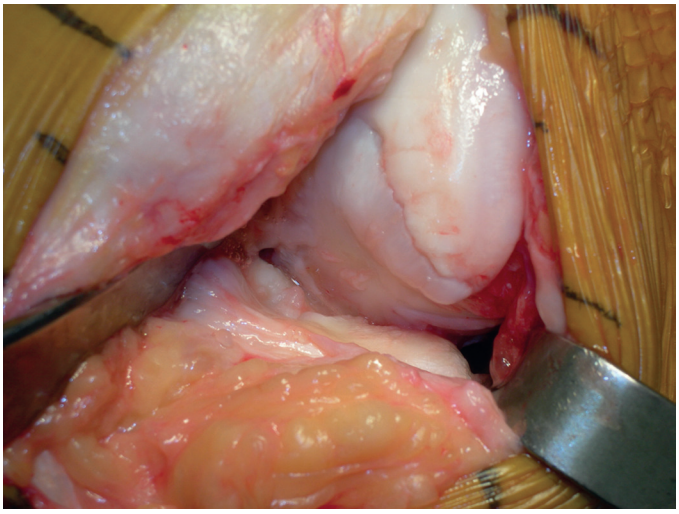


FIG 32-9 Intraoperative appearance of an osteochondral lesion secondary to osteonecrosis of the left lateral femoral condyle in a 44-year-old woman. (Same patient as shown in Figure 32-1.)

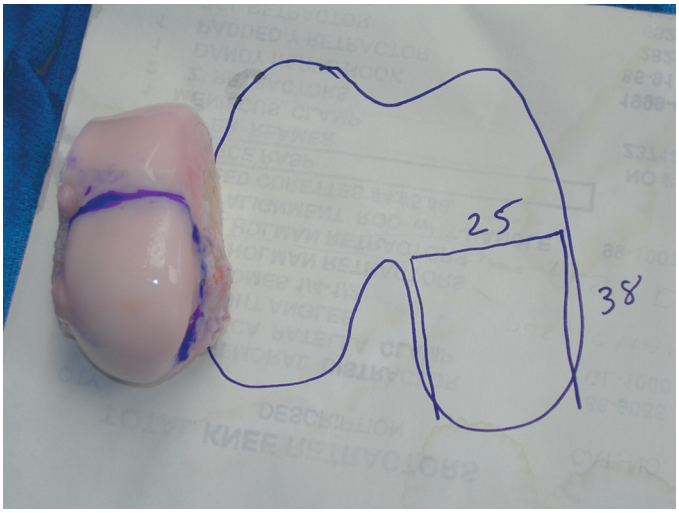


FIG 32-10 Left lateral femoral condyle allograft illustrates the templating for a shell allograft. Note the ink marks on the native cartilage and measurement transferred to a corresponding map.

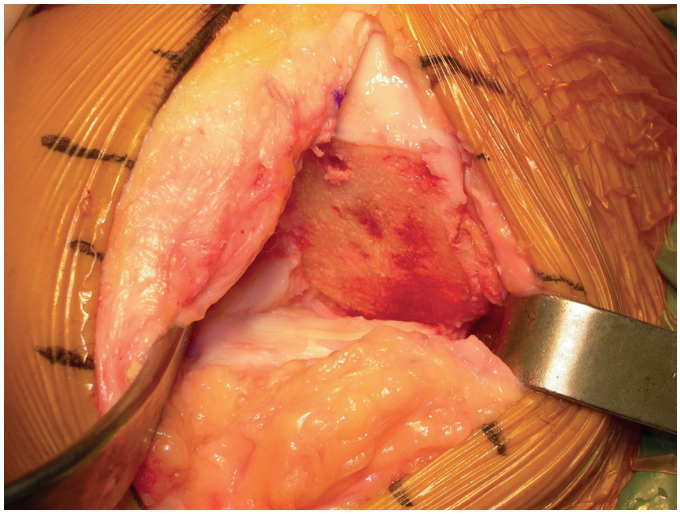


FIG 32-11 Intraoperative view after freehand preparation of the graft bed in preparation for a shell allograft.



FIG 32-12 Comparison of the removed collapsed native condyle on the right and the shell allograft on the left.

bone loss in the defect, more bone can be left on the graft, and the defect can be grafted with cancellous bone before graft insertion. The graft and host bed are then copiously irrigated and the graft placed flush with the articular surface. The need for fixation is based on the degree of inherent stability. Bioabsorbable pins, as described previously, are typically used when fixation is required (Fig. 32-13), but countersunk compression screws may be used as an alternative, optimally avoiding the weight-bearing portion. After cycling the knee through a full ROM and irrigating the joint, standard closure is performed.

Postoperative Management

The use of continuous passive motion during early postoperative management is optional. Patients are generally allowed full ROM unless the graft involves the patellofemoral joint or there are other additional reconstructive procedures, such as meniscal repair, anterior cruciate ligament (ACL) reconstruction, or osteotomy, which would alter the rehabilitation plan. Typically, braces are not used postoperatively except for patellofemoral grafts in which flexion is limited to less than 45 degrees for the first 4 to 6 weeks and in cases of bipolar tibial femoral grafts in which an unloader or ROM brace is used to prevent excessive stress on the grafted compartment.

Patients are begun on early ROM exercises and quadriceps strengthening (e.g., straight-leg raises) and are maintained in a toe touch only weight-bearing status for a period of at least 8 weeks, and often 12 weeks, depending on the size and containment of the graft, type of fixation, and ultimately, radiographic evidence of incorporation. At 4 weeks, patients are allowed closed-chain exercises such as cycling. Progressive weight bearing as tolerated is usually allowed at 3 months, and if functional rehabilitation is complete, the patient is allowed to return to recreation and sports at approximately 6 months. Patients are generally cautioned about excessive impact loading of the allograft, particularly in the first year. As with any cartilage replacement procedure, long-term outcomes in osteochondral allografting are directly and inversely related to the time to treatment and overall burden of disease in the affected joint. In a young patient with a focal lesion (traumatic or OCD), it is not unrealistic to expect him or her to go back to normal impact-loading activities after 12 months and to return to preinjury function, whereas the goals in a salvage situation are usually to delay or even eliminate the need for prosthetic replacement by reducing pain and allowing a return to functional activities of daily living as well as low-impact recreational activities.

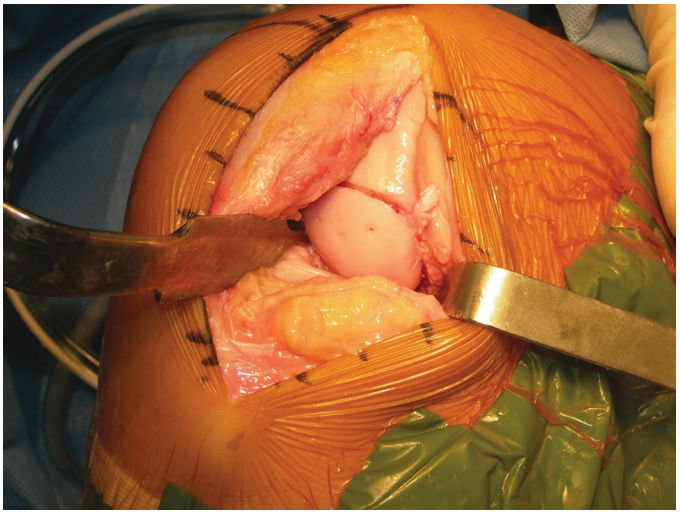


FIG 32-13 Osteochondral shell graft in place shows restoration of the condylar topography and weight-bearing portion of the articular cartilage in the lateral femoral condyle.

OUR CLINICAL OUTCOMES

We believe that osteochondral allografting is an excellent treatment option for advanced OCD lesions. We previously published the results of 66 knees in 64 patients with OCD of the femoral condyle, treated with fresh osteochondral allografts, implanted within 5 days of graft recovery.[17] Patients were evaluated preoperatively and postoperatively using an 18-point scale, which measures function, ROM, and absence of pain, allotting 1 to 6 points each, for a maximum of 18 points (Table 32-1).

There were 45 males and 19 females, with a mean age of 28.6 years (range, 15-54 years). All lesions were ICRS grade III-IV OCD; 40 involved the medial femoral condyle and 25 the lateral femoral condyle. All patients had undergone an average of 1.6 previous operations. The average allograft size was 7.5 cm^2. The mean follow-up was 7.7 years (range, 2-22 years); one patient was lost to follow-up. Overall, 47 of 65 knees (72%) were rated good or excellent, scoring 15 points or above on the 18-point scale. Seven (11%) were rated fair, and one (2%) was rated poor. The average clinical score improved from 12.9 points preoperatively to 16.1 points postoperatively ($P < .01$).

Preoperative, immediate postoperative, and most recent follow-up AP and lateral radiographs were available for 32 of 66 knees, with a mean follow-up of 3.1 years. In these, evidence of graft union, collapse, resorption, and the presence of degenerative changes were recorded by a musculoskeletal radiologist. Twenty-four of the grafts (75%) demonstrated healing; 26 (81%) were intact. Subchondral cysts were present in five (16%) knees. Sclerosis was found in six (19%) cases. Ten patients had reoperations on the allograft, with a mean time to reoperation of 56 months, including three patients who went on to arthroplasty. Subjective knee function improved from a mean of 3.4 to 8.4 points ($P < .01$) on a 10-point scale for the 59 patients who completed questionnaires. With greater than 70% good or excellent results, fresh osteochondral allograft transplantation has proved to be a successful surgical treatment for OCD of the femoral condyle in multiple-operated knees. In our experience, results are even more favorable for osteochondral allografts as a primary treatment measure in native OCD lesions.

Although OCD remains a perfect indication for osteochondral allografting, focal lesions of diverse etiologies are amenable to this application; the results were presented of 43 knees with isolated chondral lesions of the femoral condyle.[54] A total of 39 patients (43 knees) underwent fresh osteochondral allograft transplantation for treatment of chondral and osteochondral lesions. Twenty-six male and 17 female knees with a mean age of 16.4 years (range, 11-17.9 years) at index surgery were followed-up at a mean of 8.4 years (range, 1.7-27.1 years). Thirty-four knees (79%) had at least one previous surgery. The most common underlying causes of the lesions were osteochondritis dissecans (61%), avascular necrosis (16%), and traumatic chondral injury (14%). Mean allograft size was 8.4 cm^2. The most common allograft location was the medial femoral condyle (41.9%) followed by the lateral femoral condyle (35%). Each patient was evaluated with the International Knee Documentation Committee (IKDC) pain, function, and total scores; a modified Merle d'Aubigné-Postel (18-point) scale; and Knee Society function score. Failure was defined as revision osteochondral allograft or conversion to arthroplasty. Five knees experienced clinical failure at a median of 2.7 years (range, 1.0-14.7 years). Four failures were salvaged successfully with another osteochondral allograft transplant. One patient underwent prosthetic arthroplasty 8.6 years after revision allograft. Graft survivorship was 90% at 10 years. Of the knees whose grafts were in situ at latest follow-up, 88% were rated good or excellent (18-point scale). The mean IKDC scores improved from 42 preoperatively to 75 postoperatively, and the Knee Society function (KS-F) score improved from 69 to 89 (both $P < .05$). Eighty-nine percent of patients reported "extremely satisfied" or "satisfied." With 88% good or excellent results and 80% salvage rate of clinical failures with an additional allograft, osteochondral allograft transplantation is a useful treatment option in pediatric and adolescent patients.

We studied osteochondral allografts transplantation to treat isolated femoral condyle lesions.[43] There were 122 patients (129 knees) who underwent osteochondral allograft transplantation of the femoral condyle. The mean age was 33 years, and 53% were male. Clinical evaluation included the 18-point scale, IKDC, and KS-F scores. Graft

TABLE 32-1 18-Point Scale

Points	Pain	Criteria
1	Severe	Not relieved by rest and analgesics
2	Severe	Relieved by rest and analgesics
3	Moderate	Regular analgesics needed
4	Mild	Occasional analgesics needed
5	Minimum	Occasional ache
6	None	

Points	Function
1	Bedridden or household walker with two canes or crutches
2	Time and distance outside limited; walks with external aids
3	Walks <0.8 km with external aids; stair climbing limited
4	Walks >0.8 km with external aids; stair climbing not limited
5	No external aids; limps
6	Unlimited walking without a limp

Points	Range of Motion
1	<60 degrees of flexion
2	15-90 degrees of flexion
3	0-90 degrees of flexion
4	>90 degrees of flexion; ≤15 degrees contracture
5	>90 degrees of flexion without contracture
6	≥130 degrees of flexion without contracture

failure was defined as revision osteochondral allografting or conversion to arthroplasty. A determination was made of whether or not patients' characteristics or attributes of the graft influenced failure. Minimum follow-up was 2.4 years (median, 13.5 years); 91% had more than 10 years of follow-up. The 18-point scale improved from a mean of 12.1 to 16, the IKDC pain score improved from a mean of 7.0 to 3.8, the IKDC function score improved from a mean of 3.4 to 7.2; the KS-F score from a mean of 65.6 to 82.5. Sixty-one knees (47%) underwent reoperations. Thirty-one knees (24%) failed at a mean of 7.2 years. Survivorship was 82% at 10 years, 74% at 15 years, and 66% at 20 years. Age older than 30 years at time of surgery and having two or more previous surgeries for the operated knee were associated with allograft failure. Follow-up of femoral condyle osteochondral allografting demonstrated durable improvement in pain and function, with graft survivorship of 82% at 10 years.

Osteonecrosis of the knee is a serious potential complication of corticosteroid therapy with limited treatment options. Osteochondral allografting is a salvage alternative in patients who are of an age and activity level not ideally suited for arthroplasty. We reported the clinical outcomes of fresh osteochondral allografting in individuals with steroid-induced modified Association Research Circulation Osseous (ARCO) stage 3 to 4 osteonecrosis of the femoral condyles.[27] Clinical evaluation was performed using the modified D'Aubigné and Postel (18-point) scale. Subjective outcome measures included a patient questionnaire evaluating pain, function, and satisfaction. Of 24 patients who underwent osteochondral allografting for osteonecrosis between 1984 and 2005, 17 (12 females and 5 males) fulfilled inclusion criteria with minimum 2-year follow-up (mean follow-up, 65 months; range, 24-236 months). The 17 patients had a mean age of 28.8 years (range, 16-68 years). Five had bilateral surgery, for a total of 22 knees. Of these knees, 16 had unicondylar lesions (12 lateral, 4 medial) and six had bicompartmental involvement. Fifty-six percent of knees had previous surgery (average, 1.5; range, 1-5 surgeries). The mean graft surface area was 11.0 cm^2 (range, 5.3-19.0 cm^2). Twelve of 22 (54.5%) required additional bone grafting. Seventeen of 22 (77%) were considered successful (score, ≥15 points). The mean score improved from 11.1 to 15.9 points ($P < .0001$). Two patients had further surgery: one underwent arthroscopic debridement, and another underwent total knee arthroplasty 76 months after the index surgery. Fourteen patients completed questionnaires; all reported statistically significant higher ($P < .0001$) pain relief, improved function, and overall satisfaction with their outcome. Fresh osteochondral allografting was successful in 77% of these relatively young patients and resulted in significant improvement in function and pain with high patient satisfaction, leading us to consider osteochondral allografting as a reasonable salvage option for patients with avascular necrosis of the knee joint.

Recently, we reported the outcomes of osteochondral allografting in 28 knees with patellar cartilage injuries.[29] All patients had minimum 2 years of follow-up. The mean age of the patients was 33.6 years (range, 14-64 years); 54% were female. Twenty-six (92.9%) knees had previous surgery (mean, 3.2 procedures; range 1-10). The mean allograft area was 10.1 cm^2 (range, 4.0-18.0 cm^2). Any reoperation resulting in removal of the allograft was considered a failure of the OCA transplantation. Patients were evaluated preoperatively and postoperatively using the 18-point scale, the IKDC pain and function scores, and the KS-F score. Seventeen of the 28 knees (60.7%) had further surgery following the OCA transplantation. Eight of the 28 knees (28.6%) were considered OCA failures (four conversions to total knee arthroplasty, two conversions to patellofemoral knee arthroplasty, one revision OCA, 1 patellectomy). Patellar allografting survivorship was 78.1% at 5 and 10 years; 55.8% at 15 years. Among the 20 knees (71%) with grafts in situ, the mean follow-up duration was 9.7 years (range, 1.8-30.1 years). Pain and function improved from the preoperative visit to latest follow-up. Eighty-nine percent of patients were extremely satisfied or satisfied with the results of the OCA transplantation. We concluded that the treatment of patellar cartilage injuries remains a difficult clinical challenge regardless of the surgical intervention chosen, with relatively high reoperation and revision rates; however, patellar allografting is a useful salvage treatment option for patellar cartilage injuries.

Lately, a major concern has been raised because of the conflicting results of autologous chondrocyte implantation (ACI) after a failed previous cartilage repair. ACI after previous treatment with subchondral marrow stimulation interventions were proven to fail at a rate of three to five times higher than primary ACI.[51,56] We postulated that OCA transplantation is fundamentally different than ACI. In a recent study, we identified 46 knees that had OCA transplantation performed as a primary treatment (group 1) and 46 knees that underwent OCA transplantation after failure of previous cartilage repair (group 2).[28] All patients had a minimum of 2 years of follow-up. Patients in each group were matched for age (±5 years), diagnosis (osteochondral lesion, degenerative chondral lesion, traumatic chondral injury), and graft size (small <5 cm^2; medium, 5-10 cm^2, large >10 cm^2). The groups had similar body mass indexes, gender distributions, and graft locations (femoral condyle, patella and trochlea); failure was defined as any reoperation resulting in removal of the graft. On review, 91.3% of knees in group 1 and 95.7% in group 2 were located in femoral condyle. Functional outcomes were evaluated using the 18-point scale, IKDC subjective knee evaluation form, Knee Osteoarthritis and Injury Outcomes Scores (KOOS) scale, and KS-F scale. Patient satisfaction using a 5-point scale from "extremely satisfied" to "dissatisfied" was recorded at latest follow-up. Eleven of 46 knees (24%) in group 1 had reoperations compared with 20 of 46 knees (44%) in group 2 ($P = .04$). The OCA was classified as a failure in five knees (11%) in group 1 and seven knees (15%) in group 2 ($P = .53$). At 10 years of follow-up, survivorship of the graft were 87.4% and 86% in groups 1 and group 2, respectively. Both groups showed improvement in pain and function on all subjective scores from preoperatively to latest follow-up (all $P < .001$). Eighty-seven percent of patients in group 1 and 97% in group 2 were "satisfied" or "extremely satisfied" with the OCA transplantation. Favorable results were shown in both groups with significant improvement of functional scores and excellent survivorship. Despite the higher reoperation rate in the previously treated group, previous cartilage surgery did not adversely affect the survivorship and functional outcome of OCA transplantation.

Recently, we reported that revision osteochondral allograft transplantation of the knee demonstrated acceptable clinical outcomes, although they were inferior to primary allograft transplantation procedures.[32] Thirty three patients (33 knees) who underwent revision osteochondral allograft transplantation between 1983 and 2012 were at least 2 years out from surgery and had a minimum 2-year follow-up. Failure of the revision allograft was defined as conversion to partial or total knee arthroplasty. The mean follow-up after revision osteochondral allograft transplantation was 10 years, with 75% of patients having more than 5 years of follow-up. Thirteen patients (39%) had failed results after revision osteochondral allograft transplantation, with a mean time to failure of 5.5 years. The remaining 20 patients (61%) had surviving revision allografts, with a mean graft survival of 10 years. Mean pain and function scores at the last follow-up were improved. Survivorship of the revision allograft was 61% at 10 years.

Treatment options also remain limited in younger, active individuals with impeding knee arthrosis. We reported the results of osteochondral allografting in 37 knees with multifocal chondral lesions and arthritic changes.[58] All patients demonstrated radiographic evidence of

arthrosis. Assessment was performed with the modified D'Aubigné and Postel (18-point) scale and IKDC score. Radiographs were evaluated by modified Fairbanks/Ahlbäck criteria. Again, subjective outcome measures included a patient questionnaire evaluating pain, function, and satisfaction. The 37 patients (25 males, 12 females) had a mean age of 42 years (range, 15-67 years) and an activity level not ideally suited for arthroplasty. The mean follow-up was 36 months (range, 24-84 months). Three patients were lost to follow-up. Nineteen of the allografts were unipolar, 10 involved bipolar/kissing lesions, and 5 multiple surfaces. The mean allograft area was 10.5 cm^2. Twenty-six of 34 (76%) were considered successful (score, ≥15 points), and eight (24%) were unsuccessful (3 converted to total knee arthroplasty, 2 underwent repeat allografting declined further surgery but were considered failures owing to fair or poor postoperative scores). The average 18-point scores improved from 11.5 to 16.2 points, whereas IKDC scores improved from 33.0 to 64.7 points ($P < .01$).

Nineteen of 31 preoperative radiographs (61%) were grade 3 (>50% joint space narrowing), and 12 of 31 (39%) were grade 1 to 2 (<50% narrowing). Postoperatively, 13 of 31 radiographs (42%) were grade 3, and 18 of 31 (58%) were grade 1 to 2. Eighteen of 34 patients (53%) were extremely satisfied, 15 (44%) were satisfied, 1 (3%) was somewhat satisfied, and none were dissatisfied. Overall, clinical success of fresh allografting for knee arthrosis was 76%. Objective and subjective improvements were statistically significant. Success may be challenged with longer follow-up. Treatment options for knee arthritis in the young, active patient are currently extremely limited, and fresh osteochondral allografting is an emergent bioorthologic alternative in this growing and challenging segment of the population.

We recently reported outcomes of 48 knees with reciprocal bipolar cartilage lesions.[50] Twenty-one males and 25 females averaged 40 years of age (range, 15-66 years). Thirty-four lesions were tibiofemoral and 14 patellofemoral. Forty-two patients (88%) had an average of 3.4 previous surgeries (range, 1-8). Mean allograft area was 19.2 cm^2. Clinical evaluation included the 18-point scale, IKDC pain and function, and KS-F scores. Further surgeries on the operative joint were documented. Survivorship of the bipolar OCA was 64.1% at 5 years. Thirty knees had further surgery; 22 knees (46%) were considered failures (3 OCA revisions, 14 total knee arthroplasties, 2 unicondylar arthroplasties, 2 arthrodesis, and 1 patellectomy). Among patients whose OCA was still in situ at follow-up, the mean follow-up was 7 years (range, 2-19.7 years). The mean 18-point score improved from 12.1 to 16.1; 88% (23 of 26 knees) of surviving allografts scored higher or greater than 15. The mean IKDC pain score improved from 7.5 to 4.7, and the mean IKDC function score improved from 3.4 to 7.0. The mean KS-F score improved from 70.5 to 84.1. We conclude that OCA transplantation is a useful salvage treatment option for reciprocal bipolar cartilage lesions of the knee. High reoperation and failure rates were observed, but patients with surviving allografts had significant clinical improvement.

CLINICAL OUTCOMES FROM OTHER AUTHORS

Autografts

Hangody and Fules[31] reported their 10-year clinical experience with autologous osteochondral mosaicplasty (Table 32-2). These investigators performed 831 mosaicplasties involving 597 femoral condyles, 118 patellofemoral (patella and/or trochlea) joints, 76 talar domes, 25 tibial condyles, 6 capitulum humeri, 6 femoral heads, and 3 humeral heads. Concomitant surgery (ACL reconstruction, realignment procedures, and meniscal surgeries) was performed in 85% of the patients. Good to excellent results were reported in 92% of the patients who had femoral condyle grafts, 87% of those who had tibial grafts, and 79% of those who had patellar grafts. Long-term donor site morbidity was found in 3% of the patients.

Marcacci and coworkers[46] reported on 37 athletes younger than 50 years of age with at least a 2-year follow-up. In this study, 23 of 37 patients (62%) underwent an associated procedure with arthroscopic mosaicplasty of the femoral condyle. The data revealed that 78% of the patients had good to excellent results. Twenty-seven patients returned to sports at the same level, five patients returned at a lower level, and five were unable to return to sports. Medial femoral condyle lesions statistically did not fare as well as lateral condyle lesions. Donor site morbidity was not an identifiable problem in this case series.

The same group prospectively evaluated 30 patients with full-thickness chondral lesions (<2.5 cm^2) of the knee treated with arthroscopic autologous osteochondral transplantation.[45] The ICRS objective evaluation showed 76.7% of patients had good or excellent results at 7-year follow-up, and IKDC subjective score significantly improved from preoperative (34.8 points) to 7-year follow-up (71.8 points). The Tegner score showed a significant improvement after the surgery at 2- and 7-year follow-up (from 2.9 to 6.2 and 5.6 points, respectively); however, sports participation declined from 2- to 7-year follow-up. MRI evaluation showed good integration of the graft in the host bone and complete maintenance of the grafted cartilage in more than 60% of cases.

In a study by Jakob and associates,[34] 92% of patients (48 of 52) demonstrated improved knee function at the latest follow-up (average, 37 months) from open knee mosaicplasty. In 30 of 52 patients (58%), a concomitant procedure was performed. Four patients required reoperation because of graft failure.

With a mean follow-up of 45.1 months, Chow and colleagues[11] reported on 30 patients who had undergone arthroscopic autologous

TABLE 32-2 Selected Outcomes of Osteochondral Autografting in the Knee

Study	Site of Lesion	Knees (*n*)	Follow-up (yr)	Outcome (%)
Hangody & Fules[31] (2003)	Femur	597	1-10	92 Good/excellent
	Patellofemoral	118		87 Good/excellent
	Tibia	25		79 Good/excellent
Marcacci et al[46] (2005)	Femur	37	2.0	78 Good/excellent
Marcacci et al[45] (2007)	Femur	30	7.0	77 Good/excellent
Jakob et al[34] (2002)	Femur	52	3.1	92 Improved
Chow et al[11] (2004)	Femur	30	3.8	83 Good/excellent
Outerbridge et al[57] (2000)	Femur	18	7.6	81 High functional level
Karataglis et al[38] (2006)	Femur and patellofemoral	37	3.1	87 High functional level

osteochondral transplantation to the femoral condyle. Good to excellent results were reported in 83% (25 of 30) of patients. Lysholm scores increased from an average of 43.6 points preoperatively to a mean of 87.5 points postoperatively. Two patients (7%) had poor results and later underwent total knee arthroplasty.

Outerbridge and coworkers[57] followed 18 knees for an average of 7.6 years after osteochondral autografting of the femoral condyle using the ipsilateral lateral patellar facet as the donor graft. These investigators reported an increase in Cincinnati knee scores from an average preoperative score of 37 points to an average final follow-up score of 85 points. Eighty-one percent (13 of 16) of the patients returned to a high functional level. Twelve percent (2 of 16) experienced moderate patellofemoral joint symptoms. Nevertheless, all patients were satisfied with the procedural results and, given the choice, would have the same surgery done again for an identical lesion on the contralateral knee.

Karataglis and associates[38] reported on their mid- and long-term functional outcomes of 36 patients (37 knees) who underwent the osteochondral autograft transplantation technique with an average follow-up of 36.9 months. The lesions were located on the femoral condyle in 26 cases, on the trochlea in seven cases, and on the patella in four cases. Thirty-two of 37 patients (86.5%) reported significant improvement of their preoperative symptoms. All but five patients returned to previous daily and work activities. Eighteen patients returned to sports. Nine patients required second-look arthroscopies because of swelling, pain, or clicking. In two of those cases, the grafts were found to be loose and required revision. Symptoms improved significantly in four of those nine patients after repeat arthroscopy. Donor site morbidity was not seen in this series.

Allografts

Garrett[21] reported on the experience with fresh osteochondral allografts used as both a press-fit plug and a large shell graft in the treatment of 17 patients with OCD, all of whom had undergone previous surgery. Sixteen patients (94%) reported relief of symptoms at 2- to 9-year follow-up. This work is remarkable for the first reported use of dowel grafts in the literature.

Chu and colleagues[12] reported on 55 consecutive knees undergoing osteochondral allografting for diagnosis such as traumatic chondral injury, avascular necrosis, OCD, and patellofemoral disease. The mean age was 35.6 years, with follow-up averaging 75 months (range, 11-147 months). Of the 55 knees, 43 were unipolar replacements, and 12 were bipolar resurfacing replacements. On the 18-point scale, 45 of 55 of these knees (76%) were rated good to excellent and three as fair. Of note, 36 of the 43 knees (84%) that underwent unipolar femoral grafts were rated good to excellent compared with only six of the 12 knees (50%) with bipolar grafts.

McDermott and coworkers[49] reported on 100 patients treated with fresh osteochondral grafts implanted within 24 hours of recovery. Fifty patients had a unifocal traumatic defect of the tibial plateau or femoral condyle, 38 of which (76%) were considered successful at an average follow-up of 3.8 years. Patients with osteoarthritis and osteonecrosis had poorer results.

Ghazavi and associates[22] reported on 126 knees in 123 patients with an average follow-up of 7.5 years. One hundred and five of 123 patients (85%) were rated as successful; the remaining 18 failed. Advanced age (>50 years), bipolar defects, malalignment, and Workers' Compensation cases were considered main factors related to failure.

Beaver and colleagues[6] performed a survivorship study on 92 knees allografted for posttraumatic cartilage lesions with failure defined as the need for a revision operation or the persistence of symptoms. There was a 75% success rate at 5 years, 64% at 10 years, and 63% at 14 years. Advanced age (>60 years) and bipolar defects were again identified as factors for failure.

Aubin and coworkers[3] later followed 60 patients, 41 of whom (68%) had undergone simultaneous realignment osteotomy and 10 (15%) concomitant meniscal transplantation. Kaplan-Meier survivorship analysis that showed 51 grafts (85%) survived at 10 years and 44 (74%) at 15 years.

McCulloch and associates[48] presented the results of 25 consecutive patients who underwent prolonged fresh osteochondral allograft transplantation for defects in the femoral condyle. The average patient age was 35 years (range, 17-49 years). The average length of follow-up was 35 months (range, 24-67 months). Statistically significant improvements ($P < .05$) were reported for the Lysholm (39-67 points), IKDC scores (29-58 points), all five components of the KOOS, and the Short Form-12 physical component score (36 to 40 points). Overall, patients reported 84% satisfaction (range, 25%-100%) with their results and believed that the knee functioned at 79% of their unaffected knee (range, 35%-100%). Radiographically, 22 of the grafts (88%) were incorporated into host bone.

Williams and colleagues[71] prospectively followed 19 patients with symptomatic chondral and osteochondral lesions of the knee who were treated with fresh osteochondral allografts, with a mean preimplantation storage time of 30 days (range, 17-42 days). The mean age at the time of surgery was 34 years. The mean lesion size was 602 mm^2. MRI was used to evaluate the morphologic characteristics of the implanted grafts. The mean duration of clinical follow-up was 48 months (range, 21-68 months). The mean score (and standard deviation) on the Activities of Daily Living Scale increased from a baseline of 56 ± 24 to 70 ± 22 points at the time of the final follow-up ($P < .05$). The mean Short Form-36 (SF-36) score increased from a baseline of 51 ± 23 to 66 ± 24 points at the time of final follow-up ($P < .005$). At a mean follow-up interval of 25 months, cartilage-sensitive MRI demonstrated that the normal articular cartilage thickness was preserved in 18 implanted grafts, and allograft cartilage signal properties were isointense relative to normal articular cartilage in 8 of the 18 grafts. Osseous trabecular incorporation of the allograft was complete or partial in 14 patients and poor in 4 patients. Complete or partial trabecular incorporation positively correlated with SF-36 scores at the time of follow-up ($R = .487$; $P < .05$).

Recently, Raz and associates[62] reported outcomes of osteochondral allograft transplantation for posttraumatic osteochondral and osteochondritis dissecans defects in the distal aspect of the femur. Sixty-three patients underwent osteochondral allograft transplantation to the distal aspect of the femur. Fifty-eight patients aged 11 to 48 years at the time of surgery (mean age, 28 years) were followed for a mean of 21.8 years (range, 15-32 years). Thirteen of the 58 patients required further surgery; three underwent graft removal, nine were converted to total knee arthroplasty, and one underwent multiple debridements followed by above-the-knee amputation. A Kaplan-Meier analysis of graft survival showed rates of 91%, 84%, 69%, and 59% at 10, 15, 20, and 25 years, respectively. Patients with surviving grafts had good function, with a mean modified Hospital for Special Surgery (HSS) score of 86 at 15 years or more following the allograft transplant surgery. Late osteoarthritic degeneration on radiographs was associated with lower HSS scores and poorer clinical outcomes. Fresh osteochondral allograft was found to provide a long-term solution for large articular cartilage defects in the distal aspect of the femur in young, active patients.

Several therapeutic case series studies reported the functional outcome of osteochondral allograft transplantation in the knee. Besides the high heterogeneity of the studies reported, they are summarized in the Table 32-3.

TABLE 32-3 Functional Outcomes of Osteochondral Allografting in the Knee

Study	Patients (*n*)	Graft Location	Follow-up (yr), Mean (Range)	Age (yr), Mean (Range)	MAIN OUTCOMES: Rating System	MAIN OUTCOMES: Preoperative Score (Mean or Range)	MAIN OUTCOMES: Follow-up Score (Mean or Range)	Failure (*n*)	Comments
Gracitelli et al[29] (2015)	27 (28 knees)	PF	9.7 (1.8-30.1)	33.6 (14-64)	IKDC	36.5	66.5*	8 (28.5%)	45% required further surgery (not failures)
Meric et al[50] (2015)	46 (48 knees)	TF, PF	7 (2-19.7)	40 (15-66)	IKDC pain, IKDC function	7.5 ± 2.2 3.4 ± 1.5	4.7 ± 3.1* 7.0 ± 2.0*	22 (46%)	Bipolar lesions
Murphy et al[54] (2014)	39 (43 knees)	MFC, LFC, plateau, PF	8.4 (1.7-27.1)	16.4 (11.0-17.9)	IKDC	42.0 ± 16.6	75.2 ± 20.2*	5 (11.6%)	88% good/excellent results
Shasha et al[66] (2013)	38	MFC, LFC	4.1 (1-9)	29.83 ± 5.3	KOOS	NA	249.51 ± 51.26	0	Disappointing results in an active-duty population
Horton et al[32] (2013)	33	MFC, LFC, plateau, PF	10 (2.4-26)	33 (16-64)	IKDC	NA	70.5 (25-95)	13 (39%)	Only revised allografts
Giorgini et al[23] (2013)	11	MFC, LFC, plateau, kissing lesions	2.2 (1-4.5)	34 (18-66)	IKDC	27.4 ± 14.9	47.4 ± 15.7	1 (9%)	Short follow-up duration
Raz et al[62] (2014)	58	MFC, LFC	21.8 (15-32)	28 (11-48)	HSS	NA	86 at 15 yr	13 (22.4%)	62% concomitant realignment procedures
Krych et al[41] (2012)	43	MFC, LFC, trochlea	2.5 (1-11)	33 (18-49)	IKDC	46.3 ± 14.9	79.3 ± 15.5*	0	NA
Levy et al[43] (2013)	122 (129 knees)	MFC, LFC	13.5 (2.4-27.5)	32.8 (15-68)	IKDC pain, IKDC function	7.0 ± 1.9, 3.4 ± 1.3	3.8 ± 2.9, 7.2 ± 2.0*	31 (24%)	Largest cohort
Scully et al[65] (2011)	18	MFC, LFC	3.4	27 (30-35)	Return to duty	NA	9/16 completed MEB; 12 returned to combat duty, 1 retired, 1 noncombatant	0	Short follow-up duration
Görtz et al[26] (2010)	22 (28 knees)	MFC, LFC, bicondylar	5.6 (2-19.5)	24.3 (16-44)	IKDC pain, IKDC function	7.1 3.5	2.0,* 8.3*	5 (18%)	Steroid-associated osteonecrosis
LaPrade et al[42] (2009)	23	MFC, LFC, multiple	3 (1.9-4)	31 (18-47)	IKDC	52	68.5*	0	NA
Rue et al[64] (2011)	30 (31 knees)	MFC, LFC	2.9 (1.9-5)	37 (20-48)	IKDC	31.4 ± 12.8	57.1 ± 17.8*	2 (6.4%)	Combined meniscus transplant and cartilage restoration procedures
Pearsall et al[59] (2008)	48	MFC, LFC, PF	3.08 (2-5.2)	46 (16-71)	KSS	112.8	154.2*	9 (19%)	Mixed population (autograft, allograft fresh and frozen)
Davidson et al[16] (2007)	67	MFC, trochlea; MFC + trochlea	3.3 (1.6-5)	33 (21-48)	IKDC	27 (9-55)	79 (56-99)*	NA	Also included histologic study
McCulloch et al[48] (2007)	25	MFC, LFC, multiple	2.9 (2-5.6)	35 (17-49)	IKDC	29	58	2 (8%)	Meniscus transplants included
Williams et al[71] (2007)	19	MFC, LFC	2.9 (2-5.6)	34 (19-49)	ADLS	56 ± 24 (20-100)	70 ± 22 (30-98)*	4 (21%)	NA
Emmerson et al[17] (2007)	64 (66 knees)	MFC, LFC	7.7 (2-22)	29 (15-54)	Merle D'Aubigné-Postel	3.0 ± 1.7	16.4 ± 2.0*	5 (7.5%)	70% good or excellent results
Gross et al[30] (2005)	60	MFC, LFC, plateau	FC 10 (4.8-21.5), plateau 11.8 (2-24)	FC 27 (15-47), Plateau 43 (26-69)	HSS	NA	FC 83, Plateau 85.3 ± 11	FC 12 (60%), plateau 21 (65%)	Survival analysis: 95% at 5 years, 80% at 10 years, 65% at 15 years
Jamali et al[35] (2005)	18 (20 knees)	Patella, trochlea	7.8 (2-17.8)	42 (19-64)	Merle D'Aubigné-Postel	11.7 (7-15)	16.3 (12-18)*	5 (20%)	8 patients extremely satisfied; 6 satisfied

*Statistically significant.

ADLS, Activities of Daily Living Scale; *FC*, femoral condyle; *HSS*, Hospital for Special Surgery; *IKDC*, International Knee Documentations Committee; *KOOS*, Knee Injury and Osteoarthritis Outcome Score; *LFC*, lateral femoral condyle; *MEB*, Medical Education Board; *MFC*, medial femoral condyle; *NA*, not available; *PF*, patellofemoral; *TF*, tibiofemoral.

COMPLICATIONS

The unique issue regarding possible postoperative complications with fresh allografts relates to transmission of disease from the graft. Infection after the implantation of a fresh osteochondral allograft is rare, but its consequences can be devastating. Generally, all grafts are currently harvested and tested in accordance with American Association of Tissue Banks standards. However, allograft-associated bacterial infections have been reported. Death in the immediate postoperative period has even occurred as a result of implantation of a contaminated fresh osteochondral graft. As with most procedures, infection may become apparent any time from days to weeks after surgery. Deep infection needs to be distinguished from a superficial infection with the use of physical examination findings and joint aspiration. Deep infection involving the allograft should be addressed immediately with removal of the allograft because of the risk that the fresh tissue is the source of the infection or a nidus for a recurrence. Patients need to be informed of this risk preoperatively and again counseled to look for signs of infection before and after discharge from the hospital.

Failure of the allograft procedure can occur owing to nonunion or late fragmentation and graft collapse. Disease progression (arthritis) may also lead to inferior clinical outcome. Although healing of the graft-host interface reliably occurs, particularly with smaller grafts, the degree of revascularization appears to be variable. Fragmentation and collapse typically occur in areas of unvascularized allograft bone. Patients typically present with new-onset pain or mechanical symptoms. Radiographs may show joint space narrowing, cysts, or sclerotic regions. MRI can help rule out contributory concomitant joint pathology in the differential diagnosis of postoperative symptoms. In the event of mechanical allograft failure, MRI will often show areas of graft collapse. However, care must be taken in the interpretation of MRI because even normal, well-functioning grafts demonstrate signal abnormalities. Depending on the status of the knee joint, the treatment options include observation, removal of the fragmented portion of the graft, repeat allografting, or conversion to arthroplasty.

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33

Rehabilitation After Articular Cartilage Procedures

Kevin E. Wilk, Michael M. Reinold

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VIDEO CONTENT

Video 33-1 Patient 1: 1-Day Postoperative Osteochondral Autograft for OCD Medial Femoral Condyle
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Video 33-3 Patient 3: 38-Year-Old, 8-Week Postoperative Carticel Central Patellar Lesion

INTRODUCTION

Articular cartilage defects of the knee appear to be an increasing cause of pain and functional disability in orthopedics and sports medicine. This pathology creates a significant challenge to the health care team, especially the physician who must decide on the appropriate treatment plan (see Chapter 31).[23,24,70,72] The avascular nature of articular cartilage predisposes the individual to progressive symptoms and degeneration owing to the extremely slow and frequent inability to heal. Nonoperative rehabilitation and palliative care are frequently unsuccessful, especially as the size of the lesion increases, and further treatment is required to alleviate symptoms. This presents a significant challenge for patients, particularly young and more active individuals.

Traditional methods of treating these lesions have led to unfavorable results, stimulating the need for newer surgical procedures designed to facilitate the repair or transplantation of autogenous cartilage tissue. Postoperative rehabilitation programs vary greatly among physicians and should be individualized based on specifics of the lesion (size, depth, location, containment, quality of tissue), patient (age, activities, goals, quality of tissue, lower extremity alignment, body mass index [BMI], general health, and nutrition), and surgery (exact procedure, tissue involvement, and concomitant surgeries). Thus the development of an appropriate rehabilitation program is challenging and must be highly individualized to ensure successful outcomes.

The programs described in this chapter are designed according to the knowledge of basic science, anatomy, and biomechanics of articular cartilage as well as the biologic course of healing after surgery. The goal is to restore full function in each patient as quickly as possible without overloading the healing articular cartilage. In this chapter, the essential principles of rehabilitation after articular cartilage repair procedures are discussed as well as specific rehabilitation guidelines for debridement, abrasion chondroplasty, microfracture, osteochondral autograft transplantation (OAT), and autologous chondrocyte implantation (ACI).

PRINCIPLES OF ARTICULAR CARTILAGE REHABILITATION

Several principles exist that must be considered when designing a rehabilitation program after articular cartilage repair procedures (Table 33-1). These key principles have been designed based on our understanding of the basic science and mechanics of articular cartilage. These principles include individualization, creating a healing environment, understanding the biomechanics of the knee, reducing pain and effusion, restoring soft tissue balance, restoring muscle function, restoring proprioception and neuromuscular control, controlling the application of loads, and team communication. These principles

CRITICAL POINTS Principles of Articular Cartilage Rehabilitation

Individualization

- Develop the program based on specifics regarding the patient (demands of activities of daily living, work, and sport activities, body mass index), lesion (location, size), and operative procedure.
- Age, obesity, poor nutrition, history of repetitive impact loading may slow down the rehabilitation process.
- Younger patients with isolated defects and relatively healthy surrounding articular cartilage will progress more rapidly than older individuals with degenerative changes.

Create a Healing Environment

- Biologic phases of maturation have been identified.
- Controlled weight bearing and range of motion are essential to facilitate healing and prevent degeneration: stimulate matrix production, improve the tissue's mechanical properties, and nourish the articular cartilage.
- Reduce weight bearing with the use of a pool and force platforms in early phases.

Biomechanics of the Knee

- Articulation between the femoral condyle and the tibial plateau is constant throughout knee range of motion.
- Area of contact between the patella and the trochlea gradually increases as the knee is flexed.
- Rate of weight bearing, passive range of motion, and exercise progression is based on the exact location of the lesion.
- Exercises are altered based on the biomechanics of the knee to avoid excessive compressive or shearing forces.
- Open kinetic chain exercises are typically performed from 90 to 40 degrees of flexion.
- Closed kinetic chain exercises are performed initially from 0 to 30 degrees and then progressed to 0 to 60 degrees.

Reduce Pain and Effusion

- Look for a progressive decrease in volitional quadriceps activity with knee pain, distention.
- Any increase in intraarticular joint temperature stimulates proteolytic enzyme activity, detrimental to articular cartilage.
- Reduction in knee pain and swelling is crucial to minimize reflexive inhibition and restore normal quadriceps activity.

Restore Soft Tissue Balance

- Avoid arthrofibrosis by restoring full passive knee extension, patellar mobility, and soft tissue flexibility of the knee and entire lower extremity.
- Achieve at least 0 degree of extension within the first few days after surgery.

Restore Muscle Function

- Use electrical muscle stimulation and biofeedback with exercises to facilitate active contraction and volitional control of the quadriceps musculature.
- Machine weights and closed kinetic chain exercises are included as the patient progresses. Emphasize total leg strength rather than concentrating solely on the quadriceps.
- Train core, hip, and ankle.

Enhance Proprioception and Neuromuscular Control

- Proprioceptive and neuromuscular control drills of both lower extremities are included to restore dynamic stabilization of the knee.

Control the Application of Loads

- Gradually increase the amount of stress applied to the injured knee as the patient returns to functional activities.
- Monitor pain and effusion as signs of overloading.
- Consider orthotics, insoles, and bracing to alter the applied loads on the articular cartilage during functional activities.

Team Communication

- Communication among surgeon, physical therapist, and patient before and after surgery is essential.

Rehabilitation Philosophy

- All members of the health care team should convey the same rehabilitation message.
- Slower is better for healing and maturation of articular cartilage.
- Medical team is more interested in long-term results rather than outcome 6 months after surgery.

TABLE 33-1 Key Principles to Consider When Designing Rehabilitation Programs after Articular Cartilage Repair Procedures

1. Individualize the program.
2. Create a healing environment.
3. Avoid overloading healing tissue.
4. Understand the arthrokinematics of the knee.
5. Understand the biomechanics of exercises.
6. Reduce pain and effusion.
7. Restore soft tissue balance.
8. Restore muscle function.
9. Enhance proprioception and neuromuscular control.
10. Control the application of loads.
11. Promote team communication.
12. Rehabilitation philosophical approach:
    Gradual progressive loading.
    "Slower functional progression is better."
    Think long-term functional results.

are briefly described as they relate to the rehabilitation program after articular cartilage repair procedures.

Individualization

One of the most important principles involving rehabilitation after articular cartilage repair procedures is the need for an individualized approach for each patient. Several variables must be considered when developing a unique rehabilitation progression for each patient. These include specifics regarding the patient, lesion, and surgery (Table 33-2).

The quality of each individual's articular cartilage is the result of several factors including age, BMI, general health, nutrition, history of previous injuries, and genetics. The composition of articular cartilage undergoes a gradual degeneration over time that results in a breakdown of tissue matrix and a reduction in the load-bearing capacity of the cartilage.[14] The specific factors that contribute to this deterioration remain controversial, but it appears that age, obesity, BMI, poor nutrition, and a history of repetitive impact loading (through work or sport activities) may result in osteoarthritic changes.[14] Thus younger patients with isolated defects and relatively healthy surrounding articular cartilage will progress more rapidly than older individuals with more

TABLE 33-2 Specific Variables That Must be Considered When Designing Postoperative Rehabilitation Protocols After Articular Cartilage Procedures

Lesion Specifics
Location of lesion
Size of lesion
Depth of lesion
Containment of lesion
Quality of surrounding tissue
Patient Specifics
Age
Body mass index
General health
Nutrition
Quality of articular cartilage
Previous activity level
Specific goals
Motivation level
Surgical Specifics
Surgical procedure
Tissue involvement
Concomitant procedure

degenerative changes and less dense cartilage structure. Furthermore, the patient's motivation and previous activity levels must be considered when determining the rehabilitation approach to ensure that the goals of each patient are addressed. However, the nature of articular cartilage lesions will limit the rate of progression for even highly motivated and elite-level athletes. The rehabilitation program should be individualized to the specific demands of each patient's activities of daily living, work, and sport activities.

Several variables must be considered in regard to the lesion that may have a dramatic effect on the rehabilitation process. Most important are the exact location and size of the lesion. Lesions on a weight-bearing surface of a femoral condyle must avoid deleterious compressive forces and will require a different rehabilitation approach than those located within the trochlea or undersurface of the patella, where shear forces should be avoided. Furthermore, the size, depth, and containment of each lesion must be considered. Lesions that are large or deep or that have poor containment with healthy surrounding articular cartilage may require a slightly slower rehabilitation progression to ensure that the repair tissue or graft has an adequate amount of time to heal. In addition, the patient's lower extremity alignment must be carefully considered and often treated. For example, a patient's knee in a genu varum alignment with a medial compartment lesion may also require a high tibial osteotomy[3,7,17] or an osteoarthritis unloader brace.

BMI is another factor to consider. Mithoefer and coworkers[48] reported a correlation between BMI and outcomes after microfracture because the greater the BMI, the more likely the clinical outcome would be less favorable.

Lastly, the specifics of each surgical procedure will vary the rehabilitation process. Arthroscopic procedures such as chondroplasty or microfracture may progress at a different pace than those with larger incisions and greater tissue involvement, such as OAT or ACI, which require a slower rehabilitation process to protect the healing structures. Each specific surgical procedure has different biologic healing responses postoperatively, which are discussed in detail later in this chapter. Furthermore, any concomitant procedures to address alignment, stability, or meniscal function may also alter the rehabilitation program because of the need to protect other healing tissues. The importance of communication between the surgical team and the rehabilitation team cannot be overemphasized. Appropriate information regarding the specifics of each surgical procedure must be shared to ensure the highest quality of care for each individual.

Create a Healing Environment

The next principle of articular cartilage rehabilitation involves creating an environment that facilitates the healing process while avoiding potentially deleterious forces to the repair site. This involves a thorough knowledge of the physiologic repair process after surgery. Through animal studies, as well as closely monitoring the maturation of repair tissue in human patients via arthroscopic examination, the biologic phases of maturation have been identified after several articular cartilage repair procedures.[10,11,28,55,57] Knowledge of the healing and maturation process after these procedures will ensure that the repair tissue is gradually loaded and that excessive forces are not introduced too early in the healing process. These are discussed in detail in regard to each specific surgical procedure.

Two of the most important modes of rehabilitation of articular cartilage procedures are weight-bearing restrictions and range of motion (ROM) limitations. Unloading and immobilization have been shown to be deleterious to healing articular cartilage, resulting in proteoglycan loss and gradual weakening.[4,29,71] Therefore controlled weight bearing and ROM are essential to facilitate healing and prevent degeneration. This gradual progression has been shown to stimulate matrix production and improve the tissue's mechanical properties.[12,13,73]

Controlled compression and decompression forces observed during weight bearing may nourish the articular cartilage and provide the necessary signals to the repair tissue to produce a matrix that will match the environmental forces.[4,29,71] A progression of partial weight bearing with crutches is used to gradually increase the amount of load applied to the weight-bearing surfaces of the joint. The use of a pool or aquatic therapy may also be beneficial to initiate gait training and lower extremity weight-bearing exercises (see Chapter 34). The buoyancy of the water has been shown to decrease the amount of weight-bearing forces to approximately 25% of the individual's body weight when submerged to the level of the axilla and 50% of the individual's body weight when submerged to the level of the waist.[34] Commercially available devices to unload the patient's body weight during treadmill ambulation may also be useful.

A force platform is another useful tool during the early phases of rehabilitation when weight bearing is limited. This can be used to monitor the percentage of weight bearing on each extremity during closed kinetic chain (CKC) exercises such as weight shifts, minisquats, and leg press (Fig. 33-1).

The pool and force platforms may be used during early phases of rehabilitation to perform limited weight-bearing activities designed to facilitate a normal gait pattern and enhance strength, proprioception, and balance. The goal of these techniques is to initiate weight-bearing activities during the early protective phases of rehabilitation rather than remain strictly non–weight bearing and immobilized. Our opinion is that beginning controlled weight-bearing activities is a critical component to the overall successful outcome of the procedure. Although the return to functional activities will differ for each patient, early initiation of controlled exercise enables the individual to return to functional activities sooner than those who are immobilized and non–weight bearing. This may have a positive effect on patient satisfaction.



FIG 33-1 Exercises such as a weight shift **(A)** and leg press **(B)** performed on a force platform (Balance Trainer) that can measure the amount of weight distribution between each extremity **(C)**.

Passive range of motion (PROM) activities, such as continuous passive motion (CPM) machines or manual PROM, performed by a rehabilitation specialist are also begun immediately after surgery in a limited ROM to nourish the healing articular cartilage and prevent the formation of adhesions. Motion exercises may assist in creating a smooth low-frictional surface by sliding against the joint's articular surface and may be an essential component in cartilage repair.[64,65] Our opinion is that PROM is a safe and effective exercise to perform immediately postoperatively, with minimal disadvantageous shear or compressive forces, if done with patient's relaxation. This ensures that muscular contraction does not create deleterious compressive or shearing forces. Furthermore, the use of CPM has been shown to enhance cartilage healing and long-term outcomes after articular cartilage procedures.[61,62] In a study comparing the outcomes of patients after microfracture procedures, Rodrigo and associates[61] reported an 85% satisfactory outcome in patients who used a CPM machine for 6 to 8 hours per day for 8 weeks compared with a 55% satisfactory outcome in patients who did not use a CPM machine. Thus CPM or PROM using the contralateral leg should be performed for several hours during the day (some advocate 6 to 8 hours each day). PROM may also be performed on an isokinetic device (Biodex Corporation) in the passive mode or with a bike with adjustable pedals that can alter the available ROM (Unicam Corporation, Fig. 33-2). We advocate low-intensity (light-resistance) bicycling for long duration to stimulate articular cartilage regeneration.

Biomechanics of the Knee

The next rehabilitation principle involves the biomechanics of the tibiofemoral and patellofemoral joints during normal joint articulation. Articulation between the femoral condyle and the tibial plateau is constant throughout knee ROM. The anterior surface of each femoral condyle is in articulation with the middle aspect of the tibial plateau near full knee extension. With weight bearing, as the knee moves into greater degrees of knee flexion, the femoral condyles



FIG 33-2 Bicycle riding on a Unicam machine **(A)** that can adjust the pedal axis **(B)** to alter the range of motion performed.

progressively roll posteriorly and slide anteriorly, causing the articulation to shift posteriorly on the femoral condyle and tibial plateaus.[38,44]

The articulation between the inferior margin of the patella and the trochlea begins at approximately 10 to 20 degrees of knee flexion depending on the size of the patella and the length of the patella tendon.[16,37] As the knee proceeds into greater degrees of flexion, the contact area of the patellofemoral joint moves proximally along the patella. At 30 degrees, the area of patellofemoral contact (inferior facets) is 2 cm^2 approximately.[37] The area of contact gradually increases as the knee is flexed. Borotikar and associates[8] measured the in vivo contact area between the femur and patella using dynamic MRI during knee flexion-extension and reported a mean of 125 mm^2 at 10 degrees of flexion, which increased to 229 mm^2 at 40 degrees of flexion. At 60 degrees of knee flexion, the middle facets of the patella articulate with the trochlea. At 90 degrees of knee flexion, the contact area increases up to 6 cm^2, and the superior facets articulate.[37]

Using this knowledge of joint arthrokinematics, the rate of weight bearing, PROM, and exercise progression may be based on the exact location of the lesion (Fig. 33-3).[6,20,26,27] For example, a patient with a lesion on the anterior aspect of the femoral condyle may perform exercises into deeper degrees of knee flexion without causing articulation at the repair site. Conversely, lesions on the posterior condyle may require the avoidance of exercise in deep knee flexion owing to the rolling and sliding component of the articulation during deeper knee flexion. Furthermore, the rehabilitation program for lesions on a non-weight-bearing surface, such as the trochlea, may include immediate partial weight bearing with a brace locked in full knee extension without causing excessive compression on the repair site.

Rehabilitation exercises are altered based on the biomechanics of the knee to avoid excessive compressive or shearing forces. Although the exact ROM in which articulation of the lesion occurs is the most important factor to consider when designing the rehabilitation program, the amount of compressive and shear forces observed at the joint also vary throughout the ROM. Open kinetic chain (OKC) exercises, such as knee extension, are commonly performed from 90 to 40 degrees of knee flexion. This ROM provides the lowest amount of patellofemoral joint reaction forces while exhibiting the greatest amount of patellofemoral contact area,[36,37,69] thus distributing the force along a greater surface area. CKC exercises such as the leg press, vertical squats, lateral step ups, and wall squats are performed initially from 0 to 30 degrees and then progressed to 0 to 60 degrees where tibiofemoral and patellofemoral joint reaction forces are lowered.[36,37,69] Clinically, these exercises are begun using a leg press machine rather than the vertical minisquat owing to the ability to control the amount of weight applied to the lower extremities in the horizontal position in comparison with the vertical squat. As the repair site heals and symptoms subside, the ROM in which exercises are performed is progressed to allow greater muscle strengthening in a larger arc of motion. Exercises are progressed based on the patient's symptoms and the clinical assessment of swelling and crepitation.

Reduce Pain and Effusion

Numerous authors have studied the effect of pain and joint effusion on muscle inhibition. A progressive decrease in volitional quadriceps activity has been noted as the knee exhibits increased pain and distention.[68] Therefore the reduction in knee joint pain and swelling is crucial to minimize this reflexive inhibition and restore normal quadriceps activity. Furthermore, any increase in intraarticular joint temperature has been shown to stimulate proteolytic enzyme activity, which has a detrimental effect on articular cartilage.[35,53]

Treatment options for swelling reduction include cryotherapy, elevation, laser therapy, high-voltage stimulation, and joint compression through the use of a knee sleeve or compression wrap (Fig. 33-4). Patients presenting with chronic joint effusion may also benefit from a knee sleeve or compression wrap to apply constant pressure while

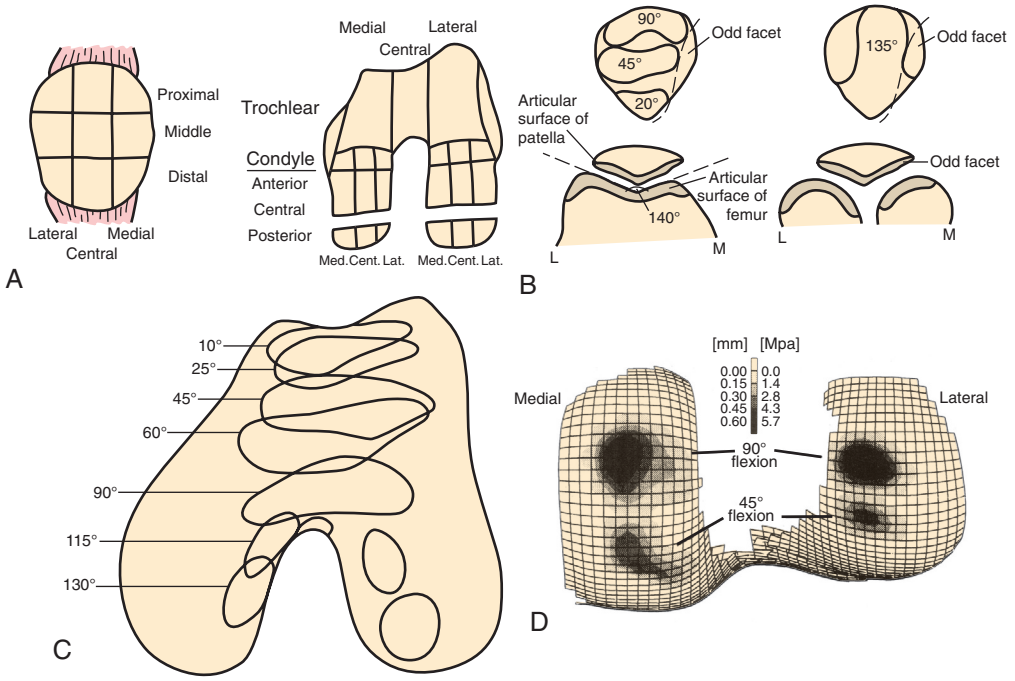


FIG 33-3 **A,** The lesion location diagram from the International Knee Documentation Committee evaluation form used to document the location of articular cartilage lesions on the patella, trochlea, and femoral condyles. This form may be used to correlate with the exact location of lesion articulation with the patella **(B),** trochlea **(C),** and femoral condyles **(D).** The diagrams represent the point of articulation of the patellofemoral and tibiofemoral joints at various degrees of knee range of motion. Surface displacements (mm) and surface stresses (MPa) at 45 and 90 degrees of knee flexion are depicted on **D.** (**A,** From the International Knee Documentation Committee. **B** and **C,** From McConnell J, Fulkerson J. The knee: patellofemoral and soft tissue injuries. In Zachazewski JE, Magee DJ, Quillen WS, editors. Athletic Injuries and Rehabilitation. Philadelphia: WB Saunders; 1996;693-729. **D,** From Blankevoort L, Kuiper JH, Huiskes R, Grootenboer HJ. Articular contact in a three-dimensional model of the knee. *J Biomech.* 1991;24:1019-1031.)

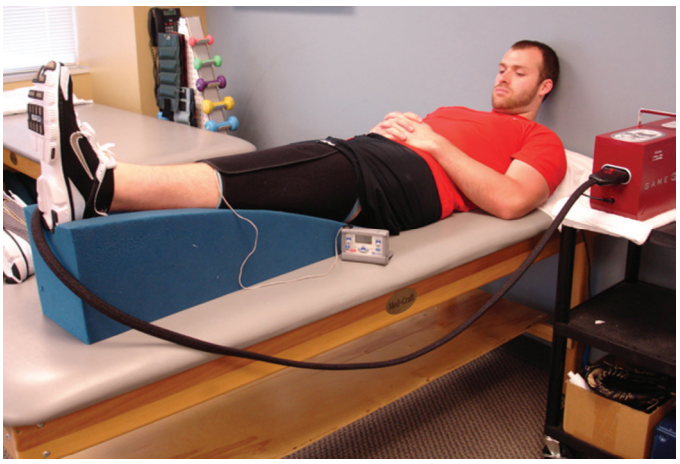


FIG 33-4 Cryotherapy and intermittent compression applied through a commercial cold device (Gameready, Coolsystems Corporation) with elevation and high-voltage electrical stimulation (300PV, Empi Corporation) for swelling control.

performing everyday activities in an attempt to minimize the development of further effusion (Fig. 33-5).

Pain can be reduced passively through the use of cryotherapy, transcutaneous electrical nerve stimulation, and analgesic medication. Immediately after injury or surgery, the use of a commercial cold wrap can be extremely beneficial. PROM may also provide neuromodulation of pain during acute or exacerbated conditions.[63]

Restore Soft Tissue Balance

One of the most important aspects of articular cartilage rehabilitation involves the avoidance of arthrofibrosis, particularly with the OAT and ACI procedures, owing to the large open incision and extensive soft tissue trauma. This is achieved through the restoration of full passive knee extension, patellar mobility, and soft tissue flexibility of the knee and entire lower extremity. The inability to fully extend the knee results in abnormal joint arthrokinematics and subsequent increases in patellofemoral and tibiofemoral joint contact pressure, increased strain on the quadriceps muscle, and muscular fatigue.[54] Therefore a drop-lock postoperative knee brace locked into 0 degree of extension is used during ambulation, and PROM out of the brace is performed immediately after surgery.

The goal is to achieve at least 0 degrees of knee extension within the first few days after surgery. Specific exercises include manual PROM exercises performed by the rehabilitation specialist, supine hamstring stretches with a wedge under the heel, and gastrocnemius stretching with a towel. Overpressure of 6 to 12 lb may be used for a low-load long-duration stretch as needed to achieve full extension (Fig. 33-6). Patients are instructed to perform low, long-duration stretches for 10 to 12 minutes several times each day (usually five to six times per day). Modalities such as moist heat and ultrasound may also be applied to facilitate greater ROM improvements before and/or during these stretching techniques.[39,60]

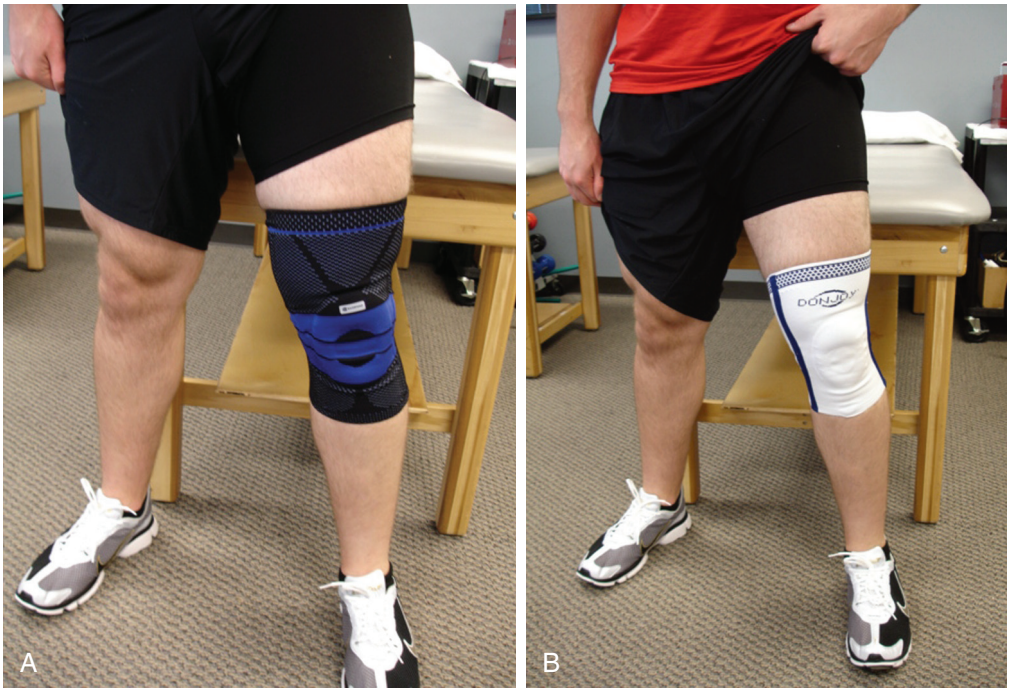


FIG 33-5 **A,** Knee compression sleeve (Bauerfeind Corp). **B,** Compression sleeve (DJ Orthopaedics).



FIG 33-6 Low-load long-duration stretching into knee extension using 8 to 10 pounds of overpressure. A wedge is applied under the heel to facilitate full extension (ERMI device, Get Motion Corporation).

The loss of patellar mobility after surgery may be caused by various reasons, including excessive scar tissue adhesions from the incision anteriorly as well as along the medial and lateral gutters. The loss of patellar mobility may result in ROM complications and difficulty in recruiting a quadriceps contraction. Patellar mobilizations in the medial-lateral and superior-inferior directions are performed by the rehabilitation specialist and independently by the patient during his or her home exercise program.

Soft tissue flexibility and pliability are also important for the entire lower extremity. Soft tissue mobilization and scar management are performed to prevent the development of adhesions around the anterior, medial, and lateral aspects of the knee. In addition, flexibility exercises are performed for the entire lower extremity, including the hamstrings, hip, and calf musculature. As ROM improves and the lesion begins to heal, quadriceps stretching may be performed as tolerated by the patient.

Restore Muscle Function

The next principle involves restoring muscle function of the lower extremity. As previously stated, inhibition of the quadriceps muscle is a common clinical enigma in the presence of pain and effusion during the acute phases of rehabilitation. Electrical muscle stimulation (EMS) and biofeedback are often incorporated with therapeutic exercises to facilitate the active contraction of the quadriceps musculature (Fig. 33-7, *A*).

EMS and biofeedback on the quadriceps musculature appear to facilitate the return of muscle activation and may be valuable additions to therapeutic exercises.[15,66] Clinically, EMS is begun immediately after surgery while the patient performs isometric and isotonic exercises such as quadriceps sets, straight leg raises, hip adduction and abduction, and knee extensions (see Fig. 33-7, *B*). EMS is used before biofeedback when the patient presents acutely with the inability to activate the quadriceps musculature. EMS is useful to attempt to recruit a maximum amount of muscle fibers during active contraction and may be used throughout the rehabilitation process. Once independent muscle activation is present, biofeedback may also be incorporated to facilitate further neuromuscular activation of the quadriceps. The patient must concentrate on neuromuscular control to independently activate the quadriceps during rehabilitation. The quadriceps and the hip/core muscles are emphasized to assist in dissipating ground reaction forces.

Exercises that strengthen the entire lower extremity, such as machine weights and CKC exercises, may be included as the patient progresses to more advanced phases of rehabilitation. It is important that total leg strength be emphasized rather than concentrating solely on the



FIG 33-7 Neuromuscular electrical stimulation (300PV, Empi Corporation) applied to the quadriceps muscle **(A)** during exercises such as knee extension **(B).**

quadriceps. Furthermore, the importance of incorporating core stability exercises cannot be overlooked. Training of the core, hip, and ankle located proximally and distally along the kinetic chain is emphasized to assist in controlling the production and dissipation of forces in the knee. In addition, the hip and ankle assist in controlling abduction and adduction moments at the knee joint. Often issues with alignment and muscle imbalances in the lumbopelvic region will place disadvantageous stress on the knee.

Enhance Proprioception and Neuromuscular Control

Proprioceptive and neuromuscular control drills of the lower extremities should be included to restore dynamic stabilization of the knee joint postoperatively. Proprioceptive deficits have been noted in the injured and postoperative knee.[18,59] Specific drills initially include weight shifting side to side, weight shifting diagonally, minisquats, and minisquats on an unstable surface such as a tilt board (Fig. 33-8). The use of kinesiotaping and other taping may enhance proprioception in patients during rehabilitation, especially if they exhibit poor proprioception. Additionally, perturbations can be added to challenge the neuromuscular system as well as additional exercises including lunges, step-ups, and balance onto unstable surfaces (Figs. 33-9 and 33-10).

Control the Application of Loads

The next principle of rehabilitation involves gradually increasing the amount of stress applied to the injured knee as the patient returns to functional activities. The rehabilitation process involves a progressive application of therapeutic exercises designed to gradually increase function in the postoperative knee. This progression is used to provide a healthy stimulus for healing tissues while ensuring that forces are gradually applied without causing damage. Common clinical signs that a patient may be progressing too quickly and overloading the healing tissue are joint line pain and effusion. This should be monitored throughout the rehabilitation process.

In addition, patients may benefit from the use of orthotics, insoles, and unloading braces to alter the applied loads on the articular cartilage during functional activities. These devices are used to avoid excessive forces by unloading the area of the knee where the lesion is located. Unloading braces are often used for patients with subtle uncorrected abnormal alignments (genu varum) or large or uncontained lesions or who had concomitant osteotomies and meniscal allografts (Fig. 33-11).

Team Communication

The next principle, and maybe the most important principle of rehabilitation involves communication among the surgeon, the physical therapist, and the patient. Communication between the surgeon and the rehabilitation team is essential to determine the accurate rate of progression based on the location and size of the lesion, tissue quality, and concomitant surgical procedures. In addition, communication between the medical team and the patient is essential to provide the patient with education regarding the avoidance of deleterious forces as well as improving compliance with precautions. Frequently, a preoperative physical therapy evaluation may be useful to mentally and physically prepare the patient for the articular cartilage procedure and postoperative rehabilitation.

Rehabilitation Philosophy

It is important that all members of the health care team (e.g., physician, physical therapist, athletic trainer, nurses) convey the same rehabilitation message. We advocate gradual progressive loading of healing articular cartilage. The purpose of this concept is to recondition the articular cartilage. Another message is "slower is better." It takes a long period of time for articular cartilage to heal, mature, and return to weight-bearing activities. One last philosophical point is "faster is not better, even if you feel pain free." Patients are instructed that the medical team is more interested in long-term results than outcome 6 months after surgery.



FIG 33-8 Minisquats on an unstable surface such as a tiltboard. The patient is instructed to squat while preventing movement of the board.



FIG 33-9 Single-leg balance on an unstable surface such as foam. The patient may use a weighted ball while performing reciprocal movement patterns with the uninvolved upper and lower extremities to alter the center of gravity throughout the exercise.

REHABILITATION AFTER ARTICULAR CARTILAGE REPAIR PROCEDURES

The rehabilitation progression is designed based on the four biologic phases of cartilage maturation: proliferation, transitional, remodeling, and maturation.[10,11,19,28,32,51,55,57] The length of each phase will vary depending on the lesion, patient's age and general health, and surgical specifics discussed previously; however, the concepts of each phase are consistent. The following sections overview the generalized rehabilitation process during each of the four phases.

Phase I: Early Protection Phase

The first phase of cartilage healing is the *proliferation phase*, which typically involves the first 4 to 6 postoperative weeks. During this phase, the initial healing process begins. It is imperative to decrease swelling, gradually restore PROM, and enhance volitional control of the quadriceps during this period of rehabilitation.

Controlled active ROM and PROM and a gradual weight-bearing progression are critical components to the rehabilitation process. As previously discussed, PROM and controlled partial weight bearing will help promote the nurturing of the cartilage through diffusion of synovial fluid as well as provide the proper stimulus for the cells to produce specific matrix markers. Individuals begin with partial weight-bearing activities using crutches. Progressive loading exercises using the pool and force platforms are gradually implemented to increase the amount of load applied to the weight-bearing surfaces of the joint. The use of a pool or aquatic therapy may be beneficial to begin gait training and lower extremity exercises once the incisions are well healed.

PROM activities, such as manual PROM performed by a rehabilitation specialist and CPM machines, are also begun immediately after surgery to nourish the healing articular cartilage and prevent the formation of adhesions. The use of a CPM typically begins 6 to 8 hours after surgery and is performed for at least 2 to 3 weeks, with recommended use up to 6 to 8 weeks. It is recommended that the CPM be used throughout the day for up to 6 to 8 hours. The patient is instructed to also perform active-assisted ROM frequently throughout the day. Patella mobilization, soft tissue mobilization, and soft tissue flexibility exercises are also performed to minimize scar tissue formation and avoid loss of motion. Low-intensity stationary cycling may be implemented in this phase.



FIG 33-10 Lateral step-up exercises performed while standing on an unstable surface such as a piece of foam. This exercise requires eccentric control of the lower extremity to perform the step-up exercise as well as to balance throughout the movement.



FIG 33-11 An osteoarthritis unloading brace (OA Defiance, Don Joy Corporation) using a four-point leverage system to unload the medial compartment of the knee by providing a mild valgus stress to the knee.

Early strengthening exercises are performed to restore volitional quadriceps control and neuromuscular control through the use of concomitant EMS. Exercises performed during this phase are limited based on the specific weight-bearing status of each patient and typically include quadriceps sets, straight-leg raises, and early baseline proprioception exercises such as weight shifting.

Exercises for areas elsewhere in the kinetic chain can be implemented in this phase as tolerated. These include strengthening exercises of the hip and baseline core stabilization exercises. During this phase it is essential to strengthen the hip abductors, external rotators, and extensors to control a valgus collapse to the knee joint. Manual therapy to restore hip and ankle mobility as well as lumbopelvic alignment are also important in this phase and are unique to each individual. Creating this foundation will allow a more progressive rehabilitation approach once the postoperative restrictions are removed later in the process.

Phase II: Transition Phase

The second phase is the *transitional phase*, which typically includes postoperative weeks 4 through 12. The repair tissue at this point is gaining strength, which will allow for the progression of rehabilitation exercises. During this phase, the patient progresses from partial to full weight bearing, while full ROM and soft tissue flexibility are achieved. Continued maturation of the repair tissue is fostered through higher-level functional and ROM exercises. It is during this phase that patients typically resume most normal activities of daily living. The rehabilitation program will gradually progress strengthening activities to include machine weights and CKC exercises, such as leg press, front lunges, wall slides, and lateral step ups, as the patient's weight-bearing status returns to normal.

At this time, the rehabilitation process involves the progressive application of therapeutic exercises designed to gradually increase function in the postoperative knee. The progression of weight-bearing activities and restoration of ROM, as previously discussed, involves the gradual advancement of activities to ensure that complications do not arise while facilitating healing. A principle of gradual progressive loading is implemented during this phase. Once weight bearing is initiated, the clinician may consider an osteoarthritis unloader brace. Common complications include motion restrictions and scar tissue formation. Furthermore, an overaggressive approach early within the

rehabilitation program may result in increased pain, inflammation, or effusion as well as graft damage. This simple concept may be applied to the progression of strengthening exercises, proprioception training, neuromuscular control drills, and functional drills. For example, exercises such as weight shifts and lunges are progressed from straight-plane anterior-posterior or medial-lateral directions to involve multi-plane and rotational movements. Exercises using two legs, such as leg press and balance activities, are progressed to single-leg exercises. Thus the progression through the postoperative rehabilitation program involves a gradual progression of applied and functional stresses. This progression is used to provide a healthy stimulus for healing tissues while ensuring that forces are gradually applied without causing damage.

Phase III: Remodeling Phase

The third phase, known as the *remodeling phase*, generally occurs from 3 to 6 months postoperatively. During this phase, there is a continuous remodeling of tissue into a more organized structure. The tissue continues to increase in strength and durability. As the tissue becomes more firm and integrated, more functional training activities may be performed. At this point, the patient typically notes improvement of symptoms and has normal ROM. The patient is encouraged to continue with her or his rehabilitation program independently to maximize strength and flexibility. Low- to moderate-impact activities such as bicycle riding, golfing, and recreational walking may often be gradually incorporated. The senior author's (K.E.W.) experience has shown that during this phase when overzealous patients are "feeling good," they may overexert their program, which may compromise the repair site.

Phase IV: Maturation Phase

The final phase is known as the *maturation phase*, which typically begins in a range of 4 to 6 months and can last up to 15 to 18 months. This depends on the type of surgery, size, and location of the lesion. During this phase, the repair tissue reaches its full maturation. The duration of this phase varies based on several factors such as lesion size and location and the specific surgical procedure performed. The patient will gradually return to full premorbid activities as tolerated. Impact-loading activities are gradually introduced. Although such procedures as OAT and ACI are designed to restore function rather than to facilitate return to high-impact athletic activities, a return to athletic activities is determined based on the unique presentation of each patient. A return to competitive athletics has been documented after microfracture,[50] OAT,[31] and ACI[47,58] procedures.

SPECIFIC POSTOPERATIVE GUIDELINES

Debridement and Chondroplasty

Rehabilitation after an arthroscopic debridement or chondroplasty is fairly simple owing to the nature and goal of the procedure to facilitate tissue healing rather than create repair tissue. Initial weight bearing is limited for the first 3 to 5 days using axillary crutches, although weight bearing is permitted as tolerated. PROM exercises are progressed as tolerated immediately with no postoperative limitations in motion. Full passive motion is typically achieved within 2 to 3 weeks. OKC exercises are performed initially, although CKC strengthening exercises and bicycle riding are normally incorporated by the end of the first week. The patient is allowed to return to full functional activities and progress to moderate-impact activities, such as light jogging and sports, beginning at week 4. The progression of impact loading may be delayed if significant degenerative changes are present within the knee or if symptoms of pain or effusion persist. The rate of progression is highly variable and should be based on the extent of the procedure and unique situation of each patient.

Microfracture

The operative procedure referred to as a microfracture to the knee joint is the most common procedure performed to the knee to treat focal articular cartilage lesions. Rehabilitation after a microfracture procedure progresses more cautiously than that of a debridement or chondroplasty (Table 33-3). The program is based on size, location, number of areas treated, and concomitant procedures. The early protection phase begins immediately after surgery and lasts until the fourth week postoperatively. During this time, defects begin to fill with a fibrin clot, although no fibrocartilage is present.[19] A period of non–weight bearing is applied for the first 2 to 6 weeks postoperatively for most lesions. Marder and colleagues[43] compared the results of patients with small focal lesions of less than 2.0 cm^2 using two postoperative rehabilitation programs. Group I used touch-down weight bearing and a CPM machine for 6 to 8 hours a day for 6 weeks. Group II was allowed weight bearing as tolerated immediately after surgery and used active-assisted heel-slides for ROM (without the use of a CPM). These authors reported significant improvements in both groups and no significant differences in the subjective or objective outcomes between groups a minimum of 2 years postoperatively. Thus it appears that it may be possible to begin early controlled weight bearing for small, focal lesions without applying deleterious forces to the repair site. The emphasis here is that early weight bearing should be initiated in patients with small focal lesions. If the rehabilitation specialist is unsure of the surgical details, a more conservative approach must by implemented.

Initial controlled touch-down weight bearing is begun for lesions that are localized and smaller than 2.0 cm^2 in patients with good tissue quality. For patients with patellofemoral lesions, immediate weight bearing is performed owing to the lack of lesion articulation during weight bearing; however, a drop-locked knee brace is worn to avoid deleterious sheer forces to the healing repair site.

Owing to the arthroscopic nature of the procedure, PROM is performed immediately without restrictions. Full PROM of at least 0 to 125 degrees is achieved between weeks 3 and 4, often with little difficulty.

The transition phase begins at week 4 and progresses to week 8. During this phase, the patient may progress to full weight bearing and more functional CKC exercises by the end. At 6 weeks postoperatively, a thin layer of tissue covers the base of the lesion.[21] Although the repair is still incomplete, fibrocartilaginous tissue is present, and by 8 weeks, some tissue with hyalinelike characteristics has been detected.[19] By 12 weeks, the defect is completely filled and the quality of cartilaginous tissue improves significantly.[21] Thus gentle CKC exercises may begin by week 8 but should not be advanced significantly until week 12.

Weight bearing is thus progressed to full at week 8 for most lesions when the strength of the repair tissue is increasing. However, the progression to more advanced exercises, including impact loading, is delayed until the end of the remodeling phase when the defect is completely filled. The patient may gradually begin to return to former activities during the maturation phase between months 4 to 6; however, larger lesions may need to delay the progression to high-impact activities for up to 8 months.

Clinical outcome studies indicate that a significant number of patients will be able to return to sports after a microfracture procedure.[22,40,50] Mithoefer and coworkers[50] reported on 32 patients who routinely participated in high-impact and pivoting sports. At a minimum 2-year follow-up, 66% had good to excellent results, and 44% had returned to high-impact sports. However, after initial improvement, scores decreased in 47% of athletes. Return to sports

TABLE 33-3 Rehabilitation After Microfracture Procedure

Phase I: Early Protection Phase (Weeks 0-4)

Goals
- Protect healing tissue from load and shear forces
- Decrease pain and effusion
- Restore full passive knee extension
- Gradually restore knee flexion
- Regain quadriceps control

Brace
- No brace; may use elastic wrap to control swelling

Weight Bearing
- Weight-bearing status varies based on lesion location, size.
- For medium to large femoral condyle lesions (>2.0 cm^2): non–weight bearing for 2 weeks, begin toe-touch weight bearing (~20-30 lb) at week 3; progress to partial weight bearing (~25% body weight) at week 4.
- For small femoral condyle lesions (<2.0 cm^2): immediate toe-touch weight bearing (per physician) (~20-30 lb) at weeks 0-2; progress to 50% weight bearing at week 3; 75% weight bearing at week 4.
- For patellofemoral lesions: immediate toe-touch weight bearing of ~25% body weight with brace locked in full extension; progress to 50% weight bearing at week 2, 75% weight bearing at week 3 with brace locked in full extension, full weight bearing at week 4.

Range of Motion
- Immediate motion exercise on day 1
- Full passive knee extension immediately
- Initiate continuous passive motion day 1 for total of 8-12 hr/day (0-60 degrees; if patellofemoral lesion >6.0 cm^2, 0-40 degrees)
- Progress continuous passive motion range of motion as tolerated 5-10 degrees/day
- May continue continuous passive motion for total of 6-8 hr/day for up to 6 wk
- Patellar mobilization (4-6 times/day)
- Motion exercises throughout the day
- Passive knee flexion range of motion at least 2-3 times/day
- Progress passive knee range of motion as tolerated, no restrictions
- Minimum range of motion goals: 0-90 degrees at week 1; 0-105 degrees at week 2; 0-115 degrees at week 3; and 0-125 at degrees week 4
- Stretch hamstrings and calf

Strengthening Program
- Ankle pumps with rubber tubing
- Quadriceps setting
- Multiangle isometrics (cocontractions quadriceps/hamstring)
- Active knee extension 90-40 degrees for femoral condyle lesions (no resistance), avoid for patellofemoral patients
- Straight-leg raises (four directions)
- Stationary bicycle when range of motion allows; low resistance
- EMS and/or biofeedback during quadriceps exercises
- Initiate weight shifting exercises with knee in extension at weeks 1-2 for patellofemoral lesions and small femoral condyle lesions and at week 3 for larger femoral condyle lesions
- Leg press 0-60 degrees at week 3 for small femoral condyle lesions and patellofemoral lesions; progress to 0-90 degrees at week 4
- Toe-calf raises at week 4 for small femoral condyle and patellofemoral lesions
- Use of pool for gait training and exercises at weeks 3-4 (when incision is fully healed)
- Stationary bike at weeks 3-4, low resistance
- *No* active knee extension exercises for patellofemoral lesions

Functional Activities
- Gradual return to daily activities
- If symptoms occur, reduce activities to reduce pain and inflammation

Swelling Control
- Ice, elevation, compression, and effusion modalities as needed

Criteria to Progress to Phase II
- Full passive knee extension
- Knee flexion to 125 degrees
- Minimal pain and swelling
- Voluntary quadriceps activity

Phase II: Transition Phase (Weeks 4-8)

Goals
- Gradually improve quadriceps strength and endurance.
- Gradual increase in functional activities.

Weight Bearing
- Progress as tolerated
- Large femoral condyle lesions: 50% weight bearing with crutches at week 6; 75% weight bearing at week 7, full weight bearing at week 8, discontinue crutches

Range of Motion
- Gradual increase in range of motion
- Maintain full passive knee extension
- Progress knee flexion to 135 degrees or more by week 8
- Continue patellar mobilization and soft tissue mobilization, as needed
- Continue stretching program

Strengthening Exercises
- Progress to closed kinetic chain exercises
- Initiate leg press for large femoral condyle lesions at week 6
- Minisquats 0-45 degrees at week 7
- Toe-calf-raises at week 8 for femoral condyle lesions
- Progress to balance and proprioception drills
- Initiate front lunges, wall squats, front and lateral step-ups at week 5 for small femoral condyle and patellofemoral lesions and at week 8 for large femoral condyle lesions
- For femoral condyle lesions, progress to open kinetic chain knee extension, 1 lb/wk
- For patellofemoral lesion, may begin open kinetic chain knee extension without resistance in a range of motion that does not allow for articulation of the lesion
- Continue stationary bicycle, low resistance (gradually increase time)
- Continue use of EMS and/or biofeedback as needed
- Continue use of pool for gait training and exercise

Functional Activities
- As pain and swelling (symptoms) diminish, gradually increase functional activities
- Gradually increase standing and walking

Criteria to Progress to Phase III
- Full range of motion
- Acceptable strength levels:
  - Hamstrings within 20% of contralateral leg
  - Quadriceps within 30% of contralateral leg
- Balance testing within 30% of contralateral leg
- Able to bike for 30 min

Continued

TABLE 33-3 Rehabilitation After Microfracture Procedure—cont'd

Phase III: Remodeling Phase (Weeks 8-16)

Goals

- Improve muscular strength and endurance
- Increase functional activities

Range of Motion

- Patient should exhibit 125-135 degrees + flexion

Exercise Program

- Leg press (0-90 degrees)
- Bilateral squats (0-60 degrees)
- Unilateral step-ups progressing from 2 to 8 inches
- Forward lunges
- Walking program at week 10
- Progress to open kinetic chain extension (0-90 degrees); for patellofemoral lesions, may begin at week 12, perform from 90-40 degrees or avoid angle where lesion articulates; progress 1 lb every 2 weeks beginning at week 20 if no pain or crepitus; must monitor symptoms
- Continue progressing balance and proprioception
- Bicycle
- Stair-climbing machine
- Swimming
- Ski or elliptical machine

Functional Activities

- As patient improves, increase walking (e.g., distance, cadence, incline)

Maintenance Program

- Initiate at weeks 12-16
- Bicycle: low resistance, increase time
- Progressive walking program
- Pool exercises for entire lower extremity
- Straight-leg raises
- Leg press
- Wall squats
- Hip abduction/adduction
- Front lunges
- Step-ups
- Stretch quadriceps, hamstrings, calf

Criteria to Progress to Phase IV

- Full nonpainful range of motion
- Strength within 80%-90% of contralateral extremity
- Balance and/or stability within 75%-80% of contralateral extremity
- No pain, inflammation, or swelling

Phase IV: Maturation Phase (Weeks 16-26)

Goals

- Gradual return to full unrestricted functional activities

Exercises

- Continue maintenance program progression 3-4 times/wk
- Progress resistance as tolerated
- Emphasis on entire lower extremity strength and flexibility
- Progress agility and balance drills
- Impact-loading program specialized to patient demands
- Progress sport programs depending on patient variables

Functional Activities

- Patient may return to various sport activities as progression in rehabilitation and cartilage healing allow. In general, low-impact sports such as swimming, skating, rollerblading, and cycling are permitted at about 2 months for small femoral condyle and patellofemoral lesions and at 3 months for large femoral condyle lesions. Higher-impact sports such as jogging, running, and aerobics may be performed at 4 months for small lesions or 5 months for larger lesions. High-impact sports such as tennis, basketball, football, and baseball are allowed at 6-8 months.

was significantly higher in athletes younger than 40 years of age, patients with a lesion size less than 200 mm^2, those with preoperative symptoms less than 12 months' duration, and patients who had no prior surgical intervention. In a separate report, Mithoefer and associates[49] described the results of microfracture for isolated femoral chondral lesions. They reported that 67% of patients had a good to excellent result; 25%, a fair result; and 8%, a poor result. The investigators were able to obtain follow-up magnetic resonance imaging (MRI) on 50% of the patients. MRI revealed good tissue healing and filling in 54%, moderate tissue filling in 29%, and poor healing result in 17%. Successful outcomes correlated to a low BMI, good healing or lesion filling, and short duration of symptoms. The worst results were seen in patients with a BMI of 30 kg/m. Kreuz and colleagues[42] compared the results of microfracture in patients older than 40 years of age with those younger than 40 years of age. These authors reported superior outcomes in patients 40 years or younger. Between 18 and 36 months postoperatively, the investigators found a deterioration in International Cartilage Repair Society (ICRS) scores, which was significantly pronounced in older patients. Furthermore, MRI performed at 36 months after surgery indicated better fill in patients younger than 40 years.

Osteochondral Autograft Transplantation Procedure

Rehabilitation after OAT procedures requires the avoidance of early deleterious forces to avoid disrupting the healing transplanted bone plugs (Table 33-4). Currently, the pace of the rehabilitation program after OAT procedures is based not only on the size of the lesion but also on the amount of transplanted bone plugs and location. The program is progressed more cautiously when numerous bone plugs are used owing to the potential for a less congruent surface. The early protection phase lasts until the eighth week postoperatively. During this phase, an initial 44% reduction in the push-in and pull-out strength of the transplanted bone plugs has been observed (at 1 week postoperatively),[74] emphasizing the need for strict non–weight bearing postoperatively. Partial weight bearing is usually initiated 2 to 4 weeks after surgery based on the size of the lesion and the number of transplanted bone plugs. Although the original hyaline cartilage remains intact and viable,[51] the strength of the bone plugs is the limiting factor when designing the postoperative rehabilitation program.

By 4 weeks, the cancellous bone plugs have united,[32] and by 6 weeks, there is full subchondral integration and 29% of grafts show bonding between the articular cartilage of the bone plugs and the surrounding articular cartilage.[51] Although integration has occurred, a 63% decrease in graft stiffness is still observed at 6 weeks postoperative.[51] During this time, weight bearing is gradually progressed as the strength of the repair increases. At 8 weeks postoperative, fibrocartilage has been observed to grow to the surface and seal the recipient and donor site hyaline cartilage, and weight bearing is progressed to full. Immediate

TABLE 33-4 Rehabilitation After Osteochondral Autograft Transplantation

Phase I: Early Protection Phase (Weeks 0-6)

Goals
- Protect healing tissue from load and shear forces
- Decrease pain and effusion
- Restore full passive knee extension
- Gradual improvement of knee flexion
- Regain quadriceps control

Brace
- Locked at 0 degrees during weight-bearing activities
- Sleep in locked brace for 2-4 weeks

Weight Bearing
- Weight-bearing status varies based on lesion location and size
- For femoral condyle lesions: non–weight bearing for 2-4 weeks (physician direction); if large lesion (>5 cm^2) may need to delay weight bearing up to 4 weeks, progress to toe-touch weight bearing (~20-30 lb) at weeks 3-4 and partial weight bearing (~25%-50% body weight) at week 6
- For patellofemoral lesions: immediate toe-touch weight bearing 25% body weight with brace locked in full extension; progress to 50% weight bearing at week 2-3 in brace and 75% at week 4-5 in brace

Range of Motion
- Immediate motion exercise on day 1
- Immediate full passive knee extension
- Initiate continuous passive motion on day 1 for total of 8-12 hr/day (0-60 degrees; if patellofemoral lesion >6.0 cm^2, 0-40 degrees)
- Progress continuous passive motion range of motion as tolerated 5-10 degrees/day
- May continue continuous passive motion for total of 6-8 hr/day for up to 6 weeks
- Patellar mobilization (4-6 times/day)
- Motion exercises throughout the day
- Passive knee flexion range of motion at least 2-3 times/day
- Passive knee range of motion as tolerated
- For femoral condyle lesions, minimum knee flexion range of motion goal is 90 degrees by 1-2 weeks, 105 degrees at week 3, 115 degrees at week 4, and 120-125 degrees by week 6
- For patellofemoral lesions, minimum knee flexion range of motion goal is 90 degrees by weeks 2-3, 105 degrees by 3-4 weeks, and 120 degrees by week 6
- Stretch hamstrings and calf

Strengthening Program
- Ankle pump using rubber tubing
- Quadriceps setting
- Multiangle isometrics (cocontractions quadriceps/hamstring)
- Straight-leg raises (four directions)
- Active knee extension 90-40 degrees for femoral condyle lesions if no articulation at week 4 (no resistance)
- EMS and/or biofeedback during quadriceps exercises
- Stationary bicycle when range of motion allows; low resistance
- Isometric leg press at week 4 (multiangle)
- Use of pool for gait training and exercises at week 6
- Initiate weight-shifting exercises with knee in extension at week 3-4 for patellofemoral lesions
- *No* active knee extension exercises for patellofemoral lesions
- *No* closed kinetic chain exercises for femoral condyle lesions

Functional Activities
- Gradual return to daily activities
- If symptoms occur, reduce activities to reduce pain and inflammation
- Avoid extended standing

Swelling Control
- Ice, elevation, compression, and edema modalities as needed to decrease swelling

Criteria to Progress to Phase II
- Full passive knee extension
- Knee flexion to 120 degrees
- Minimal pain and swelling

Phase II: Transition Phase (Weeks 6-12)

Goals
- Gradually increase range of motion and weight bearing to full
- Gradually improve quadriceps strength/endurance
- Gradually increase functional activities

Brace
- Discontinue brace at 6 weeks, consider unloading brace for femoral condyle lesions

Weight Bearing
- Progress weight bearing as tolerated
- For femoral condyle lesions: 75% body weight with crutches at 6-7 weeks, progress to full weight bearing at 8-10 weeks; may need to delay full weight bearing up to 14 weeks if large lesion; discontinue crutches at 8-10 weeks
- For patellofemoral lesions, progress to full weight bearing and discharge crutches at 6-8 weeks

Range of Motion
- Gradually increase range of motion
- Maintain full passive knee extension
- Progress knee flexion to 125-135 degrees by week 8-10
- Continue patellar mobilization and soft tissue mobilization, as needed
- Continue stretching program

Strengthening Exercises
- Initiate weight shifts at week 6-8 for femoral condyle lesions
- Initiate minisquats 0-45 degrees at week 6-8 for patellofemoral lesions
- Closed kinetic chain exercises (leg press) at weeks 8-10 for femoral condyle lesions: minisquats 0-45 degrees, front lunges, step-ups, wall squats; may need to delay closed kinetic chain up to 14 weeks if large lesion
- Leg press at week 8-10 (0-90 degrees for femoral condyle, 0-60 degrees for patellofemoral, progressing to 0-90 degrees as tolerated)
- Toe-calf raises at week 10-12
- Progress to active knee extension: begin resistance with femoral condyle lesions progressing 1 lb every 10-14 days; for patellofemoral lesions, begin with 0-30 degrees at week 12 and progress to deeper angles as tolerated
- Stationary bicycle (gradually increase time)
- Balance and proprioception drills
- EMS and biofeedback as needed
- Use of pool for gait training and exercise

Continued

TABLE 33-4 Rehabilitation After Osteochondral Autograft Transplantation—cont'd

Functional Activities
- As pain and swelling (symptoms) diminish, the patient may gradually increase functional activities
- Gradually increase standing and walking

Criteria to Progress to Phase III
- Full range of motion
- Acceptable strength levels:
  - Hamstrings within 20% of contralateral leg
  - Quadriceps within 30% of contralateral leg
- Balance testing within 30% of contralateral leg
- Able to bike for 30 minutes

Phase III: Remodeling Phase (Weeks 12-26)

Goals
- Improve muscular strength and endurance
- Increase functional activities

Range of Motion
- Patient should exhibit 125-135 degrees of flexion; no restrictions

Exercise Program
- Continue progressing exercises
- Leg press 0-90 degrees
- Bilateral squats (0-60 degrees)
- Unilateral step-ups progressing from 2 to 8 inches
- Forward lunges
- Begin walking program on treadmill
- Open kinetic chain knee extension (0-90 degrees) as tolerated, do not progress to heavy resistance with patellofemoral lesions; must monitor symptoms of pain and crepitus
- Bicycle
- Stair-climbing machine
- Swimming
- Ski or elliptical machine

Functional Activities
- As patient improves, increase walking (e.g., distance, cadence, incline)

Maintenance Program
- Initiate at weeks 16-20
- Bicycle, low resistance
- Progressive walking program
- Pool exercises for entire lower extremity
- Straight-leg raises into flexion
- Leg press
- Wall squats
- Hip abduction/adduction
- Front lunges
- Stretch quadriceps, hamstrings, gastrocnemius

Criteria to Progress to Phase IV
- Full nonpainful range of motion
- Strength within 80%-90% of contralateral extremity
- Balance and/or stability within 75%-80% of contralateral extremity
- No pain, inflammation, or swelling

Phase IV: Maturation Phase (Weeks 26-52)

Goals
- Gradual return to full unrestricted functional activities

Exercises
- Continue maintenance program progression 3-4 times/wk
- Progress resistance as tolerated
- Emphasis on entire lower extremity strength and flexibility
- Progress agility and balance drills
- Impact-loading program specialized to patient demands
- Progress sport programs depending on patient variables

Functional Activities
- Patient may return to various sport activities as progression in rehabilitation and cartilage healing allows. In general, low-impact sports such as skating, rollerblading, and cycling are permitted at about 6-8 months. Higher-impact sports such as jogging, running, and aerobics may be performed at 8-10 months. High-impact sports such as tennis, basketball, and baseball are allowed at 12-18 months.

weight bearing is initiated for patellofemoral lesions with a drop-lock knee brace and progressed to full without the brace at approximately 6 to 8 weeks postoperative.

ROM during the early protective phase is gradually progressed to ensure that adhesion formation and loss of motion is avoided. Owing to the large incision and invasive nature of the procedure, motion is progressed gradually to minimize effusion formation.

Exercises are progressed from non-weight-bearing, such as quadriceps sets and multiangle straight leg raises, to gentle weight bearing in a restricted weight tolerance after week 6.

During the transition phase, full ROM and weight bearing are achieved typically between weeks 8 to 10, although larger lesions may need to further delay the progress to full weight bearing for up to 12 to 14 weeks. At this point, the strengthening program is progressed to include weight-bearing CKC and machine exercises. Again, during this phase, patients return to low-impact functional activities.

During the remodeling and maturation phases, strength, proprioception, and neuromuscular control are enhanced while impact-loading stresses are gradually applied as tolerated without an increase in symptoms. Patients may return to various sport activities as progression in rehabilitation and cartilage healing allows, although this is more delayed than the previously discussed rehabilitation progressions. Generally, low-impact sports such as golf, swimming, cycling, and walking for exercise are permitted at 4 to 5 months postoperatively. Moderate-impact sports such as tennis and hiking are permitted at 6 to 8 months (depending on size and location of the lesion). The return to high-impact sports is controversial, although some clinicians allow sports such as jogging, running, and aerobics at 8 to 10 months and tennis, basketball, and baseball at 12 to 18 months. There are too few studies to indicate the long-term success in allowing the return to strenuous activities, which may risk deterioration of the reparative cartilage.

Clinical outcome results after OAT indicate good results.[1,30,52] Hangody and Fules[31] followed 831 patients and reported a good to excellent result in 92% of those who exhibited a lesion of the femoral condyle, and the same in 87% with a tibial plateau lesion. Lesions of the patella rendered the lowest outcomes, with only 79% exhibiting a good to excellent result. Furthermore, these authors reported a 3% rate of donor site morbidity. Lastly, 36 patients exhibited a painful postoperative hemarthroses. Bartha and coworkers[2] reported on 89 patients

who underwent second-look arthroscopy, 77% of whom exhibited congruent surfaces and healing of the lesion.

Autologous Chondrocyte Implantation Procedure

The rehabilitation program after ACI, and the newer matrix-induced ACI procedures,[9,41] is vital to the success and long-term outcomes of patients (Table 33-5). Early controlled ROM and weight bearing are necessary to stimulate chondrocyte development, although caution is placed on overaggressive activities that may result in cell damage or graft delamination.

Knowledge of the biologic healing response is vital for the development of appropriate rehabilitation guidelines. Rehabilitation may begin as early as the recovery room in the form of CPM. At this time, the chondrocytes are aligned and attached to the underlying surface.[67] It is imperative that the patient be appropriately positioned to allow for the effect of gravity to evenly distribute the chondrocytes on the base of the defect during these first 4 hours as the cells adhere to the surface. A study by Sohn and associates[67] showed that the defect orientation during these first 4 hours can be an important factor in the uniformity of cell distribution in the ACI procedure. These authors advanced the hypothesis, which has not yet been proved clinically, that the effects of gravity within the first few hours of cell implantation could lead to localization of induced cells in one area of the graft but not in other areas, which may affect healing of the defects. This suggests two possibilities. First, the position of the patient with a patellar defect in the prone position would contraindicate CPM because it

TABLE 33-5 Rehabilitation After Autologous Chondrocyte Implantation

Phase I: Early Protection Phase (Weeks 0-6)

Goals

- Protect healing tissue from load and shear forces
- Decrease pain and effusion
- Restore full passive knee extension
- Gradually improve knee flexion
- Regain quadriceps control

Brace

- Locked at 0 degrees during weight-bearing activities
- Sleep in locked brace for 2-4 weeks

Weight Bearing

- Weight-bearing status varies based on lesion location and size
- For femoral condyle lesions: non–weight bearing for 1-2 weeks, may begin toe-touch weight bearing immediately per physician if lesion <2.0 cm^2; begin toe-touch weight bearing (~20-30 lb) at weeks 2-3; progress to partial weight bearing (~25% body weight) at weeks 4-5
- For patellofemoral lesions: immediate toe-touch weight bearing of ~25% body weight with brace locked in full extension; progress to 50% weight bearing at week 2 and 75% weight bearing at weeks 3-4 with brace locked in full extension

Range of Motion

- Immediate motion exercise on day 1
- Immediate full passive knee extension
- Initiate continuous passive motion day 1 for total of 8-12 hr/day (0-60 degrees; if patellofemoral lesion >6.0 cm^2, 0-40 degrees)
- Progress continuous passive motion range of motion as tolerated 5-10 degrees/day
- May continue continuous passive motion for total of 6-8 hr/day for up to 6 weeks
- Patellar mobilization (4-6 times/day)
- Motion exercises throughout the day
- Passive knee flexion range of motion at least 2-3 times/day
- Passive knee range of motion as tolerated
- For femoral condyle lesions, knee flexion range of motion goal is 90 degrees by 1-2 weeks, 105 degrees at week 3, 115 degrees at week 4, and 120-125 degrees by week 6
- For patellofemoral lesions, knee flexion range of motion goal is 90 degrees by weeks 2-3, 105 degrees by 3-4 weeks, and 120 degrees by week 6
- Stretch hamstrings and calf

Strengthening Program

- Ankle pump using rubber tubing
- Quadriceps setting
- Multiangle isometrics (cocontractions quadriceps/hamstring)
- Active knee extension 90-40 degrees for femoral condyle lesions (no resistance)
- Straight-leg raises (four directions)
- Stationary bicycle when range of motion allows; low resistance
- EMS and/or biofeedback during quadriceps exercises
- Isometric leg press at week 4 (multiangle)
- Use of pool for gait training and exercises at week 4
- Initiate weight shifting exercises with knee in extension at weeks 2-3 for patellofemoral lesions
- *No* active knee extension exercises for patellofemoral lesions

Functional Activities

- Gradual return to daily activities
- If symptoms occur, reduce activities to reduce pain and inflammation
- Avoid extended standing

Swelling Control

- Ice, elevation, compression, and edema modalities as needed

Criteria to Progress to Phase II

- Full passive knee extension
- Knee flexion to 120 degrees
- Minimal pain and swelling
- Voluntary quadriceps activity

Phase II: Transition Phase (Weeks 6-12)

Goals

- Gradually increase range of motion
- Gradually improve quadriceps strength/endurance
- Gradual increase in functional activities

Brace

- Discontinue brace at week 6
- Consider unloading knee brace for femoral condyle lesions

Weight Bearing

- Progress weight bearing as tolerated
- For femoral condyle lesions: 50% body weight with crutches at 6 weeks; progress to full weight bearing at 8-9 weeks, discontinue crutches
- For patellofemoral lesions: progress to full weight bearing at weeks 6-8, discontinue crutches

Continued

TABLE 33-5 Rehabilitation After Autologous Chondrocyte Implantation—cont'd

Range of Motion
- Gradual increase in range of motion
- Maintain full passive knee extension
- Progress knee flexion to 125-135 degrees by week 8
- Continue patellar mobilization and soft tissue mobilization, as needed
- Continue stretching program

Strengthening Exercises
- Progress to closed kinetic chain exercises
- Initiate weight shifts at week 6 for femoral condyle lesions
- Leg press at weeks 7-8
- Minisquats 0-45 degrees at week 8
- Toe-calf-raises at week 6 for patellofemoral lesions, week 8 for femoral condyle lesions
- Progress to balance and proprioception drills
- Initiate front lunges, wall-squats, front and lateral step-ups at weeks 8-10
- For femoral condyle lesions, progress open kinetic chain knee extension, 1 lb/wk
- For patellofemoral lesions, may begin open kinetic chain knee extension without resistance in a range of motion that does not allow for articulation of the lesion
- Stationary bicycle, low resistance (gradually increase time)
- Treadmill walking program at week 10-12
- EMS and/or biofeedback as needed
- Pool for gait training and exercise

Functional Activities
- As pain and swelling (symptoms) diminish, the patient may gradually increase functional activities
- Gradually increase standing and walking

Criteria to Progress to Phase III
- Full range of motion
- Acceptable strength level:
  - Hamstrings within 20% of contralateral leg
  - Quadriceps within 30% of contralateral leg
- Balance testing within 30% of contralateral leg
- Able to walk 1-2 miles or bike for 30 min

Phase III: Remodeling Phase (Weeks 12-26)
Goals
- Improve muscular strength and endurance
- Increase functional activities

Range of Motion
- Patient should exhibit 125-135 degrees of flexion

Exercise Program
- Leg press (0-90 degrees)
- Bilateral squats (0-60 degrees)
- Unilateral step-ups progressing from 2 to 8 inches
- Forward lunges
- Walking program
- Progress to open kinetic chain extension (0-90 degrees), for patellofemoral lesions perform from 90-40 degrees or avoid angle where lesion articulates; progress 1 lb every 2 weeks beginning week 20 if no pain or crepitus; must monitor symptoms
- Continue progressing balance and proprioception
- Bicycle
- Stair-climbing machine
- Swimming
- Ski or elliptical machine

Functional Activities
- As patient improves, increase walking (e.g., distance, cadence, incline)

Maintenance Program
- Initiate at weeks 16-20
- Bicycle; low resistance, increase time
- Progressive walking program
- Pool exercises for entire lower extremity
- Straight-leg raises
- Leg press
- Wall squats
- Hip abduction/adduction
- Front lunges
- Step-ups
- Stretch quadriceps, hamstrings, calf

Criteria to Progress to Phase IV
- Full nonpainful range of motion
- Strength within 80%-90% of contralateral extremity
- Balance and/or stability within 75%-80% of contralateral extremity
- No pain, inflammation, or swelling

Phase IV: Maturation Phase (Weeks 26-52)
Goals
- Gradual return to full unrestricted functional activities

Exercises
- Continue maintenance program progression 3-4 times/wk
- Progress resistance as tolerated
- Emphasis on entire lower extremity strength and flexibility
- Progress agility and balance drills
- Impact-loading program specialized to patient demands
- Progress to sport programs depending on patient variables

Functional Activities
- Patient may return to various sport activities as progression in rehabilitation and cartilage healing allows. In general, low-impact sports such as swimming, skating, rollerblading, and cycling are permitted at about 6 months. Higher-impact sports such as jogging, running, and aerobics may be performed at 8-9 months for small lesions or 9-12 months for larger lesions. High-impact sports such as tennis, basketball, football, and baseball are allowed at 12-18 months.

would produce an abnormal gravity effect. Second, the use of CPM immediately after surgery is warranted to produce a "more even distribution of implanted cells within the defect." At present, no in vivo or clinical studies have been published to support this hypothesis.

Proliferation of the chondrocytes occurs in the first 6 weeks after cell implantation. During the first 24 hours after cell implantation, the cells line the base of the lesion and multiply several times to produce a matrix that will fill the defect with a soft repair tissue up to the level of the periosteal cover.[28,57] At this time, PROM and controlled partial weight bearing will help to promote cellular nutrition through synovial fluid diffusion as well as provide the proper stimulus for the cells to produce specific matrix markers. During this initial phase, controlled PROM and a gradual weight-bearing progression are two of the most important components of the rehabilitation process.

Immediate toe touch weight bearing is performed in knees with smaller lesions, progressing to 25% body weight at weeks 2 to 4, 50% body weight at weeks 5 to 6, and full weight bearing at week 8. This progression may be delayed approximately 2 weeks, with 2 weeks of non–weight bearing, if the lesion is large, deep, or uncontained. For lesions within the patella or trochlea, the patient is allowed to bear weight as tolerated immediately after surgery with a brace locked in full extension. ROM is progressed cautiously to avoid swelling similar to the OAT procedure, with at least 90 degrees of flexion at week 1, 105 degrees at weeks 2 to 3, 115 degrees at week 4, and 125 degrees at week 6. Early strength and proprioceptive exercises are performed within the patient's weight-bearing status.

During the transition phase, which includes weeks 7 through 12, the repair tissue is spongy and compressible with little resistance. Upon arthroscopic examination, the tissue may in fact have a wavelike motion when a probe is slid over the tissue.[28,57] During this phase, the patient achieves full ROM and progresses from partial to full weight bearing. Continued maturation of the repair tissue is fostered through higher level functional and motion exercises. CKC exercises, such as front lunges, step-ups, and wall-squats are performed as well as machine exercises for the entire lower extremity. Again, caution should be placed on exercises that produce sheer forces in patients with patellofemoral lesions.

The remodeling phase occurs from 12 weeks through 32 weeks postoperatively. During this phase, there is a continuous production of matrix with further remodeling into a more organized structural tissue. The tissue at this point has the consistency of soft plastic upon probing.[28,57] As the tissue becomes more firm and integrated, it allows for more functional training activities to be performed as well as elliptical, bicycle, and a gradual walking program.

The final maturation phase can last up to 15 to 18 months depending on the size and location of the lesion. During this phase, the repair tissue reaches its full maturation. The stiffness of the cartilage resembles that of the surrounding tissue.[28,57] The duration of this phase varies based on several factors such as lesion size and location.

Basic science studies have shown that it may take up to 6 months for the graft site to become firm and at least 9 months to become as durable as the surrounding healthy articular cartilage.[28,57] Thus, low-impact activities (such as golf, swimming, cycling, and walking) are initiated by months 5 to 6 and progressed to moderate-impact activities (such as tennis, hiking, skating) from months 7 to 9 as tolerated. Usually, high-impact activities such as running and skiing are permitted with a gradual return beginning at 11 to 12 months postoperative.

The results of clinical outcomes after ACI are encouraging.[5,25,33,40,45,46] Mithofer and colleagues[47] reported a 72% good to excellent result and return to play in competitive soccer players, with 80% returning back to the same level of play. Peterson and coworkers[56] reported a 90% good to excellent result using ACI on osteochondritis dissecans lesions of the knee in patients with a mean age of 26.4 years (range, 14-52 years).

CONCLUSION

The rehabilitation process after articular cartilage repair procedures is vital to the long-term success and functional outcome of the patient. The rehabilitation programs discussed are performed based on current understanding of articular cartilage and the natural healing response observed after articular cartilage repair procedures. Rehabilitation is based on several key principles designed to facilitate the repair process by creating a healing environment while avoiding deleterious forces that may overload the healing tissue. It is imperative that these principles be incorporated into the rehabilitation process along with the knowledge of the basic science and maturation process of each specific repair procedure. The medical team should consider the long-term results of the patients and functional outcomes at 1, 2, and 5 years after the surgical procedure. It is not important how quickly you may return a patient to running or sports; in fact it may be detrimental in many cases. It is more important that the procedure withstands the test of time. The basic principles outlined in this chapter may be applied and integrated as the understanding and clinical use of the next generation of procedures continue to evolve. Long-term clinical studies are needed to determine the effectiveness for each of the surgical techniques and postoperative rehabilitation programs discussed in this chapter.

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Video Content

Video 33-1
Video 33-2
Video 33-3

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34

Aquatic Therapy for the Arthritic Knee

Lori Thein Brody

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INTRODUCTION

Water has been used for healing, spiritual, and religious purposes since at least 2400 BC.[17] Water was used by the people of Asia to combat fevers as early as 1500 BC. Hippocrates (460-375 BC) used water for relief of muscle spasms and joint pain.[25] For many years, water exercise was dismissed as a medical intervention and considered to be purely recreational. The advent of spas in Europe and around the world moved water-based interventions into the leisure and recreation category, making reimbursement for water-based medical interventions difficult.

Despite a history spanning over 4000 years, a resurgence of aquatics as an intervention has occurred in the past quarter century. Throughout this history, many different terms have been used to describe rehabilitation that takes place in water. Some of these terms include *hydrotherapy, aquatic therapy, spa therapy, water therapy, water gymnastics, balneotherapy* and *pool therapy*. The term *balneotherapy* is distinguished from other forms of hydrotherapy. Balneotherapy refers to the use of hot-water or thermal treatments to decrease pain and stiffness and promote muscle relaxation. Balneotherapy often uses minerals, salts, or sulfur treatments, mud packs, and water jets to achieve these goals. *Hydrotherapy* is a general term covering any type of water intervention, which might include balneotherapy or exercise. For the purposes of this chapter, the focus remains on the use of exercise in water for the treatment of knee arthritis. For further information on balneotherapy, the reader is referred to Verhagen and coworkers.[45]

Physical therapy for patients with knee arthritis focuses on decreasing pain while improving mobility, muscle performance, motor control, and function. This is often achieved through stretching, strengthening, and balance exercises. However, many patients are unable to perform these exercises on land owing to pain, comorbidities, or other limitations. These patients often do well in an unweighted environment where they are able to perform full range of exercises directed at improved function.[44] Preferably, exercises are not confined to a single environment but represent a comprehensive program of both land-based and water-based rehabilitation. It is not suggested that aquatic rehabilitation results in superior outcomes compared with land-based rehabilitation. Rather, the pool provides an effective, safe alternative for those who cannot tolerate a comprehensive rehabilitation program on land.

The purpose of this chapter is to discuss the scientific basis for rehabilitative exercise in the water, and then apply this information to the treatment of patients with knee arthritis. Understanding the physical properties of water is critical for building a successful rehabilitation program in water. This understanding is both cognitive and kinesthetic. The reader is encouraged to experiment with these properties to fully understand how the body responds differently to exercises in water compared with land.

SCIENTIFIC FOUNDATION

The scientific foundation for aquatic rehabilitation in patients with arthritic knees is found in two major areas. The first is the basis in aqua physics in which two key forces are critical for treatment planning. The first force is that of buoyancy. Buoyancy is used to unweight an arthritic extremity, normalize gait, and increase pain-free exercise. Buoyancy can also be used as resistance depending on equipment choices and patient positioning. The second force is that of viscosity. Viscosity is used to provide resistance for strengthening muscles from the core to the foot and to provide postural challenges that improve balance. The second major scientific foundational area is that of clinical research in which aquatic rehabilitation has been shown to increase measures of physical performance and to improve patient outcomes.

CRITICAL POINTS Scientific Basis

- Buoyancy can unweight an arthritic joint while permitting rehabilitation activities to continue.
- The precise amount of weight bearing at any given depth is unknown and is related to the individual's body composition and speed of movement.
- Buoyancy can assist, support, or resist a movement depending on how the individual is oriented in the water.
- Viscosity can always override buoyancy as resistance if the surface area and speed are great enough.
- Hydrostatic pressure can minimize swelling and edema in the lower limb that can occur with land-based exercise.
- Hydrostatic pressure causes a centralization of peripheral blood flow with subsequent changes in the pulmonary and heart blood volumes.
- Heart rates for exercise while immersed to the neck will be approximately 20 beats/min lower than comparable land-based exercise owing to hydrostatic pressure.



FIG 34-1 Standing hip extension from 0 to 15 degrees of extension. This is a buoyancy-assisted exercise with a short moment arm, making it a less effective exercise for gluteal muscle strengthening.

Aqua Physics

The principles supporting the use of water in rehabilitation are based in physics. Several physical properties of water are key to understanding how water is a useful exercise mode for people with arthritis of the knee. Capitalizing on these properties can increase the opportunity for a successful outcome for these patients with complicated problems. Failure to recognize or understand how these principles work in harmony or in opposition can lead to poor outcomes. The key properties include buoyancy, hydrostatic pressure, and viscosity.

Buoyancy

Buoyancy is the upward thrust experienced during immersion that is in direct opposition to gravity. Buoyancy is used to unload the lower extremity from the effects of gravity, making it a useful tool for those with knee arthritis. Archimedes' principle states that an immersed body, at rest, experiences an upward thrust equal to the weight of the same fluid volume it displaces.[6]

Buoyancy is related to a person's specific gravity (SG), which varies with body composition. Any object with an SG of less than 1.0 g/cm^2 will float, whereas any object with an SG greater than 1.0 g/cm^2 will sink. This property forms the basis of underwater weighing to determine body composition. Because lean body mass is heavier than fat mass, those with high lean body mass tend to sink, and those with greater fat mass float. This fact makes it difficult to know precisely how much weight bearing any given individual is achieving at a given water depth. Harrison and Bulstrode[22] performed studies on percentage weight bearing during static standing in various water depths ranging from the hips to the neck. The authors found considerable variability in the amount of weight bearing with immersion at various depths. This variation might have been partly caused by using a fixed-depth pool and only nine subjects. However, the disparity may also be the result of differences in body composition and body fat distribution among individual study subjects, suggesting that weight-bearing prescription is difficult in this medium. A follow-up study by Harrison and associates[23] showed that compared with static standing, fast walking increased weight-bearing forces up to 76%. Understanding Archimedes' principle highlights the difficulties in assigning a specific percentage of weight bearing at any given depth; the weight on the limb will vary with body composition and speed of movement.

The moment of buoyancy is also important in exercise prescription. As with moments of gravity on land, the moment of buoyancy increases with increasing lever arm length and nearer the parallel. If the movement is in an upward direction, the same direction as the force of buoyancy, the activity is considered to be *buoyancy assisted*. If the movement in toward the pool bottom in opposition to buoyancy, it is considered to be *buoyancy resisted*. Movements parallel to the bottom that are neither assisted nor resisted by buoyancy are considered *buoyancy-supported* exercises. For example, in a standing position, a straight-leg lift forward would be assisted by buoyancy, whereas the return motion back to the neutral position would be buoyancy resisted. In a supine position, hip abduction and adduction would be buoyancy-supported activities. An important application of this information is strengthening hip extensor muscles. In a standing position, the motion of hip extension from neutral to 15 degrees extension (the normal range of hip extension) occurs through such a small range of motion (ROM), with a short moment arm, and is buoyancy assisted, making the exercise a little more than a gluteal isometric exercise (Fig. 34-1). However, the motion from 90 degrees of hip flexion returning to neutral is also hip extension but is now moving through a larger range with a longer moment arm against the upward force of buoyancy, making this an effective hip extensor muscle-strengthening exercise (Fig. 34-2).

Hydrostatic Pressure

Pascal's law states that a fluid exerts pressure equally on an object at a given depth.[6] Hydrostatic pressure increases with a greater depth of immersion owing to the weight of the volume of fluid overhead. The increased hydrostatic pressure close to the bottom of the pool assists venous return to the heart and prevents fluid accumulation in the lower extremities. This is useful for people with knee or ankle arthritis, who tend to experience swelling with exercise. The increased venous return to the heart also affects the cardiorespiratory system. The hydrostatic pressure when the body is immersed to the neck produces an increase in heart volume, intrapulmonary blood volume, right atrial pressure, left ventricular end-diastolic volume, stroke volume, and cardiac output.[1,11] Heart rate is unchanged or decreased compared with similar land-based activities.[1] Peripheral circulation and vital capacity are decreased.[11] This cardiopulmonary response is significant for people with cardiorespiratory conditions and for those who are trying to achieve training heart rates in deep-water exercise.[21] These changes have been noted in people both with and without cardiac disease.[12,13] Aerobic exercise in neck-deep water will result in heart rates that are



FIG 34-2 Hip extension from 90 degrees of flexion to neutral is a buoyancy-resisted exercise with a longer moment arm, making it a more effective gluteal muscle-strengthening exercise.



FIG 34-3 Note the area of high pressure anteriorly and the area of low pressure evidenced by eddies formed in the wake.

approximately 17 to 20 beats/min lower than comparable land-based exercise.[2,20,38,42]

Viscosity and Hydrodynamics: Using Speed and Surface Area

The *viscosity* of a fluid is its resistance to adjacent fluid layers sliding freely by one another.[6] Viscosity causes a resistance to flow when a body is moving through the water. As such, viscosity is clinically insignificant when a body is stationary. The viscous quality of water allows it to be used effectively for resistance because of its *hydrodynamic properties*, or fluid mechanics. The key hydrodynamic properties are turbulence and drag.[40] Turbulent flow occurs when the speed of movement of an object (or person or body part) reaches a critical velocity or when the flow of water encounters an object (or person or body part).[3] In turbulent flow, resistance is proportional to the velocity squared, and increasing the speed of movement significantly increases the resistance.[32] Eddies are formed in the wake behind the moving body, creating drag that is greater in the unstreamlined object than in a streamlined object (Fig. 34-3).

When moving through the water, the body experiences a frontal resistance proportional to the presenting surface area. Resistance can be increased by enlarging the surface area (Fig. 34-4). For example, walking forward or backward will produce greater drag in most people than walking sideways because of the greater surface area. Increasing the surface area or otherwise increasing drag increases the resistance to movement. The clinician has two variables to alter resistance produced by viscosity: the velocity of movement and the surface area or streamlined nature of the object.

Several areas of research provide evidence for examining the impact of surface area and speed on force production. Law and Smidt[27] used Hydrotone bells (Hydro-Tone Fitness Systems, Inc.) at different speeds and angles to assess the impact on force production. Results showed a 50% increase in force production at fast speeds. Force also increased at fast speeds when the bells were oriented at 45 degrees compared with 0 degrees. Orientation had no impact on force production when performed at slow speeds. Therefore both speed and surface area influence force production when using viscosity.

Similar increases in drag were noted when using the Hydrotone boots compared with a barefoot condition.[33] In a series of studies, Poyhonen and coworkers[32-34] found that increasing the surface area of the lower leg significantly increased the level of water resistance. Interestingly, electromyographic (EMG) activity of the knee flexors and extensors was similar between barefoot and increased surface area conditions despite the increased drag caused by the boot. This EMG finding was the result of self-selected speed changes by the subjects. Speed was uncontrolled in the study, and subjects performed the exercise faster in the barefoot condition. This reinforces how similar muscle activation can be obtained by manipulating speed and/or surface area when using viscosity as the primary resistance. Both strategies will overload the muscle, allowing the exercise prescription to be specific to each patient's needs.



FIG 34-4 Adding the plow increases the surface area and creates additional drag.

Electromyographic data has also been used to examine the relationship between muscle activation and speed in the shoulder musculature. Data from the deltoid and rotator cuff musculature were captured during arm elevation at three different speeds (30, 45, and 90 degrees/sec) on land and in the water.[26] The percent maximum voluntary contraction was consistently higher on land at the two slowest speeds but higher in the water at 90 degrees/sec, highlighting the positive relationship among viscosity, speed, and force generation.

Research in the cardiopulmonary effects of speed on exertion measures also supports the positive relationship between speed and work in the water. Whitley and Schoene[47] examined walking on land and in the water at four different speeds. Heart rates were significantly higher after water-walking versus treadmill walking at all four speeds. In addition, heart rates rose significantly with each increasing speed in water-walking, suggesting increasing cardiopulmonary workloads at increasing speeds. Cassady and Nielsen[10] measured oxygen consumption during calisthenic arm and leg exercises at three different speeds on land and in the water. They also found increasing heart rate with increasing speed of exercise in the water. The higher metabolic cost of exercises at a faster speed supports the theory of increased work at faster speeds in the water.

CLINICAL RESEARCH

Clinical research has supported the effectiveness of aquatic rehabilitation for persons with knee arthritis. A study examining outcomes following a water-based program for patients with lower limb osteoarthritis found that group-based water exercise classes over 1 year produced significant reductions in pain and improvements in function.[14] A randomized, controlled trial (RCT) compared the effects of a water-based resistance program with a land-based program on function and strength in patients with osteoarthritis of the hip or knee.[18] The authors found improvements in strength and function in both the land- and the water-based groups as compared with the control group. Compliance rates were 84% for water therapy and 75% for land therapy. In a similar study, Wyatt and coworkers[48] examined change in function following a land-based or an aquatic exercise program in patients with knee osteoarthritis. Both groups showed significant improvements in measures of ROM, thigh girth, pain scales, and 1-mile walk test. However, the aquatic group had significantly lower pain levels than the land group. These results reinforce that patients can improve strength and function effectively in either a land or aquatic environment.[48,39] The key is the ability to provide a comprehensive and sustainable program, whether on land, in the water, or some combination of both. Ongoing exercise at the conclusion of formal rehabilitation is essential to prevent symptom recurrences.

Addressing the issue of compliance with a rehabilitation program, Hinman and colleagues[24] performed an RCT randomly assigned 71 participants with hip or knee osteoarthritis to 6 weeks of aquatic physical therapy or no physical therapy. Patients in the aquatic physical therapy program had less pain and joint stiffness and greater physical function, quality of life, and hip muscle strength than the control group. Nearly 75% of participants reported improvements in pain and function compared with 17% in the control group. More important, 84% of participants continued the aquatic program independently at the conclusion of the study. The chronic nature of osteoarthritis requires ongoing participation in an exercise program at the conclusion of formal rehabilitation.[7]

Although the previous study compared aquatic physical therapy with no physical therapy, Fransen and coworkers[19] compared hydrotherapy with ai chi or a control group in an RCT of 152 patients with hip or knee osteoarthritis. Results showed that both hydrotherapy and ai chi participants improved in the pain and physical function subscales of the Western Ontario and McMaster Osteoarthritis Index (WOMAC), but only the hydrotherapy group achieved significant improvements in the physical performance measures of the Short-Form-12 item questionnaire (SF-12). In addition, compliance with the hydrotherapy classes was higher than compliance with ai chi.

Pools are expensive to maintain and operate. An RCT examined the cost-effectiveness of water-based therapy for lower limb osteoarthritis. A group of 312 patients with hip or knee osteoarthritis was randomized into control and water exercise groups. The control group received usual care, and the intervention group received aquatic exercise for 1 year with follow-up for an additional 6 months. Results showed a favorable cost/benefit ratio as measured by a reduction in WOMAC pain as the measure of benefit.

Structured aquatic physical therapy for patients with knee arthritis is gaining momentum, with evidence supporting the clinical and cost-effectiveness of this intervention in this population. Outcomes following aquatic physical therapy appear to be similar to land-based rehabilitation, making the pool a viable alternative for those who are unable to rehabilitate on land or who have a preference for aquatic based exercise.[4,5,16,35]

APPLICATIONS

Although patients with knee arthritis have individualized problems and differing comorbidities, some generalizations about preferred applications in this population can be made based on the pathology and commonly associated limitations. A thorough examination is the foundation for determining the appropriate exercise intervention. Awareness of the interrelationships among lower extremity joints and the spine can ensure proper positioning and targeting of the tissue of interest. Altering the position of the hip or foot can significantly affect the loads across the knee. The following discussion is meant to provide examples of how the physical properties of water can be exploited to improve function in patients with knee osteoarthritis.

Mobility

Many activities typically performed on land can be modified, adapted, and used in the pool. *Mobility* has both a static component and dynamic. Functional mobility requires both appropriate soft tissue extensibility, achieved through stretching exercises, and dynamic mobility, achieved through a combination of stretching, strengthening, balance, and neuromuscular retraining.

Soft tissue stretching exercises are readily and easily performed in the pool. Many patients with arthritis have difficulty stretching on land owing to the positions or postures required. For example, some individuals are unable to get up and down off the floor or lack a sufficient supportive surface to perform the exercises appropriately. Some stretches require bending, twisting, reaching, or have weight-bearing components that patients are unable to accomplish on land. For

CRITICAL POINTS Applications

- Stretching is readily performed in the pool because positioning is simple and gravity is minimized.
- Stretching can be performed in functional upright positions using buoyant equipment or stationary features of the pool.
- Static stretching should be combined with dynamic mobility exercises for functional mobility.
- Buoyancy, viscosity, or the water's hydrodynamic principles can be used for improving muscle performance.
- Rapid direction changes can be used to challenge buoyancy and elicit eccentric muscle contractions.
- A variety of arm and trunk movements can be used to challenge dynamic balance.
- The water- and land-based programs can be progressed in tandem, with an eye to the long-term medium that will best support a lifetime of exercise.

example, hamstring or quadriceps muscle stretches often require balancing on a single leg or getting up and down off the floor. Many of these exercises are easily performed in the pool with stationary or buoyant equipment. The water's warmth and support from buoyancy make it easier and more relaxing to achieve a successful stretch.

As on land, muscles crossing both the hip and knee or both the knee and ankle are stretched together. Thus the position of the adjacent joint becomes important. Because many of the stretches use buoyancy, it is easy to adjust the stretch to decrease stress on the joints and emphasize the soft tissue component.

Key muscles to be stretched in patients with knee arthritis include the gastrocnemius and soleus muscles as well as the quadriceps, hamstring, lateral hip (iliotibial band), and gluteal/buttock muscles (Figs. 34-5 to 34-7). As with stretching exercises on land, the intensity should be subjectively between "low" and "medium" and should be pain free. The patient should feel stretching in the muscle of interest and not in the joint itself. The patient should be able to hold the stretch for 60 seconds without an increase in pain.[3] Repeat the stretches for two to three repetitions.



FIG 34-5 Hamstring stretching using a noodle. Other stationary equipment in the pool can also be used for stretching.

Dynamic mobility is easily accomplished in the pool. Dynamic mobility has been advocated as an appropriate means to increase functional mobility because it requires not only static flexibility but also strength, balance, and neuromotor coordination.[29] Dynamic mobility activities in the pool take place in a gravity-lessened environment, which decreases joint-loading forces. The water's viscosity also slows movement and increases the reaction time for patients with balance difficulties. This property makes the pool a safe environment for such individuals.

Dynamic mobility activities can easily replicate similar activities performed on land. Walking forward with varying speed and step length can be modified to emphasize lower extremity mobility. Cue the patient for increased knee flexion and extension during the swing phase of gait. Ankle or hip mobility can be similarly cued to increase sagittal plane mobility. Backward walking is useful for increasing dynamic knee flexion because increased knee flexion is required to clear the ground during walking this direction. Frontal plane mobility is emphasized by walking sideways.

Other dynamic mobility activities include marching in place and marching across the pool. Vary the amount of hip and knee flexion based on the patient's needs. Marching does not need to proceed in a straight line but can be on a diagonal to encourage more functional movement patterns. Proprioceptive neuromuscular facilitation (PNF) patterns also encourage functional movement patterns in the lower extremity. Cueing the patient appropriately can emphasize motion at the knee joint when tolerated. For closed-chain dynamic mobility, perform squats for hip, knee, and ankle mobility in shallow water or fully flex the hips and knees by flexing and extending these joints at a ladder (Fig. 34-8). These closed-chain activities can be progressed by asking the patient to lunge during ambulation.

Dynamic mobility of other joints in the kinetic chain such as the hip and low back is necessary to accommodate potential motion losses at the knee. Motions out of the straight plane such as figure-of-eights or other movement patterns can enhance mobility at these joints. Ai chi exercise stresses balance, stability, and mobility throughout the kinetic chain (Figs. 34-9 and 34-10).

Dynamic mobility can also be performed non–weight bearing. Bicycling or running with a belt or a noodle is a good way to perform repeated hip and knee flexion and extension. The range of movement can be modified as needed for any given patient. Similarly, deep-water



FIG 34-6 Lateral hip stretching. Start in the hamstring stretch position, then horizontally adduct approximately 15 degrees and internally rotate.



FIG 34-7 Quadriceps muscle stretching with a noodle.



FIG 34-8 Knee-to-chest stretching on a ladder.



FIG 34-9 Ai chi balancing pattern of hip extension with bilateral shoulder flexion.



FIG 34-10 Ai chi balancing pattern of hip flexion with bilateral shoulder extension.

cross-country skiing requires repeated non–weight-bearing sagittal plane mobility, with greater hip motion and less knee motion. These repeated movements provide lubrication via mobility, but lack the weight-bearing component necessary for articular cartilage lubrication (Table 34-1).[46]

Muscle Performance

Clinicians can use buoyancy, viscosity, or hydrodynamics as tools to increase lower extremity and core strength in individuals with arthritis. A variety of activities using all components will produce a well-rounded rehabilitation program. The starting point is established during the patient's examination when the strength of surrounding muscles and the irritability of the joint are determined. For example, in a patient with an irritable knee and decreased strength, buoyancy might be used to assist the exercise, whereas in a patient with a less irritable joint and greater strength, buoyancy may be used as resistance. Whether using buoyancy or viscosity, exercises can be performed in an open chain, a closed chain, or some combination of both.

Exercise Using Buoyancy

For patients needing buoyancy assistance, squats, step-ups, or step-downs in deeper water will provide the necessary assistance in both the eccentric and concentric phases of the exercise. Specially designed boxes can be submerged in water of any depth to find the appropriate amount of assistance/resistance for a given patient. A box submerged in 4 to 4.5 feet of water is a good place to start for the average adult. Remember that the amount of assistance provided by buoyancy will vary with body type. Thus the exercise prescription must be specific to the individual. As the patient improves, progress the buoyancy-assisted exercises by moving the exercise to more shallow water. This will increase the forces of gravity and lessen the assistance by buoyancy. Exercises can also be progressed to positions such as the lunge position, which is more challenging. Lunges can be performed in place or moving forward (Fig. 34-11), backward, or sideways.

Strengthening exercises can also use buoyancy as resistance. Adding buoyant equipment to the foot or ankle will increase the challenge of these exercises. Straight-leg lifts in the sagittal or frontal planes will result in concentric and eccentric contractions of the muscle groups positioned in opposition to buoyancy. For example, lifting the leg forward and back down will result in eccentric and concentric contractions of the hip extensor muscles if sufficient buoyant equipment is used. If the amount of buoyant equipment is inadequate or the speed not high enough, the muscle contractions become alternating concentric contractions of the hip flexor muscles and hip extensor muscles. Therefore the relative amounts of muscle strength and buoyant equipment will determine which muscle groups are working and in what type of muscle contraction. These straight-leg lifts strengthen the core hip muscles isotonically while challenging the muscles at the knee isometrically. To challenge these muscles directly, perform buoyancy-resisted hamstring curls in a standing position with the hip flexed to 90 degrees (Fig. 34-12). Buoyancy-resisted quadriceps exercises are performed in a standing position with the knee moving from extension to flexion (Fig. 34-13). Realize that while the moving limb is working in an open chain, the opposite limb is working in a closed chain to stabilize the body against the hydrodynamic forces created by the moving limb. This principle is one of the strengths of working in the aquatic medium.

Functional movement patterns can be trained using buoyant equipment. The same PNF patterns used for mobility can be used for strengthening using buoyant equipment. For example, place a Wet Vest strap (Hydro-Fit, Inc.) around the ankle and perform PNF diagonals, alphabet writing, or other functional movement patterns with the leg

TABLE 34-1 Exercises for Mobility

Level 1 Exercise	Level 2 Exercise	Level 3 Exercise	Additional Challenge
Passive knee extension with noodle under midcalf	Noodle under ankle	Foot on rigid object	Provide downward pressure on knee
Passive knee flexion with noodle under midshin	Noodle under ankle	Foot on rigid object	Provide overpressure into flexion
March in place	March across pool	Emphasize gait components such as knee flexion or extension, vary step length	Add stop to provide additional balance challenge
Standing knee flexion/extension with support	Increase range of motion	Add buoyant equipment	Remove support
Bicycle in stable, supported position	Bicycle on noodle or with vest	Increase range of motion, speed	Vary activity to emphasize flexion or extension or both
Squats at railing	Increase depth of squat	Progress to hip and knee flexion on ladder	Bring knees closer to chest as tolerated
Stationary lunges	Increase stride length	Increase depth of lunge	Progress to forward-moving lunges
Hip mobility through single plane with support	Hip flexion/extension, abduction/adduction, figure-eights	Increase range of motion, remove support	Add carioca walking, walking with direction changes and varying step length

Progress exercises from one level to the next after successful completion of the previous level.



FIG 34-11 Lunge walking.



FIG 34-12 Hamstring curls with buoyant equipment.



FIG 34-13 Standing quadriceps strengthening with buoyant equipment.

straight. This type of movement provides resistive exercise to muscles throughout the entire leg. Place a noodle under the bottom of a foot and press down as in a leg press for a buoyancy-resisted leg press activity (Fig. 34-14). Exercises using buoyancy as the primary resistance are increased by adding more buoyancy, as in adding more weight on land.

Exercise Using Viscosity

Open- or closed-chain exercises using viscosity provide an opportunity to strengthen lower extremity muscles isotonically. It is important to consider *how* the exercises are performed to ensure that the structures of interest are being challenged. Exercises using viscosity as the primary resistance are increased by increasing the exercise speed, the surface area, or both. A study of the hydrodynamic responses to viscosity-resisted single and repeated knee flexion and extension in water found high levels of antagonist activity with the repeated activity and lower levels with the single repetition activity.[34] This is an important issue for those wanting to provide both concentric and eccentric muscle



FIG 34-14 Buoyancy-resisted leg press performed with a noodle.

contractions during aquatic rehabilitation. Although concentric and eccentric contractions of a single muscle group can be achieved using buoyancy-resisted exercise (such as standing knee extension with buoyant equipment, Fig. 34-15, *A* and *B*), this same exercise using viscosity (such as standing knee extension with a resistive fin) produces reciprocal concentric contractions (see Fig. 34-15, *C* and *D*). However, research by Poyhonen and associates[33] suggested that the muscle activity is influenced by the surface area, speed, and limb orientation. During both the flexion and extension phases of a knee flexion and extension activity in water, the agonist EMG activity decreased with a concurrent increase in the antagonist EMG during the final portion of ROM. This finding suggests that the moment of the moving water produces lift that tends to "carry" the limb through the final ROM, requiring antagonist activation to decelerate the limb at end ROM. This is more evident in extension phase of seated knee extension than in the knee flexion phase owing to the additional lift from buoyancy. Therefore the quadriceps muscles will be activated through a greater ROM if performed in standing and the hip in neutral than in a seated or standing position with the hip at 90 degrees. Similarly, if the goal is to facilitate hamstring muscle activation and minimize quadriceps muscle activation near full knee extension (as in anterior cruciate ligament injuries), then the 90 degrees of hip flexion position would be preferable (Fig. 34-16).

Progress activities using viscosity as resistance by increasing the speed and/or surface area of the exercise. Flippers or fins are good choices for increasing the surface area. Flippers tend to work best in the sagittal plane, whereas Aquafins (Hygenic Corporation) can be placed in any plane, providing resistance in the sagittal plane, frontal plane, or on any diagonal in between. Other resistive equipment, such as a Hydro Boot (Hydro-Tone Fitness Systems, Inc.), provides a larger surface area for greater resistance.[34] Leg kicks, knee exercises, or walking activities can be performed with resistive fins around the ankle. Different components of the activity can be emphasized depending on how the exercise is cued. For example, during backward walking, emphasizing the knee flexion component will challenge the hamstring and gastrocnemius muscles whereas stressing the hip extension component will challenge the hamstring and gluteal muscles. Generate more resistance by positioning the arms with increased surface area. For example, walk forward with the arms held at 90 degrees abduction or increase the challenge by walking forward while simultaneously horizontally adducting the shoulders. Be aware of the additional stress this will place on the shoulders (Table 34-2).

Finally, resistance bands typically used on land can be applied in the water. Resistive hip, knee, and ankle exercises, as well as resistive walking patterns, can be successful in water because of the resistance applied to the musculature without the weigh-bearing effects of gravity (Fig. 34-17).

Balance, Stabilization, and Gait

The hydrodynamic forces of water provide excellent opportunities for activities to challenge the core muscles and balance. A study of balance training on land and in water found both mediums resulted in improvements in the center of pressure variables,[37] although outcomes research looking at the 8-foot up-and-go test found greater improvement in an aquatic-exercise group compared with a land-exercise group.[8] An 8-week program of aquatic exercise in older adults demonstrated improvements in measures of gait stability.[28] Exercise training on an aquatic treadmill led to improvements in joint angular velocity and pain in patients with knee osteoarthritis.[36] Exercises can be stationary or moving and can be challenged in a variety of ways. Although strength is important, it is only one component of a program to enhance balance. Muscle activation patterns and knowledge of position in space also contribute to good balance.

Patients can use their arms to create forces that are resisted by their trunk and core muscles. Reciprocal shoulder flexion and extension produce rotational forces that are resisted by the core muscles. Turning the palms to the direction of movement increases surface area and increases the challenge. Likewise, symmetrical, bilateral shoulder internal and external rotation also creates rotational forces resisted by the trunk. Anterior-posterior sway is produced with any bilateral anterior-posterior movement of the arms such as flexion/extension or horizontal abduction/adduction. Increase the challenge of these exercises by increasing the exercise speed or surface area or by decreasing the base of support by bringing the feet closer together. Further increase the challenge by removing the bilateral symmetry. For example, performing shoulder horizontal abduction/adduction with a single arm minimizes the anterior-posterior sway and produces trunk rotation (Fig. 34-18).

Progress the narrow base of support to exercise on a single foot as appropriate. Rotational activities will be difficult on a single foot and may not be appropriate for all patients with complex knee problems. Other sagittal or frontal plane activities may be appropriate on a single leg and challenge balance. Simple hip flexion/extension or hip abduction/adduction on a single leg will challenge balance if no external support is provided. For people with chronic knee problems, continuous standing for several repetitions on a single leg may be inappropriate. Consider alternating legs every repetition or every few repetitions for these patients.

Other dynamic activities can capitalize on the physical properties of water. Continuous moving in one direction is not particularly challenging to the core muscles other than the generalized strengthening that occurs with walking against resistance. Once an individual begins moving through the water, the momentum of the water produces lift, carrying the body along through the water. The real challenge to balance and strength occurs with stopping and changing direction once this momentum is achieved. A beginning activity is simply stepping forward onto one foot and balancing followed by a step backwards and balancing again. Increase the challenge by taking three or four steps forward, stop and balance, followed by three or four steps backwards, stop and balance. A few steps one direction is enough to get the water moving along with the patient. Stopping and balancing,

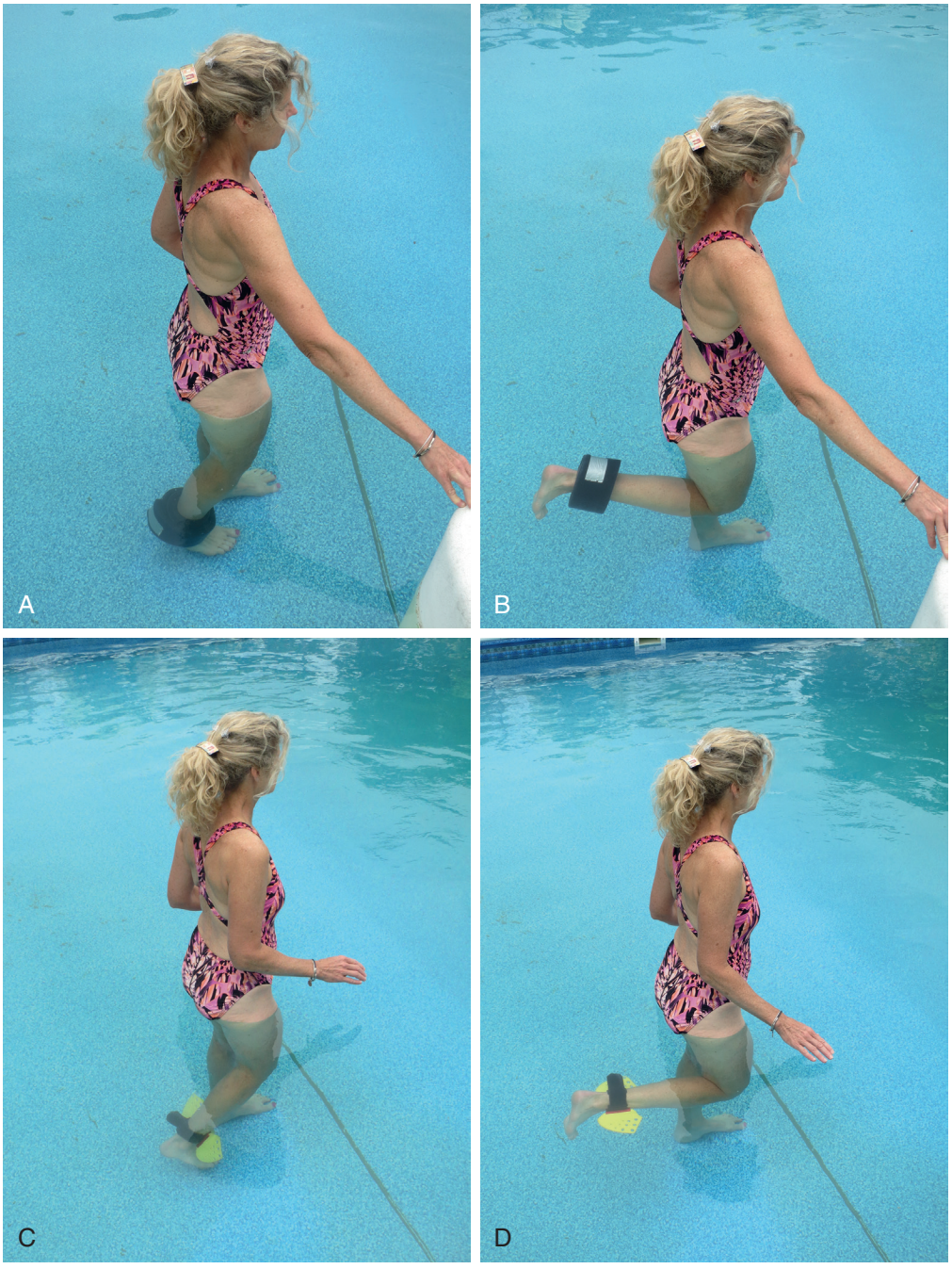


FIG 34-15 **A** and **B**, Standing knee extension using buoyant equipment with the hip in neutral results in eccentric and concentric quadriceps muscle contractions. **C** and **D,** Standing knee extension and flexion using surface area-increasing equipment results in reciprocal concentric quadriceps and hamstring muscle activation. The hip position does not change this activation pattern.

then changing direction produces significant balance challenges. This same pattern can be repeated moving in different directions. Further increase the challenge of the activity by increasing the speed of walking, decreasing arm assistance by placing the arms across the chest and/or decreasing visual input by closing the eyes. Finally, tip or turn the head to include the vestibular component.

Other balance exercises use movements of the arms or opposite leg while stabilizing on a single leg. A stepping motion with a concurrent pushing and pulling motion with resistive equipment makes an excellent core strengthening and balance exercise. In single-leg stance, pushing a ball down works on stability of the entire lower extremity. To increase the challenge, these exercises can be performed on an unstable base such as Therafoam (Hygenic Corporation) submerged in the water (Table 34-3).

Cardiopulmonary

Regular aerobic exercise is an important component of general fitness and weight loss. The American College of Sports Medicine[41] and the American Heart Association recommend performing moderately intense cardiopulmonary activity 30 minutes a day, 5 days a week, or



FIG 34-16 Standing knee flexion and extension with the hip at 90 degrees of flexion facilitates hamstring activation near full extension because these muscle work to decelerate the extending knee.

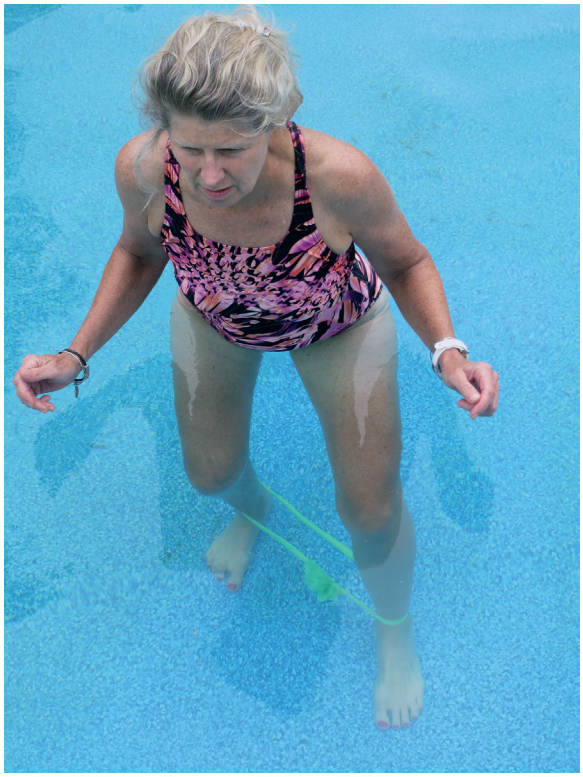


FIG 34-17 Monster walks with resistive band around ankles. The band can also be placed above the knees for less resistance across the knee joint.

TABLE 34-2 Aquatic Strengthening Activities

Level 1 Exercise	Level 2 Exercise	Level 3 Exercise	Level 4 Exercise	Comments
Standing hip flexion/extension	Add fins or buoyant equipment	Increase speed in a controlled fashion	Progress to unsupported will further challenge balance	Buoyant equipment will emphasize hip extensors; fins will equally emphasize flexors and extensors
Standing hip abduction/adduction	Add fins or buoyant equipment	Increase speed in a controlled fashion	Progress to unsupported will further challenge balance	Buoyant equipment will emphasize hip adductors; fins will equally emphasize adductors and abductors
Standing knee flexion/extension	Add fins or buoyant equipment	Increase speed in a controlled fashion	Progress to unsupported will further challenge balance	Buoyant equipment will emphasize knee flexors with hip at 90 degrees, extensors with hip in neutral; fins will equally emphasize flexors and extensors
Wall-sits	Progress to single leg	Add arm and/or contralateral leg movement to perturb	Decrease depth to increase weight bearing	
Squats with arm support	Progress to single leg	Bilateral squat without support	Decrease depth to increase weight bearing	Can add toe-raise to increase calf muscle work
Lunge	Stationary lunge with support	Stationary lunge without support	Lunge walk across pool	Can be performed in any direction
Noodle depression activities	Noodle leg press with foot kept close, more knee flexion	Noodle figure-of-eights or alphabet writing; foot further away, knee more extended	Increase depth and/or buoyancy to increase resistance	Remove support to add balance challenge
Stepping activities	Step-ups on box	Decrease depth to increase weight bearing	Perform in a variety of directions	Decrease depth to increase challenge
Resistive band exercises	Walking with band at knees	Walking with band at ankles	Standing single leg activities with support	Standing single leg activities without support
Deep-water activities	Bicycling, cross country skiing, running, vertical or supine kicking	Add fins	Increase speed or add interval training	

Progress to higher levels upon successful completion of prior levels.

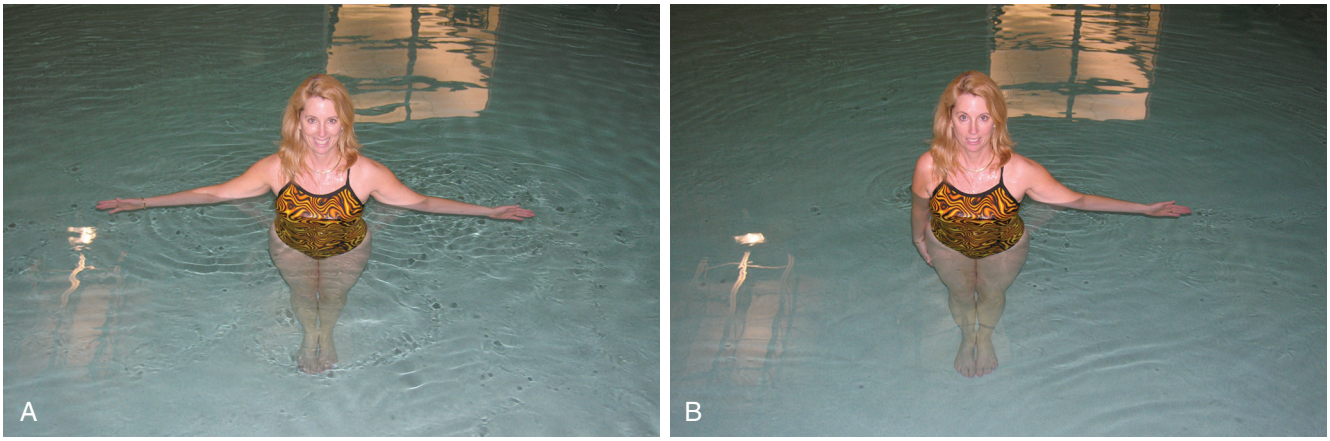


FIG 34-18 Balance exercise that performs shoulder horizontal abduction and adduction bilaterally. **A,** This position creates anterior-posterior sway. **B,** Single-arm position creates transverse plane rotation.

TABLE 34-3 Aquatic Balance Activities

Level 1 Exercise	Level 2 Exercise	Level 3 Exercise	Level 4 Exercise	Comments
Bilateral shoulder flexion/extension	Narrow base of support	Single foot	On unstable surface, such as immersible foam	Close eyes, add head movement to increase balance challenge; can also add gloves to increase resistance, or to single arm to emphasize core
Bilateral horizontal abduction/adduction	Narrow base of support	Single foot	On unstable surface, such as immersible foam	Close eyes, add head movement to increase balance challenge; can also add gloves to increase resistance, or to single arm to emphasize core
Reciprocal shoulder internal/external rotation	Narrow base of support	Single foot	On unstable surface, such as immersible foam	Close eyes, add head movement to increase balance challenge; can also add gloves to increase resistance
Stepping exercises	Step and hold forward and backward, with then without, arm balance	Three-step stop, with then without, arm balance	Stepping push-pull with resistive equipment	Close eyes, increase speed; perform in any direction
Single-leg activities, unsupported	Hip flexion/extension, abduction/adduction	Standing knee flexion/extension	Arms across chest	Close eyes, add unstable surface
Hop in place, with stable balance in between	Hop forward/back, side-to-side	Hop on diagonal	Arms across chest, close eyes	Perform 2-2, 2-1, 1-2, 1-1 footed with emphasis on stability upon landing

Progress to higher levels upon successful completion of the previous level.

performing vigorously intense cardiopulmonary activity 20 minutes a day, 3 days a week. These organizations also recommend regular strength-training exercises. For people with arthritis or complex problems at the knee, many of the traditional cardiopulmonary training activities are too painful. Most of these activities involve some weight bearing through the knee. Walking, running, elliptical trainers, stair steppers, and ski machines all require weight bearing through the knee. Bicycling places less weight-bearing loads across the knee than other cardiopulmonary training activities, but still places large demands on this joint.

The water is an excellent alternative to cardiopulmonary training on land. Patients do not need to be skilled swimmers to achieve a training effect in the pool. Alternative non-weight-bearing activities include deep-water bicycling, cross-country skiing or deep-water running. Vertical kicking or deep-water aerobics classes also provide a good training stimulus. For some individuals, walking in chest-deep water at a steady pace is sufficient cardiopulmonary training. One study found that walking backward in chest-deep water elicited greater physiological and perceptual responses than walking forward at the same speed.[30] Another investigation reported that muscle activity, cardiorespiratory responses, and rate of perceived exertion were all greater in elderly patients who walked in water compared with those who walked on land.[31]

For those who like to swim, traditional swim strokes can be modified to improve their efficiency. Adding a mask and snorkel decreases the amount of neck and trunk rotation necessary during the crawl stroke and the amount of extension necessary during breaststroke. This may increase the efficiency of the stroke and decrease stresses on the spine, allowing individuals to swim continuously enough to obtain the desired cardiopulmonary results. Adding flippers increases the torque production of the leg muscles and may decrease loads on the knees caused by inefficient kicking techniques. Simple flutter kicking with flippers is a good cardiopulmonary exercise. However, the frog or whip kick usually associated with breaststroke swimming places additional torque on the medial knee and may be painful for many people with knee arthritis.

Circuit training or interval-training techniques can also be incorporated into the cardiopulmonary program. Speed play is a simple technique to increase the musculoskeletal and cardiorespiratory demands of an activity. For example, when walking the length of the pool, begin at the usual pace, gradually build in speed to midway across the pool, and then gradually slow back to the usual pace by the time the other end of the pool is reached. This type of training can be incorporated into any of the cardiorespiratory activities, using time or repetitions as the metric for adjusting the speed. A circuit training strategy is often necessary for patients with osteoarthritis because any continuous repetitive activity can flare one or more arthritic joints. A combination program of lap swimming activities alternated with deep water running, cycling, vertical kicking, and/or cross-country skiing can provide a sufficiently varied cardiorespiratory workout without overstressing any single joint.

Research has shown that subjects exercising in the water can achieve a sufficient training stimulus.[9,15,43] D'Aquisto and colleagues[15] and Campbell and coworkers[9] found that controlling the frequency, intensity, and duration of shallow water exercise resulted in a training response sufficient to meet the American College of Sports Medicine's guidelines in younger and older women. Takeshima and associates[43] found that exercising three times per week for 12 weeks resulted in an increase in peak volume of oxygen consumption. Improvements in muscle strength, power, flexibility, agility, and subcutaneous fat were also found. All of these changes are positive for people who have complex knee problems.

Training parameters in the water are basically the same as land. Manipulating the frequency, intensity, and duration to meet the American College of Sports Medicine's guidelines follows the same thought process as those on land. One important issue is skill level in the water. Unskilled deep-water exercisers report higher rates of perceived exertion and have higher lactate levels than skilled deep-water runners. As patients become skilled and comfortable with the new techniques, the exertion levels and heart rate will decrease. Exercise in deep water will result in a heart rate approximately 20 beats/min lower than comparable land-based exercise because of the effects of hydrostatic pressure.[42]

TRANSITION TO LAND

Transition to land-based activities should be a part of the patient's treatment program. The balance between land-based and aquatic-based activities will vary from one patient to the next. Several issues must be considered when determining this balance. The patient's tolerance for land-based activities is a key consideration. If the patient is unable to achieve a sufficient training stimulus on land because of pain, swelling, or other mechanical symptoms, then the majority of the rehabilitation and maintenance program will likely contain an aquatic component. This can be achieved through an independent rehabilitation and exercise program at a local pool, or a community aquatic exercise class. In contrast, some patients may not tolerate regular aquatic exercise caused by reactions to pool chemicals. These individuals may need more land-based activities or find an alternative pool with fewer chemicals such as a salt-water system pool. Other considerations are pool availability and the patient's preferences.

The transition to land occurs similarly to other transitions in rehabilitation. Frequently, patients begin with programs that are primarily in the water, with the addition of a few land-based exercises that they tolerate and can complement the water activities. As the patient tolerates this program and healing progresses, the land-based component is gradually increased and the aquatic component is maintained or increased in parallel, as the patient tolerates. The long-term progression and outcome is dependent on the patient's long-term goals and whether these are best met with an aquatic program, a land program, or some combination of both. The ultimate goal should be the design of a program that the patient can easily maintain because of its ease, effectiveness, and enjoyment. This requires a partnership and communication between the therapist and patient.

SUMMARY

The water is an excellent exercise, training, and rehabilitation medium for patients with arthritis. The water's buoyancy unweights painful joints, allowing greater ease of movement and the ability to train and strengthen without high joint compressive forces. The unweighting reduces pain and allows more active participation in the rehabilitation process. The hydrostatic pressure controls lower extremity swelling that may accompany exercise in people with arthritis. Finally, the water's viscosity provides resistance for strengthening and support against falls caused by poor balance. Research into the efficacy of water-based exercise is ongoing. As with all interventions, exercise in the water is not for everyone. However, for those who tolerate or enjoy the water, this environment can provide opportunities to rehabilitate and exercise across the lifespan. More importantly, research has shown strong compliance with aquatic programs with continued participation at the conclusion of the structured program. For patients with knee osteoarthritis, ongoing, regular exercise, whether on land or water or both, is critical for preventing a progressive decline in function.

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35

Operative Options for Extensor Mechanism Malalignment and Patellar Dislocation

Frank R. Noyes, Sue D. Barber-Westin

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INDICATIONS

Disorders of the extensor mechanism, including the patellofemoral joint, are some of the most common causes of anterior knee pain related to inflammation of the parapatellar soft tissues, articular cartilage damage, and instability (subluxation, dislocation). Although the majority of patients respond favorably to conservative measures, surgical treatment is required for recalcitrant cases with distinct anatomic abnormalities that require correction. The key to the indications for surgical treatment is the diagnosis of the specific anatomic defects that cause the patient's symptoms. This underscores the importance of the history and physical examination discussed later in this chapter.

The terminology used to describe patellofemoral disorders in the literature can be confusing. *Patellar malalignment* may be defined as a translational or rotational deviation of the patella relative to any axis. It is caused by an abnormal relationship among the patella, the soft tissues surrounding the patella, and the femoral and tibial osseous structures. The source of such abnormal patellar kinematics may be peripatellar tissue tightness or laxity; osteochondral dysplasias, such as a shallow or convex trochlear groove; bony abnormalities of the patella; rotational malalignment of the femur and tibia proximal and distal to the knee joint; an excessive proximal or distal position of the patella relative to the trochlea (patella alta and patella baja); and inflexibility or weakness of the quadriceps, hamstrings, and iliotibial band (ITB).

Many surgical procedures have been described for realignment of the patellofemoral mechanism, including proximal realignment procedures, distal realignment procedures, or a combination of both. Proximal realignment procedures alter the medial-lateral position of the patella through balancing of soft tissue restraints proximal to its inferior pole. Included in this category are lateral retinacular release, medial retinacular capsular and medial patellomeniscal (MPML) plication, vastus medialis obliquus (VMO) advancement, and medial patellofemoral ligament (MPFL) repair or reconstruction. Distal realignment procedures modify the medial-lateral, anterior-posterior, rotations, and proximal-distal positions of the patella by transfer of the tibial tubercle. Included in this category are anterior (Maquet[100]), medial (Elmslie-Trillat[168]) and anteromedial (Fulkerson[65]) transfer of the tibial tubercle. Literally hundreds of articles have been written on these operative procedures regarding their indications, technique, and clinical outcome, and the reader is referred to review articles for further information.[4,18,30,57,61,81,102,107,142,153,155,174]

The purpose of this chapter is to provide an algorithm of the surgical treatment of specific patellofemoral disorders. Because this is an evolving surgical field, we recognize that there are many approaches and strategies to the treatment of these problems published in the review articles cited previously. In this chapter, the technique of a proximal and distal patellar realignment, a modification of

CRITICAL POINTS

Indications

- Majority of patients with patellofemoral disorders respond favorably to conservative measures.
- Surgery required for recalcitrant cases with specific anatomic abnormalities that require correction.
- Patellar malalignment: a translational or rotational deviation of the patella relative to any axis.
- Proximal realignment procedures alter the medial-lateral position of the patella through balancing of soft tissue restraints proximal to its inferior pole.
- Distal realignment procedures modify the medial-lateral, anterior-posterior, external rotation, and proximal-distal positions of the patella by transfer of the tibial tubercle.
- Operative procedures to be described:
  - Modification of Elmslie-Trillat procedure: arthroscopic lateral release if a contracted lateral retinaculum is present, a modified VMO advancement, and a modified medial transfer of the tibial tubercle.
  - MPFL reconstruction using the quadriceps tendon based on the proximal patella, combined with a distal realignment procedure when indicated.
  - Correction patella alta.
  - ITB lengthening.
- Types of extensor mechanism problems:
  - Diffuse anterior knee pain without distinct anatomic abnormalities in alignment, subluxation, or joint damage: treated conservatively.
  - Anterior knee pain with mild to moderate abnormalities: treated conservatively.
  - Patellofemoral pain with definite anatomic signs of an extensor mechanism malalignment: candidates for surgery.
- First-time patella dislocation treatment categories:
  - Anatomic abnormalities (congenital laxity MPFL, increased Q-angle, trochlear dysplasia): treated conservatively; candidates for surgery if symptomatic.
  - ± Underlying anatomic abnormalities, major joint hemarthrosis, MRI evidence of patellar or femoral osteochondral fracture: surgery, fixation fracture, MPFL repair.
  - Conservative treatment; reevaluate stability after acute injury.

Elmslie-Trillat procedure, is described. It includes an arthroscopic lateral release if a contracted lateral retinaculum is present, soft tissue balancing of medial restraints, and a modified medial transfer of the tibial tubercle when necessary. The goals of these procedures are to release abnormal lateral tethering tissues when present, provide a balanced medial tissue–ligament complex, and realign the quadriceps-patella–tibial tubercle relationship. The procedures are performed using cosmetically appealing incisions with rapid rehabilitation, immediate knee motion, early weight bearing, and early return to function.

The second operative procedure described in detail is a MPFL reconstruction using the quadriceps tendon (QT) based on the proximal patella. This procedure is performed through a limited cosmetic incision and avoids harvesting the semitendinosus tendon, use of an allograft, and bony fixation at the patella or medial femoral attachment. This procedure has proven to be useful in revision cases that failed after a proximal realignment in which an inadequate MPFL was not addressed. The operative procedure is combined with a distal realignment when indicated, as is discussed. Other operative procedures the senior author (F.R.N.) has found useful for correcting patella alta and ITB lengthening are also described. Surgical procedures for rotational malalignment of excessive femoral anteversion and external tibial torsion are discussed in Chapter 36 and are not repeated here.

The majority of patients with patellofemoral malalignment respond favorably to conservative treatment programs, covered in detail in other publications.[2,26,36,81,90] In general, three types of extensor mechanism problems present for treatment. The first group of patients have diffuse anterior knee pain without distinct anatomic abnormalities in alignment, subluxation, or joint damage that can be identified. Commonly, these are younger athletes who are involved in multiple sports, and frequently, the only finding is the presence of tenderness of peripatellar soft tissues and the anterior fat pad tissues. On occasion, a mild joint effusion may be present. Authors have stressed that these symptoms frequently represent an overuse condition from excessive participation in athletics.[26,138] Treatment consists of allowing the soft tissues time to heal and inflammation to recede by modification of athletics followed by appropriate strengthening and stretching of the muscle groups. Specific factors that may contribute to the symptomatic state include excessive conditioning, type of sport, and duration and frequency of athletic participation. Recurrence of symptoms is not an indication for surgical treatment because distinct anatomic abnormalities of the extensor mechanism are not present. A cartilage-sensitive magnetic resonance imaging (MRI) may be helpful in recurrent symptomatic knees to determine the status of the patellofemoral joint and presence of early articular cartilage damage that is aggravated by vigorous athletic activities.

There is a second group of patients with anterior knee pain that are similar in all aspects to the first group described previously, except that mild to moderate abnormalities are detected on the physical examination. For example, there may be a lateral subluxation (lateral glide) up to 50% of the patellar width and a mild to moderate increase in the Q-angle. There may be a physiologic posterolateral ligament laxity allowing increased external tibial rotation during activities (dynamic Q-angle). These patients are also treated conservatively and are not candidates for extensor mechanism realignment surgery.

The third group consists of patients who demonstrate definite anatomic signs of an extensor mechanism malalignment who are candidates for surgery. An example is patients with symptomatic lateral patellofemoral subluxation events who do not respond to conservative treatment and have a deficient MPFL. Included in this group are patients who have had a prior patellofemoral dislocation and remain symptomatic, either with recurrence of lateral patellofemoral subluxation or a repeat dislocation event.

Nonoperative treatment of first-time patella dislocations has a redislocation rate that ranges from 14% to 57% in adult populations[151,154] and from 36% to 71% in pediatric populations.[81,131] Stefancin and Parker[158] conducted a systematic review of 70 articles that focused on the management of traumatic first-time patellar dislocations and concluded that conservative treatment was indicated initially except in specific circumstances. These included the finding of an osteochondral fracture, a substantial disruption of the MPFL, a laterally subluxated patella with normal alignment of the contralateral knee, or after failed conservative treatment or recurrent dislocations. In a study that analyzed factors associated with patellar dislocations in 40,544 injured knees in the United States, Waterman and colleagues[179] reported that the peak incidence of injury occurred between 15 and 19 years of age, and 52% occurred during athletics.

Patients with an acute lateral first-time dislocation are separated into three categories:

1. Dislocation with underlying anatomic abnormalities such as congenital laxity of the MPFL, increased Q-angle, and trochlear

dysplasia, with similar abnormalities present in the opposite extremity. These patients undergo conservative treatment and are candidates for surgery if symptoms occur in the future. These patients require an MPFL reconstruction because the hyperlaxity indicates deficiency of the medial soft tissue stabilizers. This surgery is not indicated in an acute knee injury situation and may be performed on an elective basis after the patient has recovered muscle function and conditions are more ideal for surgery.

2. Dislocation with or without underlying anatomic abnormalities, as detailed previously, in which there is a major joint hemarthrosis and MRI evidence of a well-defined or probable patellar or femoral osteochondral fracture. These patients require arthroscopic examination, removal of loose bodies, and fixation of a large osteochondral fracture when present (rare). Only under rare conditions is an MPFL repair performed, when MRI helps define the location of the tear at the patellar attachment. The majority of MPFL tears represent an interstitial disruption throughout its substance or demonstrate a combination of tears at attachment sites and are not amendable to acute repair.[66,122,141]
3. Dislocation without distinct trochlear or patellar tendon insertion abnormalities in which the primary defect is an acute disruption of the medial retinacular restraints and the MPFL. In an athletic patient desiring an early return to athletics, an MPFL repair of a well-defined patella or femoral attachment tear has been advocated in some studies. Less clear are indications for acute repair of MPFL tears that are interstitial without a patella or femoral attachment tear. These interstitial tears have the ability to heal by conservative treatment and may not require further surgery.[131,151,158] Accordingly, the senior author refers to treat these dislocations initially in a conservative manner without surgical MPFL repair.

In a majority of chronic knees with recurrent bilateral patellar subluxation or dislocation, patient education is essential to explain the goals of the operative procedure. Patients are advised that any associated articular cartilage damage will likely cause future symptoms that limit athletic participation even though the recurrent patellar instability has been successfully treated.

CONTRAINDICATIONS

The primary contraindication for extensor mechanism malalignment surgery is the absence of a distinct anatomic defect because the goal of surgery is to restore as well as possible normal alignment of the extensor mechanism. The presence of chronic recurrent anterior knee pain is not an indication for surgery when the specific etiology of the pain symptoms cannot be determined. This point is worthy of emphasis because many patients present with anterior knee pain in which the specific diagnosis is not apparent despite a thorough and careful examination and evaluation. It is probable that there are pain generation factors related to early patellofemoral cartilage deterioration that are in the initial stage of the disease course. Alternatively, peripatellar and intraarticular soft tissues may be an explainable source of pain.[51,64] A common cause of unexplained pain is a subtle infrapatellar neuroma or neuritis of the sensory nerves about the knee joint, discussed in Chapters 39 and 40.

A specific contraindications to extensor mechanism surgery is the presence of excessive hip anteversion or abnormal external tibial torsion as discussed in Chapter 36. An MRI or computed tomography (CT) scan for axial rotation of the lower extremity from the hip to the ankle is required. The measurements obtained include femoral anteversion, tibial tubercle offset, trochlear groove, and external tibial torsion as are described. The anterior knee pain is caused by excessive lateral patellofemoral forces induced by external tibial torsion or increased femoral anteversion (Fig. 35-1). In these patients, a femoral or tibial derotation osteotomy may be indicated and not a proximal or distal patellofemoral procedure.[139,164]

A distal realignment is contraindicated in the skeletally immature patient. However, a proximal realignment that may include a QT autograft (for deficient, thin MPFL and retinaculum) may be performed because there is no drilling of osseous tunnels. In cases of recurrent dislocation in a skeletally immature patient, even with an abnormal lateral patellar tendon insertion offset (increased Q-angle), the MPFL reconstruction is usually very successful in providing patellar stability.[116] After growth is complete, the need for correction of the lateral patellar tendon tibial tubercle attachment may be assessed, which is frequently not required in our experience.

A relative contraindication is the presence of patellofemoral arthritis; however, in select knees, a realignment procedure may be performed with a cartilage restoration procedure.[55,67,72,77,85,99,110,136,137,150,173]

Often, patients with chronic extensor mechanism malalignment disorders have limited their activity, gained excessive body weight and have articular cartilage damage that limits rehabilitation. These problems cause muscle atrophy of the entire lower extremity. These patients require a comprehensive evaluation and team approach involving nutrition counseling, weight reduction to normal indices, prolonged rehabilitation, occupational rating and modification, and management of patellofemoral pain before any consideration of surgery. An abnormal body mass index in a patient with symptomatic patellofemoral cartilage damage contraindicates extensor mechanism surgery.

CRITICAL POINTS

Contraindications

- Primary contraindication surgery: absence of a distinct anatomic defect.
- Excessive hip anteversion or abnormal external tibial torsion.
- Distal realignment contraindicated in skeletally immature patients.
- Patellofemoral arthritis is a relative contraindication; however, in select knees, a realignment procedure is indicated along with a cartilage restoration procedure.
- Severe lower limb muscle atrophy.
- Obesity.

BIOMECHANICS OF MEDIAL AND LATERAL PATELLOFEMORAL RESTRAINTS

Multiple factors influence patellar stability, including articular geometry, dynamic muscle actions, and passive soft tissue restraints.[4,57] The

CRITICAL POINTS

Biomechanics of Medial and Lateral Patellofemoral Restraints

- Factors influencing patellar stability: geometry trochlear groove, dynamic muscle actions, passive soft tissue restraints, angle knee flexion.
- Methods to measure patellar mobility: manual, instrumented, radiographic
- Patella most unstable at 0-30 degrees of knee flexion.
- Shallow or dysplastic trochlear groove allows patella to displace more easily.
- Patella alta results in a loss of the trochlea geometric restraint until 30-40 degrees of flexion.
- MPFL primary restraint to lateral patellar translation, providing 53%-67% restraint up to 30 degrees of knee flexion.
- Mean failure load of the MPFL 208 N.



FIG 35-1 **A** to **C,** A classic case of increased femoral anteversion, external tibial torsion, and "squinting" patella requiring femoral rotational osteotomy and possible tibial rotational osteotomy, but proximal-distal realignment. **A** and **B,** Supine external-internal hip rotation abnormality. **C,** Standing rotational malalignment shows "squinting patella" and the "miserable malalignment syndrome." **D** to **J,** Physical examination parameters are demonstrated. **D,** Lateral tibial patellar tendon attachment full extension. **E** and **F,** Q-angle increase with external tibial rotation 30 degrees of flexion. **G,** Q-angle returns to 0 with internal tibial rotation 30 degrees of flexion. **H,** Normal lateral glide 30 degrees of flexion. **I** and **J,** Manual medial glide 0 and 30 degrees of flexion. Palpation of all parapatellar soft tissues, fat pad, patellar tendon, and plica area is also performed. (**A** to **C,** Courtesy Robert Teitge, MD.)

geometry of the trochlear groove,[4] the height and slope of the lateral femoral condyle, and the angle of knee flexion all affect lateral patellar translation. Amis[4] described objective patellar stability in terms of two factors: the amount of force required to displace the patella on a given linear distance from its equilibrium position (translation) or the turning moment required to induce a rotation, such as a lateral tilt. Methods used to determine patellar mobility include manual measurement, instrumented quantitative measurement, and radiographic measurement. Kolowich and coworkers[89] measured patellar glide by dividing the patella into four quadrants and describing medial and lateral mobility as a fraction of patellar width. Normal subjects had less than two quadrants of translation with the knee flexed 30 degrees. Teitge and associates[165] developed a stress radiographic method to measure patellar medial-lateral stability. Knees of normal subjects and symptomatic patients were tested between 30 and 40 degrees of flexion with 71 N of force applied. Wide variation was noted in the normal knees because lateral displacement ranged from 1 to 32 mm, and medial displacement ranged from 2 to 22 mm. The mean difference in lateral displacement between the right and left knees was 1.3 ± 1.1 mm, and the mean difference in medial displacement was 1.2 ± 1.08 mm. The investigators determined that a difference between knees in lateral displacement of 3.7 mm, or a difference in medial displacement of 3.5 mm, was abnormal.

Hautamaa and colleagues[79] developed an instrumented measurement device to determine patellar medial-lateral translation in the coronal plane. In 17 cadaver knees, with the knee flexed 30 ± 5 degrees, 5 lb of laterally directed force produced an average of 9.3 ± 0.9 mm of lateral translation. Instrumented measurement of medial-lateral patellar translation was also conducted by Fithian and coworkers[62] in normal and symptomatic patients. Right versus left knee comparisons revealed small mean differences in the control subjects for medial and lateral patellar translation (30 degrees of flexion, 2.5-lb force, 0.1 ± 1.9 mm, and 0.2 ± 1.0 mm, respectively). Significant differences were found between the control and the symptomatic subjects in the mean differences in lateral translation ($P < .01$).

It is well appreciated that the patella is most unstable in the range of 0 to 30 degrees of flexion. When the knee is near full extension, the Q-angle is maximized because of the external rotation of the tibia. In addition, with the quadriceps muscle relaxed, the patella is not engaged in the trochlear groove and thus is easily mobilized in a medial-lateral direction. As the knee is flexed, patellar stability is increased owing to the combined tensions of the quadriceps muscles and the patellar tendon that pull the patella into the trochlear groove. A shallow or dysplastic trochlear groove allows the patella to displace more easily.[146] A patella alta condition results in a loss of the trochlea geometric restraint until 30 to 40 degrees of flexion when patellotrochlear contact finally occurs.

In regard to passive soft tissue restraints, the MPFL is the primary restraint to lateral patellar translation, providing 53% to 67% restraint up to 30 degrees of flexion.[18,31,38,47,79,132] Desio and associates[47] examined nine cadaver knees (mean age, 57 years; range, 43-70 years) at 20 degrees of flexion and reported that the MPFL provided a mean of 60% of the restraining force to lateral patellar translation. The MPML provided a mean of 13% of the restraining force; the lateral retinaculum, 10%; and the medial retinaculum and medial patellotibial ligament, 3% each. Conlan and colleagues[38] reported similar findings from 25 cadaver specimens (Fig. 35-2); the MPFL provided an average of 53% of the total restraining force followed by the MPML (22% contribution), the medial retinaculum (11% contribution), and the medial patellotibial ligament (5% contribution). Sectioning of the MPFL decreased the restraining force significantly; the average stiffness decreased from 225 N/cm in the intact specimens to 104.6 N/cm ($P = .001$).

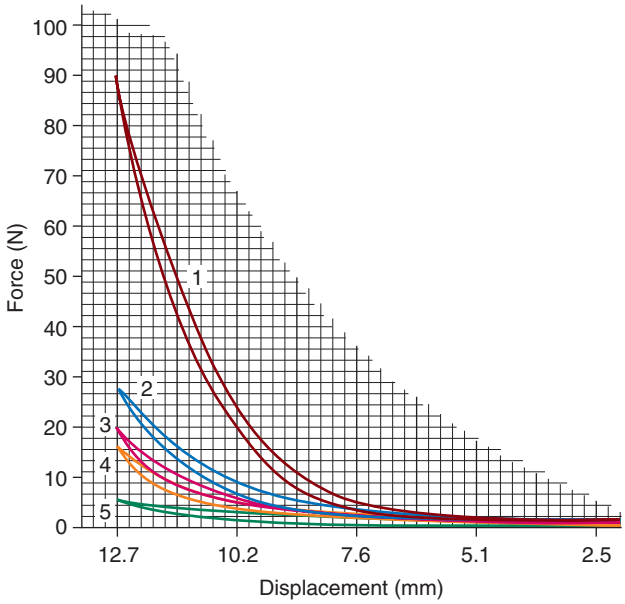


FIG 35-2 Superimposed force-displacement curves, recorded during the sixteenth testing cycle for one specimen. The medial patellofemoral ligament (MPFL) provided 67% of the medial soft tissue restraint to lateral patellar displacement (13% more than average), and the medial patellomeniscal ligament provided 12% (14% less than average). Curve 1 represents the intact ligaments, and curves 2, 3, 4, and 5 represent the MPFL, medial retinaculum, medial patellotibial ligament, and medial patellomeniscal ligament, respectively, after sectioning. (From Conlon T, Garth WP Jr, Lemons JE. Evaluation of the medial soft-tissue restraints of the extensor mechanism of the knee. *J Bone Joint Surg Am.* 1993;75:682-693.)

Nomura and coworkers[123] measured the lateral patellar translation in 10 cadaver knees (aged 45 to 60 years) with the quadriceps tensed to 10 N and a lateral force of 10 N applied before and after sectioning of the MPFL. Isolated sectioning of the MPFL significantly increased the lateral patellar translation from 20 to 90 degrees of flexion ($P < .05$).

Amis and associates[5] reported a mean failure load of the MPFL of 208 N from 10 cadaveric specimens. However, age effects may bias the results because the mean age was 70 years. These investigators reported the contribution of the MPFL in restraining lateral patellar translation was greatest with the knee at 0 degree extension. Significant increases in lateral translation occurred from 0 to 20 degrees after the MPFL was sectioned (*P* value not provided; Fig. 35-3).

PREOPERATIVE PLANNING

The physical examination is crucial in preoperative planning for patellar realignment surgery. The examination should be performed with the patient in the standing, sitting, and supine positions (see Fig. 35-1, *D* to *J*). Palpation of parapatellar soft tissues and the fat pad are performed for swelling and elicitation of pain. The examiner should look for evidence of lateralization of the extensor mechanism and tilt. The patellar compression test should be performed with flexion and extension of the knee to evaluate for articular crepitus or pain. Passive patellar tilt and tightness of the lateral retinaculum should be noted. Patellar subluxation tests (patellar glide at 0 and 30 degrees of flexion) should be performed in medial and lateral directions and patellar mobility noted. Other sources of pain such as neuroma, patellar tendonitis, synovial plica, synovitis, meniscus tears, osteochondritis dissecans, complex regional pain syndrome, and advanced tibiofemoral arthritis should be excluded.

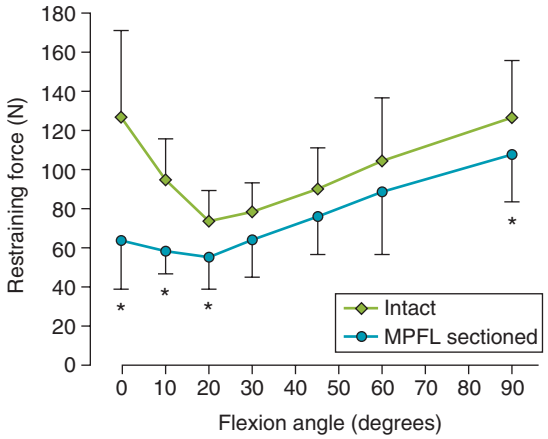


FIG 35-3 Patellar lateral displacing force at 10 mm displacement, for an intact knee with 175-N quadriceps tension, and after transection of the medial patellofemoral ligament (MPFL). The drop between the two curves shows that the contribution of the MPFL was greatest in the extended knee. Asterisks denote significant difference (*P* value not provided). (From Amis AA, Firer P, Mountney J et al. Anatomy and biomechanics of the medial patellofemoral ligament. *Knee.* 2003; 10:215-220.)

CRITICAL POINTS

Preoperative Planning

- Physical examination:
  - Palpation of parapatellar soft tissues.
  - Patellar compression test with knee flexion-extension.
  - Patellar subluxation, 0 and 30 degrees of flexion, medial-lateral.
  - Rule out other sources of pain
- Lower limb rotational alignment: femoral anteversion, tibial torsion, Q-angle 0 and 30 degrees of flexion.
- CT, MRI: trochlear dysplasia, TT/TG distance, femoral anteversion, tibial torsion.

Lower limb rotational alignment, including femoral anteversion and tibial torsion, is measured. The Q-angle is the angle formed between one line connecting the anterior superior iliac spine to the center of the patella and a second line connecting the center of the patella to the tibial tubercle. The Q-angle is measured with the knee in 0 and 30 degrees of flexion. The Q-angle arc is measured at 30 degrees with internal and external tibial rotation. Patients with a physiological laxity of the posterolateral ligament structures have an increased lateral patellar tendon deviation by virtue of the increased external tibial rotation. The clinical measurement of the Q-angle can be inaccurate for a number of reasons. If the patella is subluxed laterally, then the central reference point of measurement is also lateral, with a decrease in the Q-angle measurement unless the patella is carefully positioned within the center of the femoral groove. The Q-angle will vary depending on the amount of knee flexion and foot position; it increases with foot pronation and external tibial rotation. The proximal line to the anterior superior iliac spine is only an approximation.

Conventional radiographic techniques are often inadequate for the assessment of patellofemoral malalignment. The most commonly used Merchant technique requires 30 to 45 degrees of knee flexion. The difficulty with this technique and others is that images are not obtained near full extension where the trochlea is most shallow. As the knee flexes, the trochlear groove deepens, and the patella undergoes medialization and becomes more congruent with the femoral sulcus. The extent of trochlear dysplasia and patellar subluxation or tilt may be underestimated on the axial view owing to the amount of flexion required to obtain the image. A lateral radiograph in 30 degrees of flexion may be used to evaluate patellar height, patellar tendon length, and trochlear dysplasia. However, a true lateral radiograph, in which the distal and posterior aspects of the femoral condyles are perfectly superimposed, is required to evaluate trochlear depth, which is measured more accurately on an axial MRI.

Dejour and associates[46] analyzed the radiographs and CT scans of 143 knees with symptomatic patellar instability and 67 contralateral asymptomatic knees to determine the factors affecting patellar instability. These authors reported that trochlear dysplasia was present in 96% of unstable patellas. Dejour and colleagues[45] described a qualitative classification system of four types of trochlear dysplasia: type A, trochlear morphology preserved with a fairly shallow trochlea; type B, flat or convex trochlea; type C, asymmetry of trochlear facets with convex lateral facet and hypoplastic medial facet; and type D, asymmetry of trochlear facets and cliff pattern. Many years later, Nelitz and coworkers[117] evaluated MRI criteria of 80 knees with symptomatic patellofemoral instability to determine whether specific measurements of the femoral trochlea could be assigned to Dejour's classification system. Given the marked variation in trochlear morphology, none of the quantitative MRI measurements could be assigned to this system. A similar conclusion was reached in a study by Lippacher and associates,[96] who also noted that lateral radiographs underestimated the severity of trochlear dysplasia compared with axial MRI.

Nelitz and coworkers[117] reported median values of eight trochlear indices that distinguished Dejour type A (low-grade dysplasia) from the higher grade dysplasia categories (B-D) and, based on their findings, recommended that a two-grade system be used instead of a four-grade system. The cut-off values between low- and high-grade dysplasia were 2 mm for depth of the trochlear groove, 48% for trochlear facet asymmetry, and 11 degrees for lateral trochlear inclination.

CT and MRI have been used to assess lower limb rotational alignment and are important tests for a complete diagnosis of the anatomic abnormalities that may be present.[134] These studies obtain axial images of the patellofemoral joint at or near full extension to evaluate trochlear dysplasia and the tibial tubercle/trochlear groove (TT/TG) distance. Various investigators have studied this distance and found that it may be increased in patients with patellofemoral pain and instability.[44,88,147]

Femoral anteversion has been measured by a variety of techniques by many authors. Yoshioka and Cooke[180] measured anteversion from the bone in 32 femora and reported a mean of 13.1 ± 8 degrees (range, −11 to +22 degrees) in both males and females when the distal measurement was the tangent across the femoral condyles and a mean of 7.4 degrees when measured across the epicondyles. These authors conducted a review of the literature on this measurement and found that normal values were between 8 and 16 degrees in 12 different investigations. Teitge and associates[165] arbitrarily selected 13 degrees as the goal for correction (see Chapter 36).

The technique for measuring tibial torsion by CT has not been standardized, and wide variation exists in the literature regarding normal values. Yoshioka and colleagues[181] reported a mean lateral tibial torsion of 21 ± 4.9 degrees in males and 27 ± 11.0 degrees in females, a significant difference ($P < .05$). Eckhoff and coworkers[52] reported mean tibial "version" of 37.0 ± 1.7 degrees in control knees and 32.8 ± 1.7 degrees in a group of symptomatic knees. Turner[170] measured a mean of 19 ± 4.8 degrees in a control group compared with a mean of 24.5 ± 6.3 degrees in a group with unstable patellas. Sayli and associates[143] reported an average of tibial torsion in females of 31.07 degrees for the right side and 30.02 degrees for the left. For males, the averages were 32.7 and 35.26 degrees for the right and left sides, respectively.

Tamari and colleagues[163] conducted a reliability study that examined different methods of measuring tibial torsion. The results showed that clinical methods currently available do not accurately measure true torsion of the femur and tibia. The authors stressed that, even so, these methods may be useful for screening and descriptive purposes as indices of true torsion, and use of different reference axes could improve their reliability.

MRI has some advantages over CT, including improved ability to image cartilaginous structures, better anatomic approximation of the trochlear articular cartilage groove, and avoidance of radiation exposure. MRI also provides meaningful information about all of the soft tissue structures about the knee joint. The MRI is obtained in standard fashion, with images obtained of the hip parallel to the femoral neck and axial images obtained of the knee and ankle (Fig. 35-4). These individual images are then measured based on the techniques described by Murphy and coworkers[114] and Guenther and associates[74] (Figs. 35-5 and 35-6).

The angle between the femoral neck and the horizontal line is subtracted from the positive angle of the posterior portion of the distal femoral condyle. In rare cases, the rotation of the femoral neck and posterior femoral condyle are in opposite directions, which necessitates addition for the true femoral anteversion. The version of the knee is measured by adding or subtracting the posterior femoral angle (to the horizontal) from the proximal tibial angle (angle between the posterior aspect of the proximal tibia and the horizontal line). The tibial torsion is the difference between the proximal tibial angle and the anterior talus from the horizontal line. Chapter 36 provides a comprehensive analysis of the different anatomic landmarks and normal values that have been measured to define tibiofemoral rotational alignment and their important effects on the patellofemoral joint.

TT/TG is measured using the trochlear groove–patellar tendon insertion distance. TT/TG is measured in millimeters and is the difference from the center of the deepest point of the femoral groove to the center of the patellar tendon attachment to the tibial tubercle. This is done by superimposing the line perpendicular to these points and measuring the distance between the two lines, adjusting for magnification. Dejour and Walch[46] reported a mean TT/TG distance of 12.7 ± 3.4 mm in a group of asymptomatic knees. In a group of knees with patellar instability, the mean TT/TG distance significantly increased to 19.8 ± 1.6 mm ($P < .001$). The authors concluded that the pathologic threshold is 20 mm, which has been agreed upon by others.[164] In some knees with trochlear dysplasia, it is difficult to determine the true center point for the measurement, rendering the TT/TG offset to be inaccurate. In these knees, this measurement cannot be used as an evaluation measurement of the desired operative correction.

The TT/TG plays a role in estimating the amount of correction required at the time of the tibial tubercle realignment procedure. Intraoperatively, it is easier to accomplish linear corrections (in millimeters) than to assess angular relationships (in degrees), as in the Q-angle measurement. Importantly, this helps to prevent excessive medial translation of the tibial tubercle. The TT/TG measurement may not reflect the lateral deviation of the patellar tendon attachment with knee flexion and external tibial rotation and therefore the MRI measurements must be correlated with the physical examination. The tibial tubercle abnormality may also involve both a lateral translation and outward (external rotation) orientation.

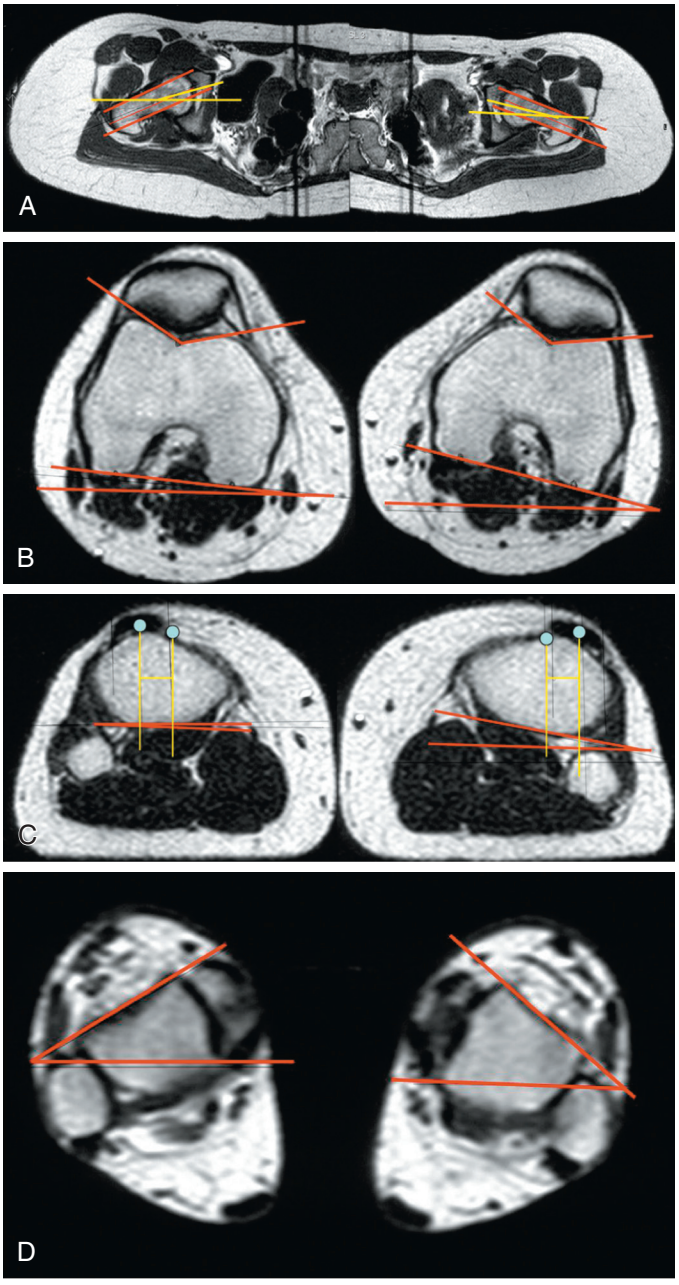


FIG 35-4 A patient's lower limb rotational magnetic resonance imaging profile. **A** and **B,** The femoral anteversion for the right knee was 16 degrees on the left and 3 degrees on the right. **B** and **C,** The knee version was 3 degrees on the right and 0 degrees on the left. The tibial tubercle/trochlear groove was 14 mm on the right and 12 mm on the left. **C** and **D,** External tibial torsion was 30 degrees on the right and 33 degrees on the left. An increased signal alternation is shown for the lateral patellar facet, which is related to the patient's primary abnormality of a bilateral external tibial torsion.

SURGICAL TECHNIQUES

The operative extremity is signed by the patient and surgeon with nursing personnel present. A time-out is performed with the patient's name, procedure, allergies, preoperative antibiotics, special precautions given and agreed upon by the surgeon, anesthetist, and nursing personnel.

The patient is positioned supine on the operating table. Under anesthesia, the peripatellar retinaculum, patellofemoral crepitation, patellar tilt, passive medial-lateral patellar glide (at 0, 30 degrees of knee flexion), and Q-angle are assessed and compared with preoperative measurements. A sterile thigh tourniquet is applied as proximal as possible, so that an intraoperative assessment of the Q-angle can be

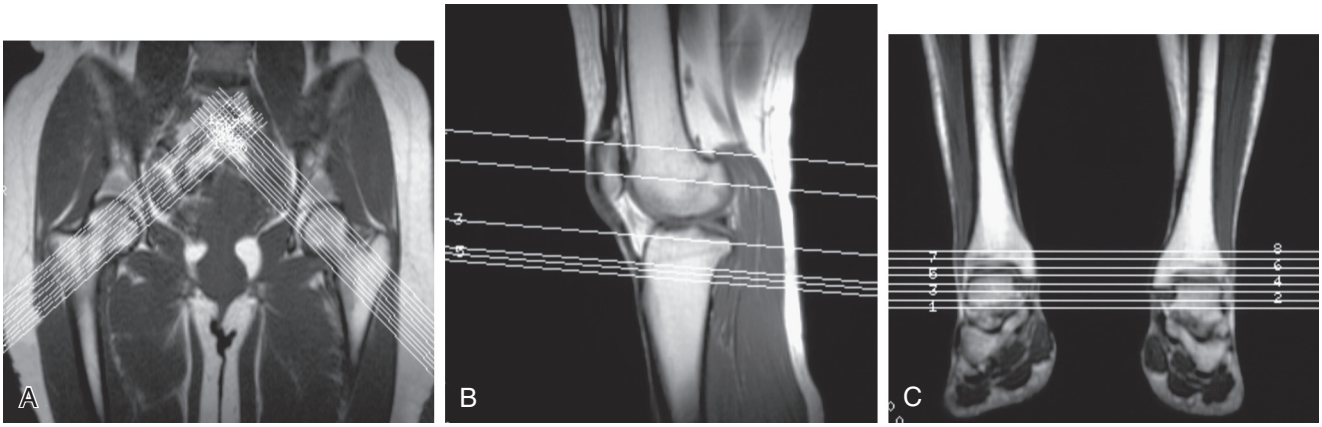


FIG 35-5 T1 Magnetic resonance imaging images obtained at the hip (**A**), knee (**B**), and ankle (**C**). This allows selection of the proper images for the measurements shown in Figure 35-6. (From Parik, SN, Noyes FR, Albright J. Proximal and distal extensor mechanism realignment: the surgical technique. *Tech Knee Surg.* 2006;5:27-38.)

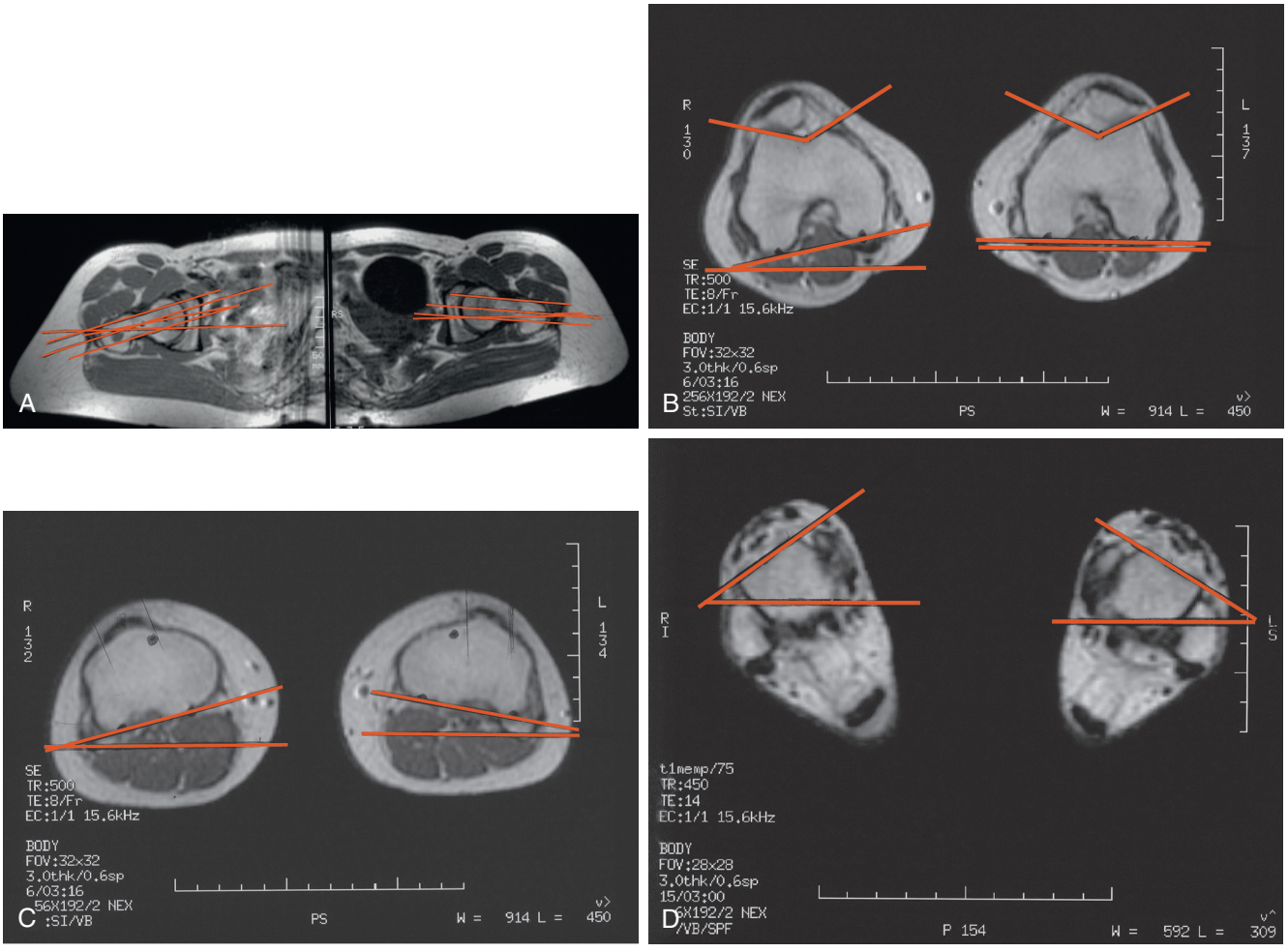


FIG 35-6 **A,** Axial view of the hip taken through the center of the femoral neck. **B,** The femoral view is taken at the proximal aspect of the femoral trochlea. **C,** The proximal tibia view is taken at the proximal insertion of the patellar tendon on the tubercle. The center of the patellar tendon is taken for the tibial tubercle/trochlear groove ratio. **D,** The axial ankle view is taken at the level of the flat edge of the talar dome (often at the same level and angle as the medial and lateral malleoli). (From Parik, SN, Noyes FR, Albright J. Proximal and distal extensor mechanism realignment: the surgical technique. *Tech Knee Surg.* 2006;5:27-38.)

CRITICAL POINTS

Surgical Technique

- Operative extremity signed by patient and surgeon with nursing personnel present.
- Patient's name, procedure, allergies, preoperative antibiotics, special precautions given and agreed upon by the surgeon, anesthetist, and nursing personnel.
- Under anesthesia, the peripatellar retinaculum, patellofemoral crepitation, patellar tilt, passive medial-lateral patellar glide (0, 30 degrees of flexion), Q-angle assessed.
- Articular cartilage lesions evaluated; loose flaps debrided.
- Lateral retinacular release
  - Only performed if patellar medial subluxation test is abnormal (patellar medial subluxation ≤8 mm on manual medial translation test, knee at 30 degrees of flexion).
  - Subcutaneous pouch created with a scissor from the anterolateral portal.
  - Arthroscopic retinacular release performed with commercial radiofrequency wand through anterolateral portal.
  - Initiated from 9 o'clock position (right knee); continued distally to 1 cm below inferior pole of patella with the knee in full extension.
  - Patellar medial subluxation test performed at 30 degrees of flexion.
  - If the release is inadequate, it is extended proximally to a 10 o'clock position.
  - Determine that there is no abnormal restraint to lateral patellar glide at 20-30 degrees of flexion, confirm absence of tight lateral tissues at 90 degrees.
- Proximal realignment
  - 3-cm vertical skin incision made along medial aspect of the patella.
  - Medial parapatellar incision made through medial retinaculum.
  - Superficial and deep retinaculum MPFL incised, 2-3 cm of VMO insertion into patella detached.
  - Quality of MPFL and medial retinaculum inspected.
  - Extensor mechanism reconstructed with medial plication of VMO and MPFL so that the VMO advancement is in line with its fibers and prior insertion.
  - VMO tissue sleeve is translated laterally and imbricated in a vest-over-pants fashion.
  - Suture placed at 1 o'clock position (right knee) so that the distal part of the VMO is brought laterally in the line of its attachment to restore normal tension at 30 degrees of flexion.
  - Suture placed at 2 o'clock position through MPFL and medial patellar insertion.
  - Suture placed at 4 to 5 o'clock position through MPML and medial retinaculum to plicate these structures in line with their normal patellar attachment.
  - Final tensioning of sutures 30 degrees of knee flexion, patella centered within trochlea.
  - Knee is taken through 0-135 degrees to observe normal tracking of the patella.
- MPFL reconstruction
  - See Table 35-1.
- Distal realignment
  - 3-cm vertical skin incision placed lateral to tibial tubercle.
  - Longitudinal incision made over periosteum along lateral border of patellar tendon.
  - Planned tibial tubercle osteotomy 15 mm wide, 8 mm thick, and 35 mm in length.
  - Hole drilled through tibial cortex; four to five holes drilled on anterolateral tibial cortex.
  - Axial 90 degrees cut made just proximal to patellar tendon insertion.
  - Drill holes along anterolateral surface of tibia connected using a 1/2-inch osteotome.
  - Osteotome carried through medial cortex directly adjacent to tibial tubercle.
  - Bone fragment mobilized and translated medially 8-10 mm based on measurements.
  - Tibial tubercle secured with a 3.2-mm drill bit.
  - When a proximal advancement is also performed, medial plication and reconstruction completed.
  - Patellar glide, tracking assessed, Q-angle measured 0 and 30 degrees of flexion.
  - Final fixation tibial tubercle three 4-mm cancellous screws
- Lateral patellofemoral (iliopatellar tract) reconstruction
  - Indicated symptomatic medial patellar subluxation, manual medial glide at 30 degrees of flexion grossly positive.
  - Goal restore lateral muscle function by reattachment of the VLO if possible and reconstruct lateral soft tissue restraints.
  - Dissect VLO attachment to the quadriceps tendon and patella.
  - Reattach VLO to lateral border of the quadriceps tendon.
  - Dissect distal VLO tendon proximally, reattach VLO as distally as possible to restore normal anatomy.
  - Knee flexed 135 degrees.
  - Semitendinosus tendon autograft used to reconstruct lateral soft tissue restraints when deficient
  - Tendon placed through a lateral patellar tunnel (10 mm) which enters and exits at the one third and two thirds junction points along the vertical height of the patella.
  - Tendon ends sutured, length 25 mm.
  - Incision made junction of iliopatellar tract and iliotibial band.
  - Usual site for graft is posterior just above the lateral intermuscular septum and proximal to the lateral epicondyle; isometric position, checked by suture at two attachment sites during 0-135 degrees of knee flexion.
  - Drill hole placed; Beath pin used to pass the two ends of the tendon into the tunnel.
  - Graft lightly tensioned with knee at 30 degrees of flexion; allow a normal 10-12 mm manual medial glide.
  - Soft tissue interference screw used for fixation.
- Patella alta correction
  - See Table 35-3.

made. Routine diagnostic arthroscopy is performed, and any intraarticular pathology is evaluated and treated. Particular attention is paid to patellar position, mobility, tracking and articular surface. Approximately one fourth of the patella should establish trochlear contact at 0 to 5 degrees of knee flexion. The medial and lateral translation of the patella is assessed at 0 and 30 degrees of knee flexion (Fig. 35-7). This is an important test because a lateral translation of the patella greater than 50% of its width indicates incompetency of the MPFL. The medial translation of the patella tests for lateral retinacular tightness, and a normal lateral translation of 10 to 12 mm should be obtained with the knee at 30 degrees of flexion. The patella and femoral groove are assessed for articular cartilage pathology or dysplasia. Articular cartilage lesions are evaluated for nature, location, and depth. The finding of loose flaps of articular cartilage requires a careful debridement; otherwise, fibrillated cartilage is left alone as it is possible to produce further damage by the debridement procedure.

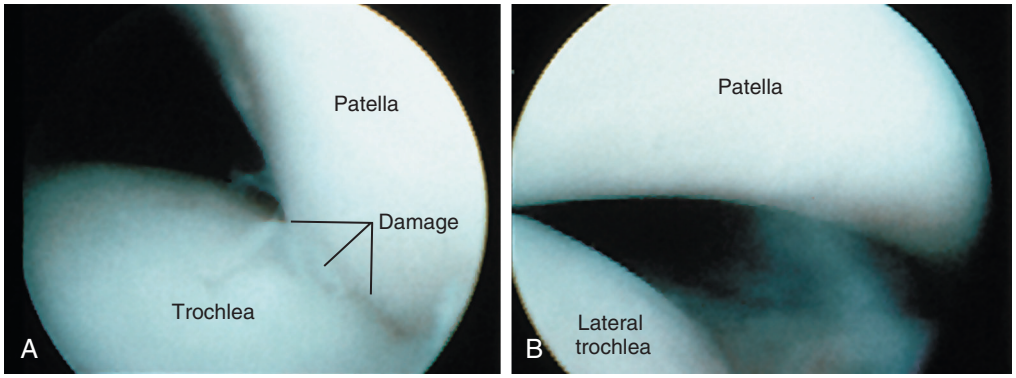


FIG 35-7 Arthroscopic medial-lateral translation manual test at 30 degrees of knee flexion shows third quadrant lateral subluxation with cartilage deterioration (**A**) and lateral subluxation viewed through the anterolateral portal (**B**).

Radiofrequency cartilage debridement devices are never used, because excessive cartilage damage occurs. Most important at the time of arthroscopy is the critical assessment of whether the realignment procedure will transfer the loading from soft or fragmented articular surface to an intact or less involved cartilage surface. The articular cartilage is graded by the classification system described in Chapter 44.[127]

Lateral Retinacular Release

A lateral retinacular release is performed only if the patellar medial subluxation test result is abnormal (the patellar medial subluxation is ≤5 mm on the manual medial translation test at 30 degrees of flexion). The goal is to perform a lateral release only when abnormally tight lateral structures and loss of normal lateral translation are demonstrated under direct visualization at arthroscopy, and not to weaken the vastus lateralis obliquus (VLO). A subcutaneous pouch is created with a scissor from the anterolateral portal over the site of the anticipated lateral release, which keeps the skin from being damaged by the intraarticular procedure. An arthroscopic retinacular release is performed using a commercial radiofrequency wand through the anterolateral portal. The lateral release is performed in two stages, from proximal to distal. The release is initiated from the 9 o'clock position (right knee) and continued distally to 1 cm below the inferior pole of the patella with the knee in full extension. The patellar medial subluxation test is then performed at 30 degrees of flexion to check for the adequacy of the release and restoration of a normal manual medial translation test. In a majority of knees, no further release is required. If the release is inadequate, it is extended proximally to a 10 o'clock position. The depth of the release involves division of the retinaculum, with care taken to avoid cutting the vastus lateralis insertion. The goal is not to perform a complete release of all lateral soft tissue restraints, which would allow the patella to be everted or have an abnormal medial translation. In select knees, there may exist excessive tightness of the VLO with marked contracture of lateral soft tissues and a tilted patella, warranting a Z-plasty lengthening through a limited lateral incision to preserve VLO function. Upon completion of the procedure, complete hemostasis is achieved by coagulation of all sources of bleeding, especially the superior lateral geniculate artery at the superolateral border of the patella.

In addition to determining that there is no abnormal restraint to lateral patellar glide at 20 to 30 degrees of flexion as already described, it is also important at 90 degrees to confirm the absence of tight lateral tissues. This is difficult to do, because lateral patellar tilting cannot be measured at high flexion angles. A measure of excessive lateral tissues can be qualitatively estimated by placing a thin-blade scissor (Metzenbaum) beneath the lateral retinaculum and observing, with knee flexion, if there is a bowstringing effect with excessive tension in the lateral soft tissues. The surgeon should always be able to gently lift and anteriorly displace the lateral soft tissues away from the lateral femoral condyle.

Proximal Realignment

The patient positioning and arthroscopic examination are performed as already described. The knee is fully flexed before inflation of the tourniquet to lengthen the quadriceps muscle. A 3-cm vertical skin incision is made along the medial aspect of the patella. The subcutaneous tissues are undermined sufficiently to create a skin flap that will allow the skin incision to be moved in proximal-distal and medial-lateral directions using four vein retractors. This decreases the length of the skin incision and allows for a cosmetic approach. The proximal retraction exposes the distal quadriceps tendon, superomedial border of the patella, and VMO insertion. The distal retraction exposes the medial border of patella, medial retinaculum, and distal retinaculum fibers referred to as the MPML. A medial parapatellar incision is then made through the medial retinaculum, extending from approximately 2 cm proximal to the superomedial aspect of the patella to the medial border of patella and progressing distally to the patella. The superficial and deep retinaculum MPFL is incised, taking care to avoid cutting through the muscle or underlying synovium. The proximal extent of the incision extends in the QT, thus detaching 2 to 3 cm of the VMO insertion into the patella. The free medial edge of the retinaculum is grasped, and the underlying synovium is dissected free. This allows the VMO, MPFL, and MPML tissue sleeve and medial retinacular tissues to be mobilized for later tensioning and advancement as required. The joint is not entered, and the synovium over the femoral condyle and medial pouch is protected to lessen postoperative scar formation at this location.

The quality of the MPFL and medial retinaculum is inspected, and a decision is made whether a MPFL reconstruction is necessary. The medial tissues should be 3 to 4 mm in thickness. A thin, abnormal medial retinaculum and MPFL indicates that a MPFL graft is required, to be described later. A mistake often made is to accept marginal MPFL tissue because it is relatively easy at this point to augment the surgery with a MPFL graft. If there is adequate MPFL tissue by visual inspection, proximal realignment is commenced. The closure procedure to be described next is performed if no distal realignment is planned; otherwise, the proximal closure is performed after the distal realignment described.

The extensor mechanism surgery involves medial plication of the VMO and MPFL so that the VMO advancement is in line with its fibers and prior insertion. The VMO tissue sleeve is translated laterally and imbricated in a vest-over-pants fashion. Three No. 1 nonabsorbable sutures are used. Three Ellis clamps are placed at the VMO center, MPFL, and MPML medial anatomic sites to reestablish a normal tension. The first suture is placed at the 1 o'clock position (right knee) so that the distal part of the VMO is brought laterally in the line of its attachment, overlapping the superior medial border of the patella and QT by 5 to 10 mm to restore normal tension at 30 degrees of flexion. The second suture is placed at the 2 o'clock position through the MPFL and medial patellar insertion. The third suture is placed at the 4 to 5 o'clock position through the MPML and medial retinaculum to plicate these structures in line with their normal patellar attachment. It is important that the final tensioning of the sutures be performed with the knee at 30 degrees of flexion with the patella held centered within the trochlea. The mistake is to adjust the tension with the knee at extension. The tightening procedure at 30 degrees of flexion allows for a normal slackness of the medial tissues and the MPFL and for a normal lateral glide of 10 to 12 mm (~25% patella width). The mistake is to apply too much tension that limits normal lateral translation, which restricts postoperative knee motion and potentially results in medial facet cartilage damage from excessive pressure. The lateral subluxation of the patella is also assessed at 0 degrees to ensure that a normal medial restraint exists, preventing abnormal lateral patellar subluxation at knee extension. The knee is taken through a range of motion of 0 to 135 degrees to observe normal tracking of the patella. If the sutures disrupt, this is an indication that the medial advancement was excessive and the suture placement and tensioning procedure is repeated.



FIG 35-8 Demonstration of complete dislocation of patella at the time of surgery after multiple prior operative procedures. A reconstruction of the medial patellofemoral ligament was required. (From Parik, SN, Noyes FR, Albright J. Proximal and distal extensor mechanism realignment: the surgical technique. *Tech Knee Surg.* 2006;5:27-38.)

Medial Patellofemoral Ligament Reconstruction

MPFL deficiency is diagnosed when the patella translates greater than 50% of its width from the center of the sulcus. Symptomatic patients with chronic dislocations or subluxations will frequently demonstrate patellar translation of 75% to 100% (of its width) under manual pressure at both 0 and 30 degrees of flexion (Fig. 35-8). An MPFL reconstruction is always indicated in revision surgery when a prior proximal realignment procedure has failed and a residual lateral patellar subluxation exists. The intraoperative examination includes the lateral subluxation test at 0 and 30 degrees of flexion. The balancing of the medial soft tissue restraints requires that tension be restored at both knee positions to guide the patella into the trochlear and resist lateral patellar subluxation at full extension and with knee flexion. The operative procedure includes a balancing of three structures, namely, the MPFL, VMO, and medial retinacular fibers, including the MPML. Preoperative radiographs and MRI define whether a patella alta or lateral patellar tendon offset exists, requiring distal tibial tubercle correction.

The patient is placed in a supine position on the operating table with the foot of the bed flexed 20 to 30 degrees. A high-thigh tourniquet is placed (sterile or nonsterile) so that the entire lower extremity is draped and provides an estimate of patellofemoral alignment. A diagnostic arthroscopy is performed as already described and the condition of the patellofemoral articular cartilage documented. Medial-lateral glide tests are performed at 30 degrees of flexion to determine the resisting function of the medial and lateral soft tissue restraints. The leg is elevated, exsanguinated, and the tourniquet inflated.

The operative steps of MPFL reconstruction are shown in Figure 35-9 and summarized in Table 35-1. A 5- to 6-cm incision is made at the medial border of the patella and extended 1 to 2 cm proximally (see Fig. 35-9, *A*). A dissection of the skin flaps is carefully performed beneath the fascia layer to preserve the skin blood supply. This allows the incision to be mobilized in a proximal-distal direction, providing a cosmetic incision one half the usual length. The dissection is carried over the medial aspect of the knee and medial epicondyle to the adductor tendon. A head light and careful dissection technique is used at this point to avoid the infrapatellar nerve branches, which can result in injury and a painful neuroma. The medial nerves are highly variable in their course as shown in Chapter 1. The skin flaps are further developed in all directions to be able to reach the proximal aspect of the QT, a distance of 6 to 7 cm from the patellar insertion for the planned turn-down of the medial QT graft.

A medial incision through the medial retinaculum is made 5 mm from the medial border of the patella from the inferior to superior pole. The medial incision is extended distally to the level of the joint. This is an incision similar to that used for a proximal realignment procedure already described, which is performed in conjunction with the MPFL reconstruction.

Using an Army/Navy retractor, the insertion of the VMO into the QT is identified. A ruler is used to measure the MPFL attachment length from the medial border of the patella, past the epicondyle to the adductor tubercle and tendon. This provides the length of the QT graft to be harvested (see Fig. 35-9, *B*). A ruler is used to mark the medial QT to harvest a graft 8 mm wide, 6 mm thick, and usually 60 mm in length. A partial- or full-thickness medial QT graft is harvested 5 mm from the medial border of the VMO to allow for VMO tendon-to-tendon suturing after harvest. The proximal graft never extends into the proximal QT-muscle junction because this would weaken the attachment. Two incisions are made into the medial QT at the marked graft site, avoiding penetration into the capsule. The incision connects to the prior medial patellar retinaculum incision. The medial QT graft

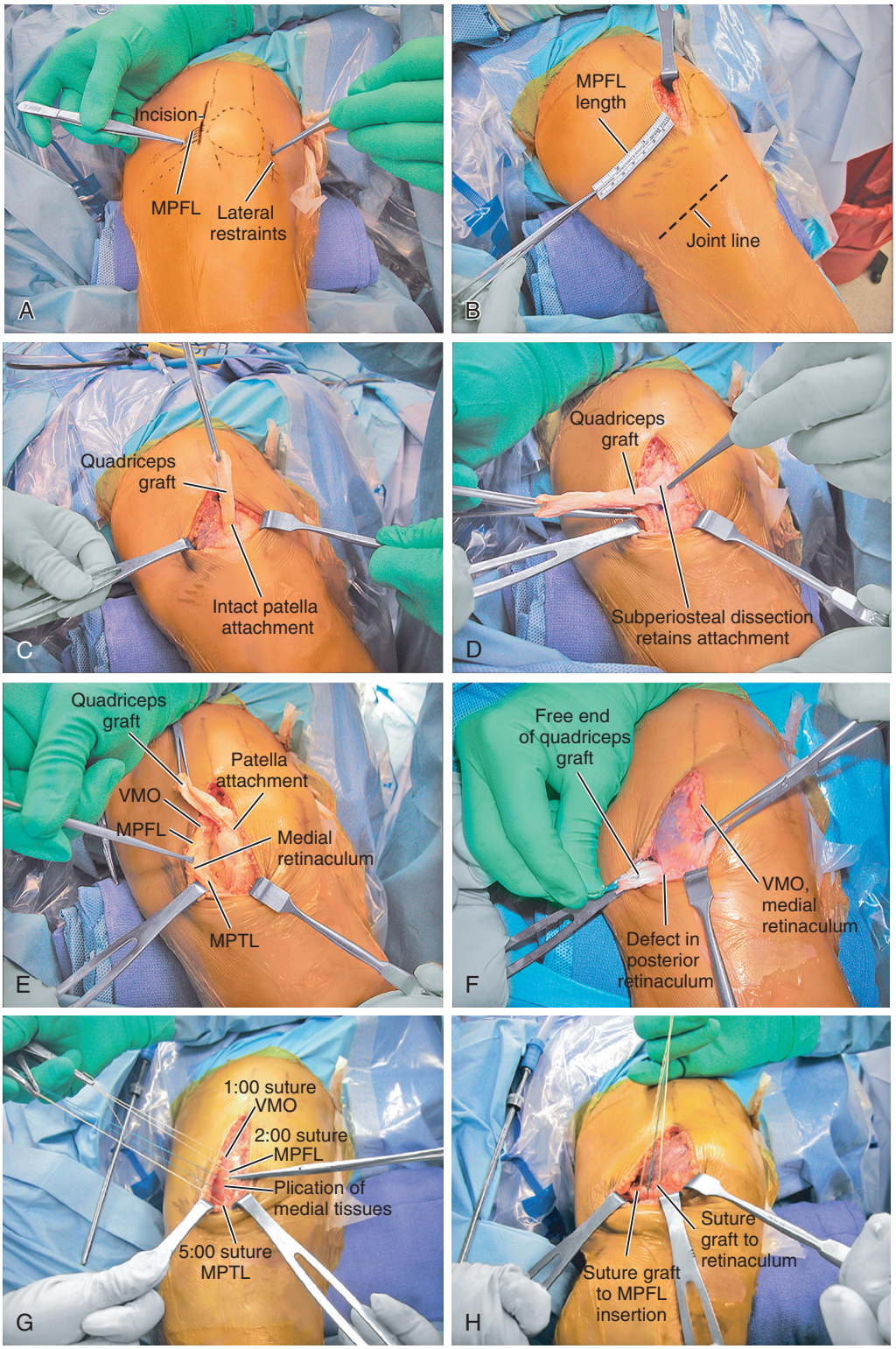


FIG 35-9 Medial patellofemoral ligament (MPFL) reconstruction with quadriceps tendon. **A,** After arthroscopic evaluation, the planned surgical incision (*thick black line*) along the medial aspect of the patella is shown. **B,** Measurement of length of graft needed (60 mm); limited cosmetic incision is shown. **C,** A medial full-thickness quadriceps tendon graft, 60 mm × 8 mm wide (measured to the superior edge of the patella) is harvested with the patellar attachment retained. In some knees, a partial-thickness autograft provides a suitably sized graft. Two to 3 mm of remaining quadriceps tendon is left attached to the vastus medialis obliquus (VMO) for later closure. **D,** Completed 60-mm quadriceps tendon graft after dissection from the superior-medial patella down to the normal anatomic attachment site of the MPFL. **E,** Dissection deep to the medial retinaculum and above synovial pouch and MPFL, medial patellomeniscal ligament (MPML). **F,** Puncture of the medial retinaculum, posterior to the medial femoral epicondyle at the native MPFL attachment just anterior to the adductor tendon, with passage of graft beneath retinaculum. Setting of the normal tension of the medial soft tissues (see text). **G,** Imbrication of the VMO, medial retinaculum, MPFL, and MPML. **H,** Suturing of the quadriceps graft to the MPFL native femoral attachment, with a backup suture to the adductor tendon. The graft and medial tissues are not overtensioned and should allow a normal lateral translation (glide) of 25% patellar width. (From Noyes FR, Albright J. Reconstruction of the medial patellofemoral ligament with autologous quadriceps tendon. *Arthroscopy.* 2006;22:904e1-904e7.)

TABLE 35-1 Key Points to Successful Medial Patellofemoral Ligament Reconstruction

Preoperative

1. Complete rehabilitation for muscle and motion deficits.
2. Comprehensive evaluation of patellar soft tissue restraints, Q-angle (0 and 30 degrees of flexion) and with internal-external rotation, standing rotational alignment, and gait (see text).
3. Complete radiographic and MRI evaluation, femoral anteversion, hip rotation, trochlear dysplasia, trochlear groove, patellar height, patella-trochlear contact at 0 degrees, lateral tibial tubercle offset, external tibial torsion.

Operative Steps

1. Confirm preoperative examination under anesthesia, medial-lateral translation tests, lateral translation >50% patellar width 0 and 30 degrees of knee flexion, measure resting Q-angle at 0 degrees and Q translation arc with internal-external tibial rotation at 30 degrees.
2. Arthroscopic procedure defines patellofemoral abnormalities, confirms medial-lateral translation 30 degrees, and need for proximal realignment. Limited arthroscopic lateral release only with contracted lateral tissues and absence of normal medial glide (see text).
3. High thigh tourniquet to view entire lower extremity and patellofemoral tracking.
4. Cosmetic limited medial incision, medial to patellar border and 1-2 cm proximal to patella; undermine incision for skin mobilization.
5. Careful subcutaneous dissection medially to adductor magnus tendon, avoiding infrapatellar nerves and proximally along medial VMO and quadriceps tendon.
6. Incise medial retinaculum adjacent to patella to the joint line, confirm thin medial tissues, insufficient MPFL requiring graft reconstruction.
7. Harvest full-thickness medial quadriceps graft 60 mm long, 8 mm wide, and 6 mm thick, leaving 5 mm medial VMO tendon for closure. Connect medial quadriceps tendon incision to prior medial retinaculum incision.
8. Careful subperiosteal dissection quadriceps graft attachment proximal and medial aspect patella to native MPFL attachment.
9. At the posterior junction of the medial retinaculum, preserve medial synovial pouch, penetrate retinaculum just above adductor tendon, rotate graft 90 degrees at patella. Pass free end of graft beneath retinaculum to exit through retinaculum hole overlying native MPFL attachment and adductor tendon.
10. Perform proximal realignment advancing the entire medial retinaculum sleeve and VMO, carefully setting tension to allow normal 25% patellar width lateral glide at 30 degrees of flexion (see text). Perform knee flexion-extension to observe normal patellofemoral tracking.
11. Determine graft tension with knee flexion 0-120 degrees. Graft should not piston or be tight with increasing knee flexion. Quadriceps graft sutured to native MPFL attachment posterior to femoral epicondyle and just anterior to adductor tendon under minimal graft tension to avoid overconstraining normal lateral patellar glide. Perform medial-lateral glides tests again and full flexion to confirm normal medial restraint and patellar stability restored. Closure of remaining quadriceps tendon incision.
12. Additional sutures to reinforce quadriceps graft at medial patellar attachment may be required.

MPFL, Medial patellofemoral ligament; *MRI*, magnetic resonance imaging; *VMO*, vastus medialis obliquus.

is transected proximally, preserving its attachment to the superomedial border of the patella (see Fig. 35-9, *C*). The three tendon components of the QT (rectus, confluent VMO-VLO, intermedius) are carefully identified, and the proximal end of the graft is sutured with a baseball-type stitch (No. 1 nonabsorbable suture).

With care taken not to transect the graft, subperiosteal dissection of the patellar attachment of the graft is performed to a point approximately 30% of the proximal height of the patella at the normal MPFL attachment (see Fig. 35-9, *D*). Later in the procedure, appropriate sutures are placed to secure the proximal patellar attachment of the QT graft to adjacent tissues. Preserving the medial synovial pouch and avoiding penetration of the joint, the medial retinaculum is bluntly dissected off the capsule past the medial epicondyle to the adductor tendon (see Fig. 35-9, *E*). At the junction immediately anterior to the adductor, distal to the insertion of the VMO, and posterior to the medial epicondyle, a hole is punctured in the retinaculum with a right-angle hemostat (see Fig. 35-9, *F*). The graft is turned 90 degrees and folded over on itself at the proximal medial portion of the patella. The free end of the QT graft is passed beneath the retinaculum, adjacent to the VMO attachment, and through the created retinaculum hole to exit and lay over the native MPFL attachment just posterior to the femoral epicondyle and anterior and slightly distal to the adductor tendon attachment (Fig. 35-10).

The final proximal realignment tensioning procedure is then performed following the steps previously outlined (and after the distal realignment when added to the overall realignment surgery). With the knee flexed 30 degrees and the patella located within the trochlea, the medial plication procedure is performed, including closure of the QT

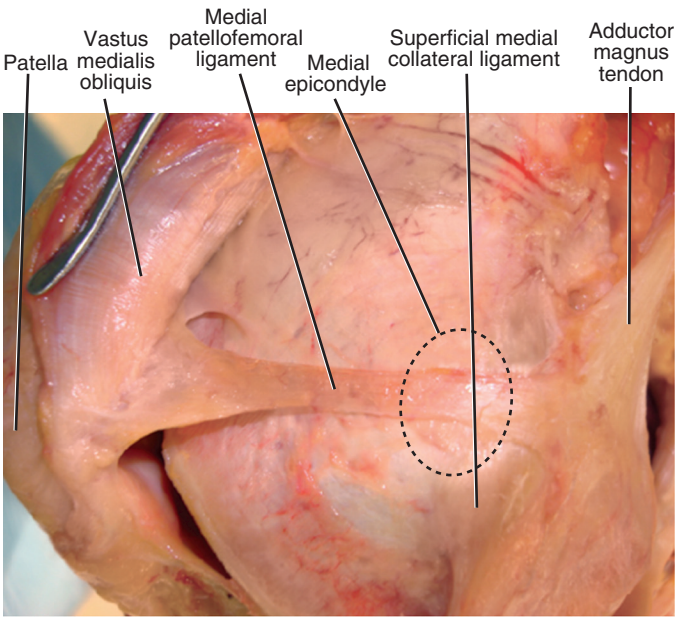


FIG 35-10 Medial patellofemoral ligament inserts into a depression behind the medial epicondyle and blends with fibers of the superficial medial collateral ligament.

graft harvest site. The entire medial soft tissue and VMO is grasped with an Ellis clamp placed at the 1 o'clock (VMO), 2 o'clock (MPFL), and 4 o'clock (retinaculum, MPML) areas and gently brought in line of its attachments to determine the amount of plication and overlap for suturing. Three sutures are placed at these respective sites with care taken not to overtension the repair. It is emphasized that there must always be a normal lateral glide of 25% of the width of the patella at 0 and 30 degrees of flexion under manual pressure to avoid limiting normal patellar mobility. The imbrication procedure restores the patella to its reduced position (see Fig. 35-9, *G*).

The final portion of the procedure consists of suturing the MPFL-QT graft to the native femoral MPFL attachment. The end of the graft is held with the clamp at the MPFL attachment, and the knee is flexed from 0 to 120 degrees to confirm that the graft is isometric and not too proximal or distal. Two nonabsorbable sutures are placed into the soft tissue of the native MPFL attachment and sutured to the graft with minimal to no tension on the graft. If the tissues are not substantial, then a suture anchor is used. The remaining graft lays over the distal adductor tendon, and a third suture of the graft to the adductor tendon is used as a back-up. The sutures avoid penetrating the medial geniculate artery at the posterior border of the VMO and the medial infrapatellar nerve when present (see Chapter 1). Again, emphasis is made that no tension is applied to the graft, which simply lies in the native MPFL attachment location, because the tension in the medial soft tissue restraints has already been set by the medial retinaculum suturing just described. Again, the lateral glide test is performed to make sure the graft is not under any resting tension and that the combined medial soft tissue imbrication and MPFL reconstruction is initially lax and allows the patella to be displaced 25% of its width, restoring the normal length of the medial soft tissues. After suturing is complete, the knee should be ranged from 0 to 135 degrees, restoring normal patellofemoral tracking. An additional two to three absorbable sutures are then placed in a figure-eight fashion, reinforcing the fixation of the graft to the medial border of the patella (see Fig. 35-9, *H*).

The advantage of this procedure is that no bone tunnels are placed into the patella or medial femoral condyle, as described in other MPFL reconstructions. The graft is sutured along the path of the native MPFL by pliable soft tissue fixation, reproducing patella and femoral attachments. It is not necessary to add a harvest of a medial hamstring tendon. Another advantage is the entire medial retinaculum and remaining MPFL and MPML tissues are restored to a normal tension. The disadvantage of the procedure is related to the medial QT graft harvest because this adds additional postoperative pain in comparison with a hamstring autograft. In knees with previous dislocations or revision cases, the restoration of the normal proximal VMO tension is performed with closure of the proximal harvest site. It is important that MPFL reconstruction be performed in the majority of knees with a prior dislocation because the medial retinacular restraints are usually thin with no identifiable competent MPFL structure. The resultant cosmetic appearance of the incision and restoration of full knee flexion are demonstrated in Figure 35-11.

The senior author has noted in the 2 to 4 postoperative week time period, the occurrence of pain with knee flexion along the MPFL reconstruction that reflects soft tissue graft and retinaculum irritation from the immediate motion program. There is a balance to be established with gentle range of motion of 0 to 90 degrees to prevent adhesions and allow tissue edema and healing. Antiinflammatory medications and cryotherapy are important. A local injection of an anesthetic into the medial retinaculum can be used in select cases to allow the therapist to mobilize knee flexion. In some cases, a gentle range of motion under chemical analgesia is necessary where only light pressure is required to restore full range of knee motion. This allows the patient to immediately regain knee motion and the relief of pain is somewhat dramatic. The surgeon should be aware of this problem, inherent in all MPFL reconstructions and necessity to restore early normal knee flexion.

Distal Realignment

A lateral radiograph is used to confirm that a normal patellar tendon length and patellar height exist, as described in Chapter 38. A 3-cm vertical skin incision is placed lateral to the tibial tubercle (Fig. 35-12). The subcutaneous tissues are undermined sufficiently to create a skin flap that allow the skin incision to be moved in all directions and maintain a small cosmetic incision. The patellar tendon insertion is identified and a retractor placed behind it to identify its insertion site on the tibial tubercle. A longitudinal incision is made into the periosteum along the lateral border of the tibial tubercle patellar tendon insertion. Subperiosteal dissection is carefully performed to expose the anterolateral aspect of the tibia, reflecting the periosteum and the muscular origin of the anterior compartment. Care is taken in the dissection not to enter into the muscle tissues to decrease postoperative pain and swelling. The planned tibial tubercle osteotomy is 15 to 20 mm in width, 8 mm thick, and 35 mm in length. At the distal extent of the osteotomy, a hole is drilled through the tibial cortex, using a 3.2-mm drill bit and drill guide. This is to prevent the osteotomy from extending distally. The drill hole is placed beneath the anterior tibial periosteum, which is preserved to maintain the normal

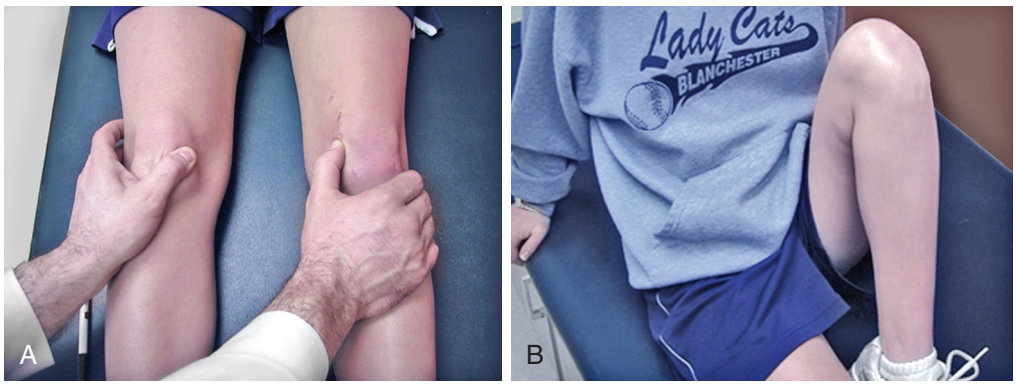


FIG 35-11 Three-month postoperative case demonstrating excellent healing and function of reconstructed medial patellofemoral ligament in resisting lateral patellar translation (**A**), and full flexion of the knee (**B**). (From Noyes FR, Albright J. Reconstruction of the medial patellofemoral ligament with autologous quadriceps tendon. *Arthroscopy.* 2006;22:904e1-904e7.)

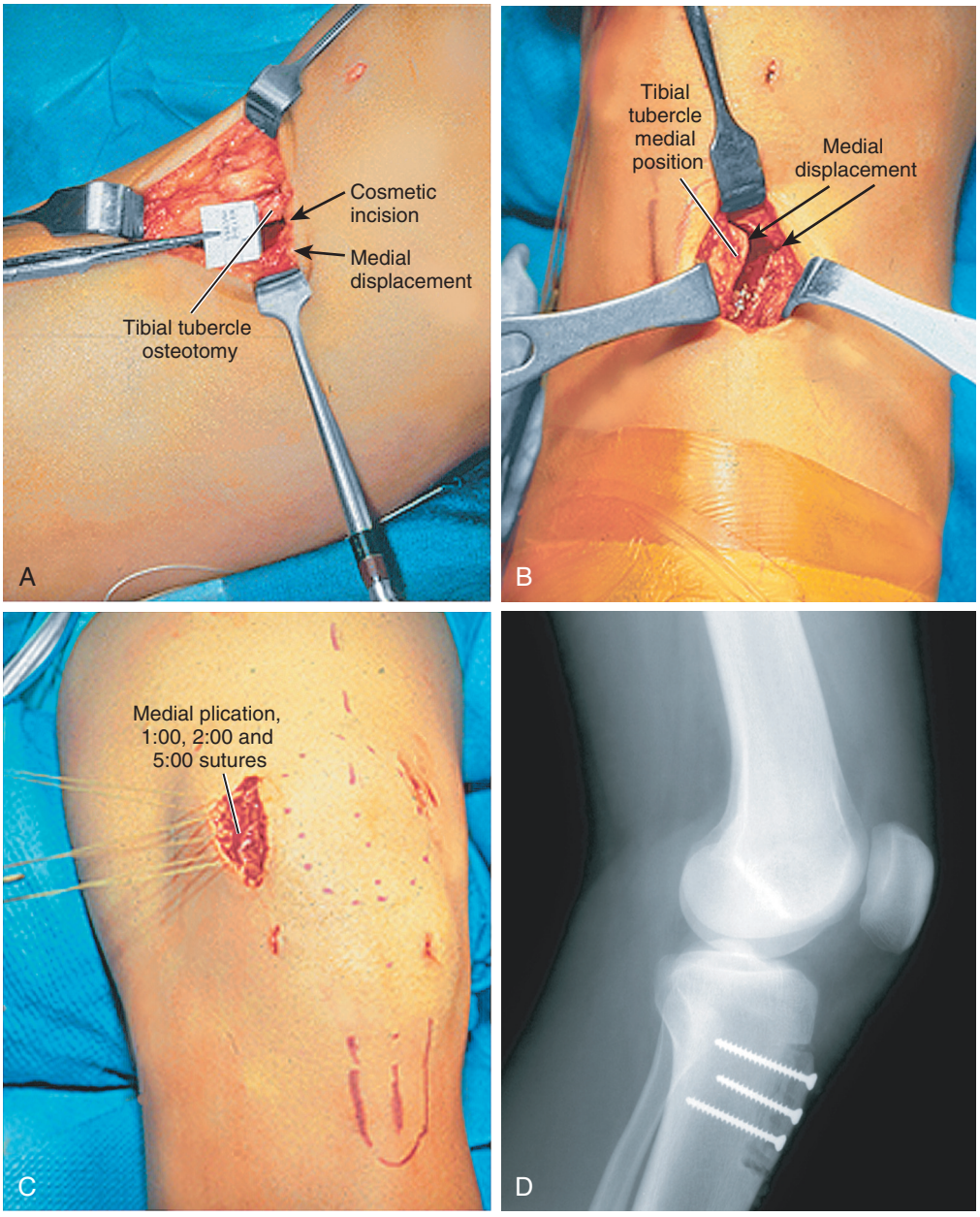


FIG 35-12 Demonstration of a proximal-distal realignment when a medial patellofemoral ligament reconstruction is not required. **A,** The medial retinaculum and vastus medialis obliquus 2 cm above the patella are advanced in line of their insertions to restore patellar stability. **B,** The millimeters of tibial tubercle medial displacement required are measured at surgery. **C,** A dovetail tibial tubercle osteotomy has been performed, maintaining the distal and medial soft tissues. **D,** Postoperative radiograph. (**A** to **C,** From Parik SN, Noyes FR, Albright J. Proximal and distal extensor mechanism realignment: the surgical technique. *Tech Knee Surg.* 2006;5:27-38.)

proximal to distal position of the tibial tubercle. Similarly, four to five holes are drilled on the anterolateral tibial cortex along the line of the planned osteotomy; the angle of the osteotomy is oblique by 15 to 20 degrees from a posterolateral-to-anteromedial direction. An axial 90-degree cut is made just proximal to the patellar tendon insertion to mark the proximal extent of the osteotomy. This step-cut produces a bony buttress to prevent proximal migration of the tibial tubercle. The drill holes along the anterolateral surface of the tibia are then connected using a half-inch osteotome. The osteotome is carried through the medial cortex directly adjacent to the tibial tubercle, while the distal periosteal hinge remains intact. The bone fragment is carefully mobilized and translated medially, according to a predetermined amount based on TT/TG distance correction. This distance is usually 8 to 10 mm. The tibial tubercle is secured with a 3.2-mm drill bit.

The tourniquet is deflated so that there is no pressure on the quadriceps muscle during assessment of quadriceps function. When a proximal advancement is also performed, it is at this point that the medial plication and reconstruction are completed as already described. The ability to glide the patella medially and laterally by one quadrant, with the knee in 30 degrees of flexion, is verified. The patellofemoral tracking is next assessed by taking the knee through a range of motion. The patella should remain centralized within the femoral sulcus, with no medial or lateral tilt or subluxation in flexion or extension. The Q-angle is assessed using a goniometer, with the knee at 0 and 30

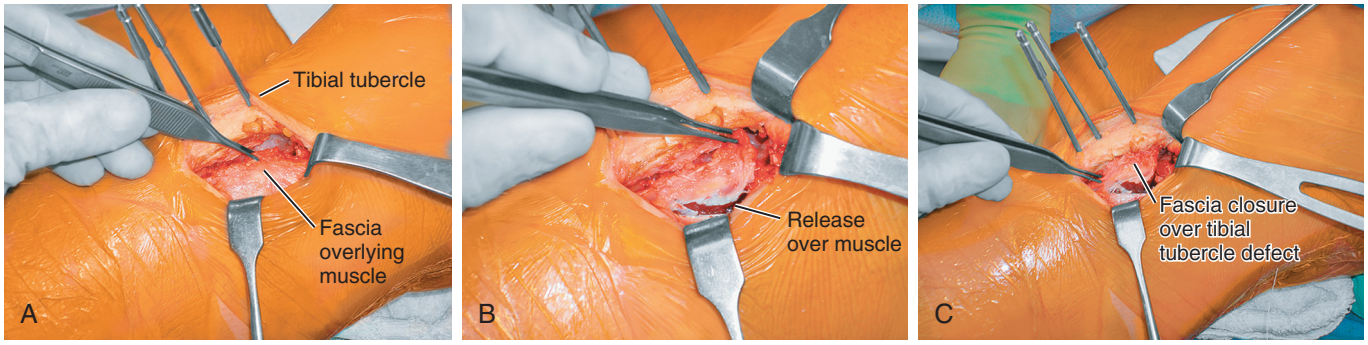


FIG 35-13 Technique for cosmetic closure of lateral tibial tubercle defect after medial displacement. **A,** The gap between the lateral soft tissues and tibial tubercle is shown. **B,** Incision 15 mm lateral to the defect and at the proximal extend of the soft tissue flap. **C,** Rotation of soft tissue flap into defect with closure to the soft tissues along the lateral border of the tibial tubercle. This simple transposition of adjacent soft tissues prevents the lateral indentation commonly visible after tibial tubercle medialization.

degrees of flexion in neutral, internal, and external rotation. The Q-angle should always be positive, even with maximum internal tibial rotation. The correction based on preoperative TT/TG distance and the preoperative measurements is confirmed. These measurements are only approximations, and the goal is to restore as closely as possible a normal lateral patellar tendon attachment. Once the ideal position is determined, the final fixation of the tibial tubercle is done with three 4-mm cancellous screws. A compression technique with overdrilling the tibial tubercle is performed, and the screw head is countersunk to prevent prominence under the skin. If the bone quality is questionable, cortical screws can be used for bicortical fixation. The screws should be tightened gently to avoid fracturing the tibial tubercle.

At this point, hemostasis is achieved, followed by the closure of the wound in layers. There is a lateral tibial tubercle defect after the medial displacement that requires a simple shifting of the anterolateral fascial tissues (Fig. 35-13), which closes the defect and prevents a cosmetic unappealing indentation and concavity in this area after healing of the incision. The skin is closed using subcuticular stitches. A Hemovac drain is not used. A double-cotton, double-Ace compression dressing is applied, and the lower extremity is placed in a brace. Cryotherapy is instituted immediately after surgery in the operating room.

Lateral Patellofemoral (Iliopatellar Tract) Reconstruction

The anatomy of the lateral iliopatellar tract is presented in detail in Chapter 1. The iliopatellar tract is divided into the superficial oblique retinaculum and a second layer termed the *deep transverse fibers*. The attachment of the vastus lateralis to the superolateral aspect of the patellae is shown in Chapter 1.

As previously discussed, a lateral release should only be performed when there is an abnormal contracture of these tissues, with an inability to perform a manual lateral translation (glide) at 30 degrees of flexion. This condition may occur with joint arthrofibrosis or from a developmental standpoint referred to as *lateral patellar compression syndrome* that may be associated with a bipartite patella. In the 1970s and 1980s, some authors recommended a lateral release that included resection of the VLO attachment for lateral patellar subluxation.[104-106] It is now appreciated that the appropriate treatment of a lateral patellar subluxation is restoration of the MPFL and not weakening the VLO. There remain descriptions of the lateral release of soft tissues and VLO to the extent that the patella can be everted, which should be avoided.

The syndrome of a medial subluxation after a release of the lateral restraining structures and VLO has been identified by numerous authors.[19,83,86,125,149] Nonweiler and DeLee[125] reported on a series of five patients who presented with medial subluxation, pain, swelling, and giving way following isolated lateral release. All underwent reconstruction of the lateral retinaculum. An average of 3.3 years postoperatively, four of the five had no symptoms of instability, and the patellar stability was similar to the contralateral limb. Hughston and Deese[83] described a series of 60 knees treated after failure of a lateral release to improve symptoms. Thirty knees had developed medial subluxation of the patella, 17 of whom underwent an isolated lateral release and 13 of whom underwent a concomitant proximal or distal realignment. Twenty-seven of these 30 knees had disabling symptoms postoperatively, and all demonstrated marked quadriceps atrophy and retraction of the VLO. Biedert and Friederich[21] described 41 cases of patients who had pain after a lateral release; 32 also had medial subluxation of the patella.

Christoforakis and colleagues[35] measured the effects of lateral release on the lateral stability of the patella in cadaveric specimens (aged 65-82 years). The patella was displaced 10 mm laterally while measuring the required force, with 175 N of quadriceps tension. Patellar force-displacement behavior was measured from 0 to 60 degrees of knee flexion in intact knees and then after lateral release, which extended from the proximal limit of the lateral retinaculum to Gerdy's tubercle. At 0, 10, and 20 degrees of flexion, the mean force required to displace the patella (10 mm laterally) was significantly reduced after lateral release by 16 to 19% ($P = .002$ to $.001$). The investigators concluded that the procedure decreased the lateral stability of the patella in normal elderly knees.

The diagnosis of a symptomatic medial patellar subluxation is not difficult. The patient complains of medial subluxation events that produce partial giving way and pain that commonly occurs with normal activities of daily living. The patient can usually distinguish the medial subluxation position of the patella from a lateral subluxation. The manual medial glide at 30 degrees of flexion is usually grossly positive, producing patient apprehension. The defect in the VLO attachment is palpable, and the patella can be everted. There is often extensive muscle atrophy that requires months of physical therapy before surgery.

The goal of surgical treatment is to restore lateral muscle function by reattachment of the VLO if possible and to reconstruct the lateral soft tissue restraints. The skin incision for the surgical approach depends on the placement of incisions from prior surgery and either a medial or lateral parapatellar incision provides exposure. It is necessary to dissect the VLO attachment to the QT and patella. It is usually

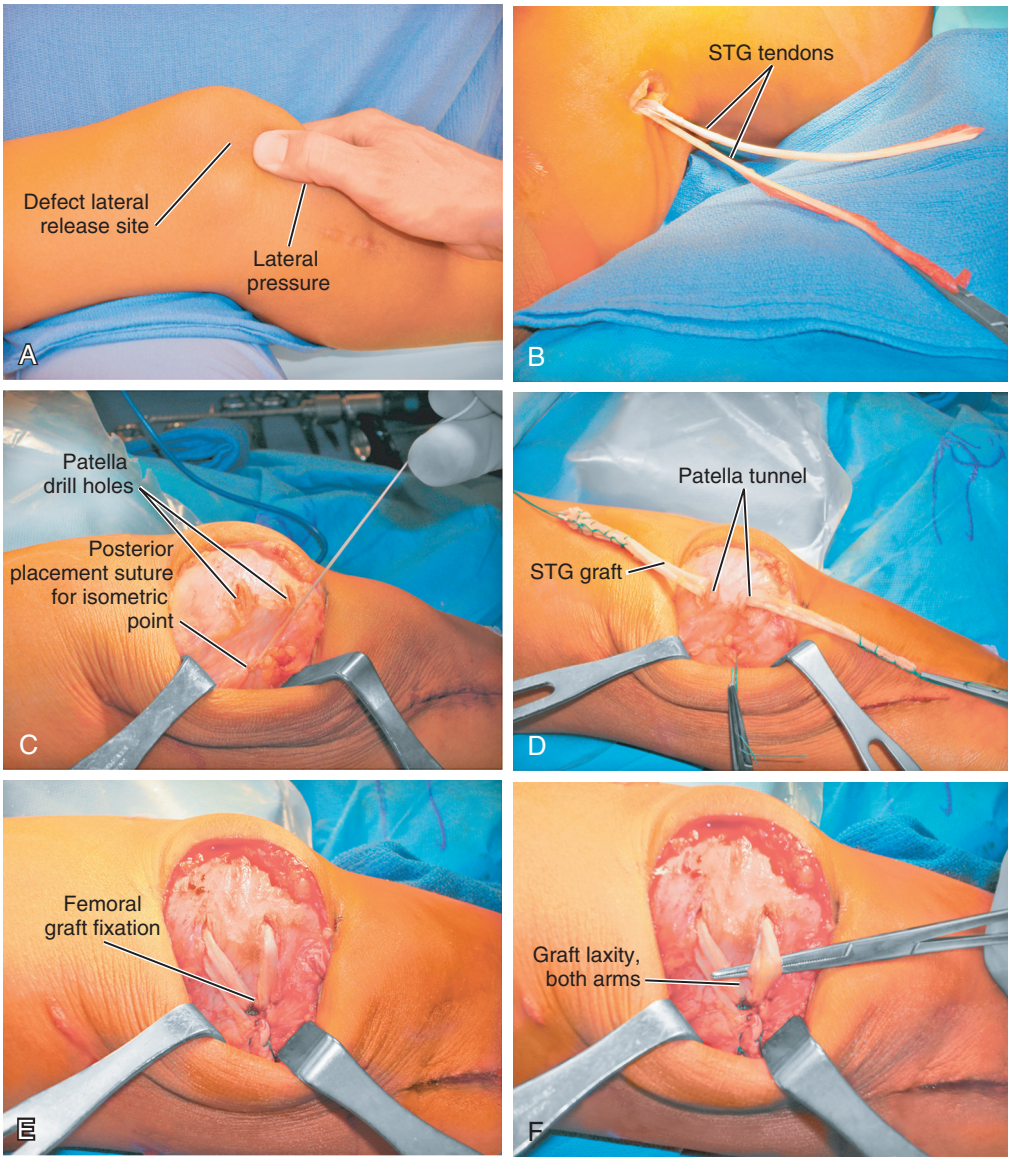


FIG 35-14 Surgical demonstration of semitendinosus-gracilis (STG) autograft lateral reconstruction for symptomatic medial subluxation after a prior proximal realignment involving complete release of the lateral soft tissue restraints. **A,** A positive manual medial glide test shows obvious medial subluxation. **B,** Harvest of STG autograft through limited medial incision. **C,** Placement of two drill holes on the lateral border of the patella avoids a tunnel into the anterior cortex, which would weaken the patella. A suture is placed to identify the location of the lateral femoral tunnel for the STG graft. The previously transected and scarred lateral retinaculum is not disturbed. In this case, the vastus lateralis obliquus insertion is shown to be intact. If it was previously released, it would be dissected and reattached. **D,** Passage of the two arms of the STG graft through the lateral patellar tunnel. **E,** Final STG graft fixation. **F,** Demonstration that the graft is under no tension with the patella at 30 degrees of knee flexion; however, the graft is adjusted to resist a 10-mm medial patellar glide (see text).

possible to reattach the VLO to the lateral border of the QT. Often, a layer of scar tissue at the site of the prior release is identified, and it is a simple matter to excise the scar and reattach the VLO. It may also be possible to reattach a portion of the VLO to the superior lateral border of the patella; however, frequently a contracture and shortening of the VLO have occurred. The distal VLO tendon is dissected proximally and an attempt made to reattach the VLO as distally as possible to restore normal anatomy. The knee is flexed to 135 degrees to ensure the distal attachment of the VLO does not limit flexion or that the sutures pull out from a shortened VLO muscle.

The reconstruction of the lateral soft tissue restraints is accomplished with a semitendinosus tendon autograft, which is preferred over an allograft to avoid delayed remodeling (Fig. 35-14). If the semitendinosus tendon is small in diameter, the gracilis tendon is also incorporated into the construct. The tendon is placed through a lateral patellar tunnel, which enters and exits at the one third and two thirds junction points along the vertical height of the patella and avoids a tunnel in the anterior patellar cortex which has been associated in some cases with fractures. The lateral patella tunnel for the graft is approximately 10 mm in length, with a diameter matching that of the

tendon. Each end of the tendon is sutured with a baseball-type stitch and the length adjusted so that 25 mm of tendon will pass into the femoral tunnel used for the posterior attachment of the graft.

An incision is made at the junction of the iliopatellar tract and the ITB to expose the lateral aspect of the femoral condyle and lateral intramuscular septum. The isometric point for the femoral tunnel on the lateral femoral condyle is identified by using a suture fixed to the lateral patellar tunnel site and a guidewire placed at the lateral femur with full extension-flexion produced. The usual site for the graft is posterior just above the lateral intermuscular septum and proximal to the lateral epicondyle. A drill hole is placed at this site and a Beath pin used to pass the two ends of the tendon into the tunnel. A soft tissue interference screw is used for fixation. The tension in the graft before fixation is adjusted by placing the knee at 30 degrees of flexion and allowing a normal 10- to 12-mm manual medial glide. The graft should be under no tension in its resting state and only under tension to resist the manual medial patellar displacement test previously described. It is important not to overtension the graft and produce a lateral soft tissue contracture, which would potentially lead to articular cartilage damage (iatrogenic lateral patellar compression syndrome). Following tensioning, the knee is taken through a full range of motion. The wound closure is routine, and a drain is not necessary. The rehabilitation program is the same as that described for an MPFL reconstruction.

Patella Alta Correction

Patella alta represents a congenital abnormality of an increased vertical position of the patella attributable to an elongated patellar tendon, resulting in the patella not engaging within the trochlea until the mid-flexion range of motion. Patients typically present with significant complaints related to lateral patellar subluxation or dislocation that can affect all activities of daily living. Ward and coworkers[178] studied patients with patella alta with MRI under partial weight-bearing loads that induced quadriceps tension at various knee flexion angles and reported increased lateral displacement and lateral tilt at 0 degree of knee flexion (Fig. 35-15). There was a decrease in patellofemoral joint contact area in subjects with patella alta at all knee flexion angles. The data did not explain the basis for anterior knee pain in symptomatic patella alta patients, and the authors recommended the need for further studies. In most patients, the patella alta abnormality does not occur in isolation, and other abnormalities of the extensor mechanism are usually present. Some patients with patella alta and anterior knee pain and joint swelling have signs of patellofemoral crepitus and arthritis (usually in the distal third of the patella) but do not experience subluxation symptoms.

The major factors for patellar instability include patella alta, MPFL deficiency, trochlear dysplasia, and patellar tendon tibial tubercle lateral offset, as already discussed. Associated increased femoral anteversion and increased external tibial torsion add to the predisposition for lateral patellar instability. The decision to correct an abnormal patellar tendon length to allow the patella to engage within the trochlea would only address one aspect of the problem in cases of lateral patellar subluxation or dislocation. Additional correction of an MPFL deficiency and lateral patellar offset may be required. At surgery, the tibial tubercle is advanced distally to restore a normal patellotrochlear relationship. In this corrected position, the medial-lateral manual translation tests determine the new tension relationship of the MPFL and lateral restraints and the need for rebalancing the tension by surgical correction.

There are differences in the methods used for measurement of patellar height regarding the anatomic points selected and the values used for the classification of an alta, normal, or infera position of the patella. Seil and colleagues[145] compared five different patellar height ratio techniques in 21 patients and reported that the classification of alta, normal, and infera depended on the normative data chosen for each technique. The normal values for patellar height and those selected to determine the presence of patella alta and patella infera are shown in Table 35-2. Noyes and colleagues[128] conducted a study to determine normal right to left patellar vertical height ratios within the same individual in a group of 51 patients (102 knees). The difference in the vertical height ratio of the patella between these two methods ranged from 0% to 9%, with an average difference of 3%. Large variations existed in the ratios among individual patients (range, 0.75-1.46).

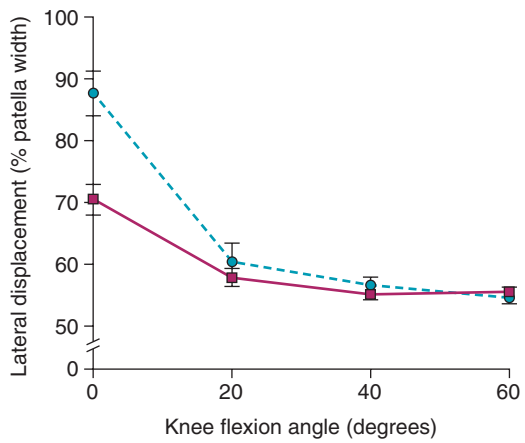


FIG 35-15 Lateral patellar displacement as a function of knee flexion angle in controls (*solid line*) and subjects with patella alta (*dashed line*). Error bars indicate one standard error. The difference between the patella alta group and the control group at 0 degrees of knee flexion was significant ($P < .05$). (From Ward SR, Terk MR, Powers CM. Patella alta: association with patellofemoral alignment and changes in contact area during weight bearing. *J Bone Joint Surg Am.* 2007;89:1749-1755.)

TABLE 35-2 Published Values for Patellar Height: Normal, Alta, Infera

Study	Technique Source	Normal Mean ± SD (Range)	Alta	Infera
Insall & Salvati[84] (1971)	Authors' own	1.02 ± 0.13 (0.7-1.3)	>1.2	<0.8
Blackburne & Peel[23] (1977)	Authors' own	0.8 ± 0.13 (0.54-1.06)	>1.2	<0.5
Caton et al[33] (1982)	Authors' own	<1.2	>1.2	≤0.6
Linclau[95] (1984)	Caton et al	1.0 ± 0.08 (0.84-1.16)	>1.2	<0.8
	Blackburne & Peel	0.8 ± 0.10 (0.61-1.01)	>1.0	<0.6
Noyes et al[128] (1991)	Caton et al	1.04 ± 0.13 (0.75-1.36)	NA	≥15%*
	Blackburne & Peel	0.84 ± 0.14 (0.61-1.33)	NA	≥14%*
	Insall & Salvati	1.05 ± 0.11 (0.86-1.28)	NA	≥11%*

*Decrease in patellar height between the involved and the contralateral knee.
SD, Standard deviation.

Shabshin and coworkers[148] reported patellar tendon length to patellar length on MRI in 245 patients using the Insall-Salvati method. The results of the measurement are shown in Figure 35-16. The patients were not selected out as to diagnosis and were referred for orthopedic evaluation for a number of disorders; thus it is not known how many patients had a clinical diagnosis of a patellar subluxation or dislocation, which is an unaccounted variable in the study. In addition, the measurements were made with the knee in full extension with the possibility of an inaccurate length for the patellar tendon in a resting position.

Biedert and Albrecht[20] described an MRI method to measure the true articular cartilage sagittal patellotrochlear relationship at 0 degree extension. The ratio of the patellar to trochlear cartilage contact was described as a percentage and the mean index was 32 ± 12%. An index value greater than 50% indicated a patella infera and less than 12.5%, a patella alta (Fig. 35-17). This is a useful index in surgical cases of patella alta in determining at surgery the distal displacement of the tibial tubercle to establish a normal patellotrochlear relationship. The authors believe this index is useful along with other published indices (e.g., Blackburn-Peel,[23] Linclau,[95] and Caton and colleagues[33]). The potential problem with the patellotrochlear index method is the inability to obtain a quadriceps contraction during the MRI to define that the patella is at a maximum proximal relationship. In the absence of a quadriceps contraction, the patella may appear to be lower and the maximum patellar height will not be measured.

In Figure 35-18, radiographs of a 16-year-old male who had multiple recurrent lateral patellar dislocations are shown that demonstrate

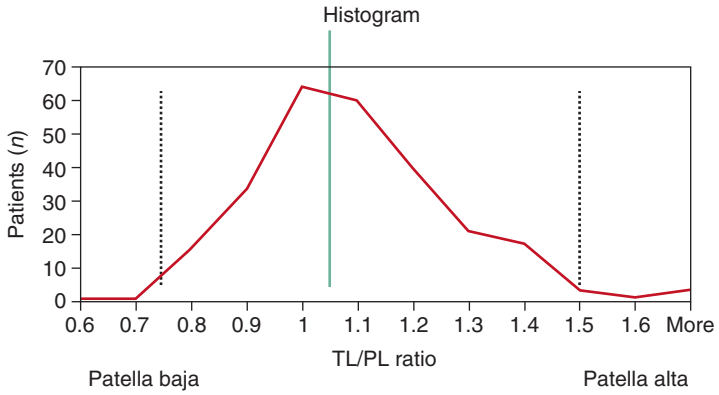


FIG 35-16 Histogram demonstrates the distribution of the Insall-Salvati Index (ISI) applied to the study population. Note the asymmetric curve, which is skewed toward the higher ratios. The *green line* shows the mean (1.05), and the *dashed lines* represent the proposed normal range, which is defined by calculating the extreme 2.5% of the ratio at each end of the curve. *PL*, Patellar length; *TL*, patellar tendon length. (From Shabshin N, Schweitzer ME, Morrison WB, Parker L. MRI criteria for patella alta and baja. *Skeletal Radiol.* 2004;33:445-450.)

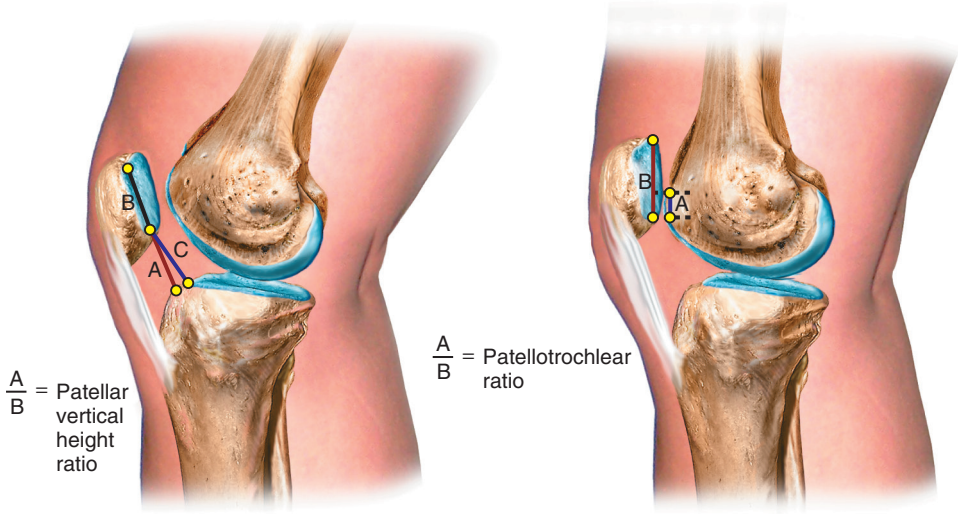


FIG 35-17 **Left,** Method used to determine patellar vertical height ratio on lateral radiograph with a quadriceps contraction to show the maximum elevated position of the patella. The numerator, *line segment A*, is the distance between the most ventral (anterosuperior) rim of the tibial plateau and the lowest end of the patellar articular surface. The denominator, *line segment B*, is the maximum length of the patellar articular surface. An alternative numerator, *line segment C*, locates the tibial reference point on the middle of the tibial plateau. The patellar vertical-height ratio equals A/B or C/B. **Right,** Alternative patellotrochlear ratio measurement. The mean ratio is 32 ± 12%; >50% indicates patella infera, and <12% indicates patella alta.

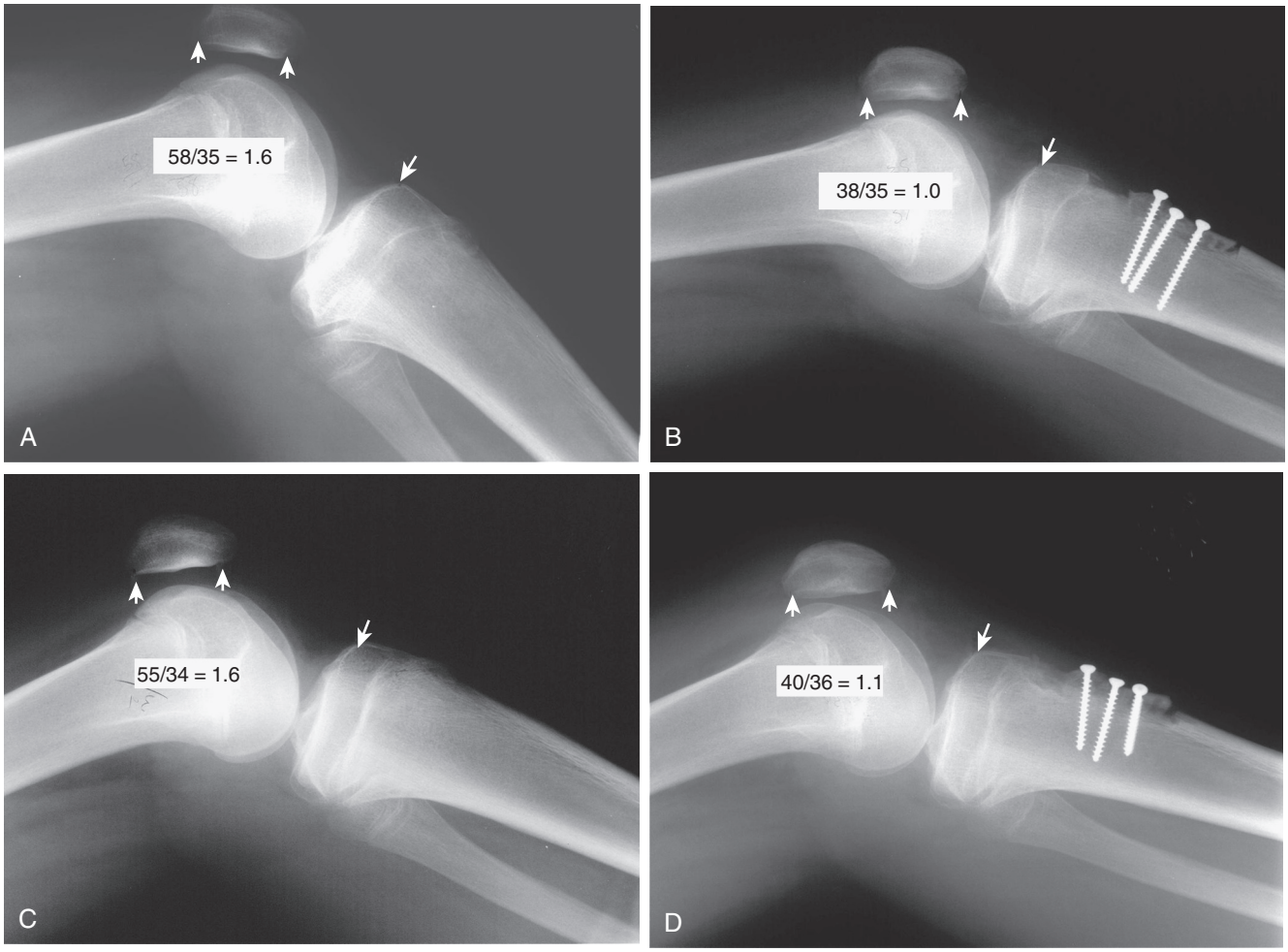


FIG 35-18 Demonstration of a symptomatic bilateral patella alta with multiple recurrent dislocations. **A** and **B,** Preoperative and postoperative radiographs of the left knee. **C** and **D,** Preoperative and postoperative radiographs of the right knee. A medial patellofemoral ligament reconstruction was performed with a quadriceps tendon autograft as previously described on both knees. The right knee was initially performed, followed 4 months later by the left knee reconstruction. The patient's growth was complete and the tibial tubercle physes closed. The patient had an uneventful successful recovery without further patellar dislocations and participates in athletic activities.

bilateral patella alta. The Linclau ratio was 1.6, and the patellotrochlear index demonstrated no patellar contact at full extension. The corrective bilateral operative procedures had to be delayed 2 years to allow for completion of growth. A distal transfer of the tibial tubercle was performed to restore these two indices to normal values. Lateral radiographs taken at surgery are required to measure that a normal patellar height ratio has been restored and to prevent too distal a transfer and a patella infera condition. A concurrent MPFL reconstruction was also performed.

Neyret and colleagues[119] measured the patellar tendon length on lateral radiographs and MRI in 42 knees with patellar dislocation and 51 control knees. These investigators reported that the patellar tendon was 8 mm longer in the former group (mean length, 52 ± 6 m, and range, 39 to 61 mm; and 44 ± 7 mm and range, 32 to 62 mm, respectively, $P < .0001$). The wide range in patellar length shows the marked variation in patellar length from patient to patient even in the dislocation group. The Caton-Deschamps index was abnormal (>1.20) in 48% of the dislocation group and 12% of controls, and the values for the MRI were 60% and 12%, respectively. There was no difference in the distance of the tendon insertion on the tibia compared with the tibial plateau. The authors suggested that when a distal transfer of the patellar tendon in patella alta cases is performed, a tenodesis of the tendon at the tibial insertion site would restore normal tendon length and decrease side-to-side patellar mobility, given the high percentage of associated trochlear dysplasia. The senior author has no experience with this operative technique and this technique is avoided because a concern exists of tilting the inferior pole of the patella in a posterior direction.

Lancourt and Cristini[93] used the Insall-Salvati method; however, these authors used the patellar tendon length as the denominator and the patellar length as the numerator, which is the reverse of the original description of this method. They reported that the Insall-Salvati index was 1.0 in normal patients, 0.80 in dislocating patella (alta), and 0.86 (infera) in chondromalacia (patella grating, crepitus), with the differences statistically significant ($P < .05$). The authors believed that patella alta results in patellotrochlear incongruity and risk for early patellofemoral arthritis. Marks and Bentley[101] used a similar Insall-Salvati method in 51 patients with patellar chondromalacia graded at arthroscopy and reported no definite relationship to patella alta, suggesting that recurrent dislocation provided a stronger relationship.

Al-Sayyad and Cameron[3] reported short-term improvements in patellofemoral scores (1-4 years postoperatively) in 25 patients with painful patella alta and no history of patellar dislocation who underwent distal transfer of the tibial tubercle. The authors did not provide a system for computing the measurement of the millimeters of distal transfer of the tibial tubercle. A patient satisfaction rate of 88% was reported. Patients with a normal-appearing trochlea had higher scores compared with those with trochlear articular cartilage damage. The study reported that cartilage lesions typically involved the inferolateral portion of the lateral patellar facet, with possible involvement of the lateral region of the trochlea. The authors stressed that patella alta may be a source of anterior knee pain not responsive to nonoperative treatment as well as leading to the development of patellofemoral arthritis.

The indications for correcting patella alta are recurrent dislocations and symptomatic anterior knee pain (and an obvious patella alta) that have not responded to conservative treatment. Commonly, associated patellar crepitus and articular cartilage degeneration are present, and the patient is advised that symptoms of anterior knee pain related to the arthritis will continue. It is thus preferable to correct a symptomatic patella alta condition early before the development of cartilage deterioration. At the time of a proximal or distal realignment, a patella alta results in the distal patella articular cartilage not engaging the trochlea but lying in a more cephalad position. It is at this point that lateral subluxation or dislocation events occur, particularly with a dysplastic shallow trochlea. In addition to correcting the patella alta, a functional MPFL is required because there is a loss of the normal geometric restraint provided by the trochlear groove. There are no established clinically proven rules regarding when correction of an abnormal patellar height is required or the amount of correction to be obtained at surgery. The goal is to restore a normal patellar height index for the index chosen and to confirm that patellotrochlear contact (~30% of the inferior patellar articular cartilage) has engaged the trochlear at full extension. These rules are empiric; however, they do provide the surgeon with guidelines to follow during the surgical technique. The operative steps for the correction of a patella alta are shown in Table 35-3.

TABLE 35-3 Operative Steps in the Technique to Correct Patella Alta

1. Determine abnormal patellar height indices shown in Figure 35-17. Determine millimeters of distal tibial tubercle transfer necessary to restore patellar height indices to normal values.
2. Determine whether any other abnormality present requiring correction: MPFL, lateral restraints, patellar tendon offset (TT/TG ratio).
3. Supine position operating table, lower limb draped with high thigh tourniquet.
4. Arthroscopic procedure performed, determine articular cartilage condition of patellofemoral joint, patellotrochlear dysplasia. Medial-lateral manual glide at 30 degrees of knee flexion to confirm function MPFL, medial and lateral restraints.
5. Skin incision 4 cm just lateral to tibial tubercle, excise lateral and medial patellar tendon retinaculum, preserve blood supply fat pad and patellar tendon. Subperiosteal limited dissection medial and lateral to tibial tubercle 35 mm.
6. Osteotomize tibial tubercle 8 mm depth × 35 mm length × 15-20 mm width. Leave the tibia section proximal to the tibial tubercle which is not included in the osteotomy as described for distal realignment technique. Remove the anterior tibial cortex just distal to the tibial tubercle the calculated distance to allow distal tibial tubercle displacement. Displace the tibial tubercle distally, avoiding recession, and correcting abnormal lateral tibial tubercle offset when present. Temporary fixation by single 2.7-mm drill bit.
7. Lateral radiograph or fluoroscopy at 0 and 30 degrees of knee flexion, measure patellar height indices and adjust tibial tubercle position to restore normal index indices. Patella should engage trochlea at 0 degrees of knee flexion (~ 30% patellar cartilage length).
8. Internal fixation tibial tubercle at new distal position, three cancellous 4.0-mm lagged screws or cortical screws as required.
9. Repeat medial-lateral manual translation (glide) tests at 0 and 30 degrees of knee flexion. Majority of knees will require MPFL reconstruction through limited medial parapatellar incision (steps already described). Lateral restraints usually do not require tensioning or release.

MPFL, Medial patellofemoral ligament; *TT/TG*, tibial tubercle/trochlear groove.

Trochleoplasty

In knees with recurrent patellar dislocation and severe trochlear dysplasia, trochleoplasty has been performed in several studies with the goal of creating a more congruent joint with improved bony stability and containment of the patella.[8,24,42,48,63,115,129,144,166,171,175,176] Currently, indications include repeat patellar dislocations (more than three episodes), type B or D trochlear dysplasia (Dejour[43]), abnormal patellar tracking with a J-sign, TT-TG distance greater than 10 to 20 mm, lateral patellar subluxation of 75% or more, and a dome-shaped trochlea on a perfect lateral radiograph.[27,37,49,130,156] Many patient candidates will have undergone prior unsuccessful patellofemoral procedures. The articular cartilage in the trochlea should be normal or nearly normal (ICRS grade 1 or 2). The most common risks of this operation include damage to the articular cartilage in the patellofemoral compartment, modification of the congruency in the joint, alterations of joint kinematics, and arthrofibrosis, all of which may lead to early arthritis.[130]

The most common open trochleoplasty techniques are the Dejour sulcus-deepening procedure,[45] the Bereiter distal femoral subchondral bone deepening technique,[176] and the Goutallier recession-wedge osteotomy procedure.[10] In the Dejour technique, subchondral cancellous bone under trochlea is removed with a high-speed burr until it is flush with the anterior femoral cortex. The trochlea is osteotomized over the position of the desired new groove, lateralized according to the preoperative TT-TG value. The trochlear facets are pushed posteriorly until they are flush with the femoral cortex, and then they are fixed with anchors and sutures. Dejour and coworkers perform concomitant soft tissue procedures as required for extensor mechanism abnormalities.[42,129]

The Bereiter technique involves removal of a 3- to 5-mm trochlear cartilage flap. The underlying cancellous bone is burred and deepened until the groove is flush with the anterior femoral cortex. A V-shaped groove is fashioned on the cancellous bone. The osteochondral flap is fixed on the newly shaped bone with tape and anchors. This technique was modified to be performed arthroscopically by Blond and Schottle.[25] Several investigators have performed this technique concurrently with an MPFL graft reconstruction.[8,24,115]

In the Goutallier procedure, the prominent groove is removed to the level of the anterior femoral cortex; no deepening of the groove is performed. The bone wedge is removed, pressure is applied on the trochlea posteriorly, and fixation is accomplished with cancellous screws. This procedure is designed to be simpler and less invasive than the others previously described because the trochlea is not violated.

In our opinion, although it would be ideal to correct a trochlear dysplasia, the problem remains that the patella is still flattened and dysplastic, and it is therefore not possible to restore a normal patellofemoral contact pattern by surgically deepening the trochlear groove. Abnormally high patellofemoral contact pressures may occur after

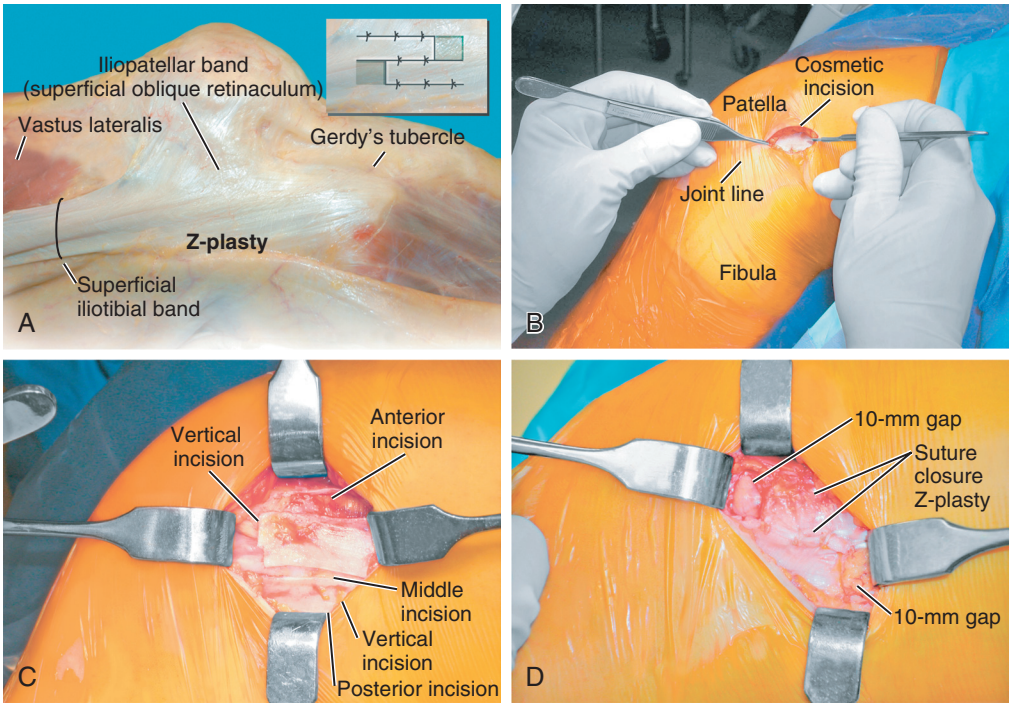


FIG 35-19 **A,** The Z-plasty iliotibial band (ITB) procedure for lengthening and preserving function. **B,** Cosmetic incision. **C,** Z-plasty incision of the ITB. Note the three longitudinal incisions and two vertical incisions. **D,** Final appearance of Z-plasty after closure. The bursae underlying the ITB is excised. The closure is under low tension and preserves ITB function.

trochleoplasty procedures, which may lead to short-term cartilage deterioration. Our approach is to restore a normal patellotrochlear contact and MPFL function and correct an abnormal lateral patellar offset when present. The exception may be a supratrochlear "bump" or prominence that may be recessed. The question of whether trochleoplasty leads to superior outcomes compared with MPFL reconstruction for recurrent patellar instability remains unanswered. To date, no randomized or comparative studies between these operations have been performed in the United States or abroad. In addition, the follow-up time periods for the modern trochleoplasty studies is short, and the long-term outcomes in regard to patellofemoral articular cartilage deterioration are unknown.

Iliotibial Band Z-Plasty Release for Contracture

The technique for a Z-plasty release of a tight ITB is demonstrated in Figure 35-19. After conservative treatment measures have failed, including one or two local cortical steroid injections, ITB stretching exercises over 4 to 6 months, and symptoms return, an ITB release may be indicated. The goal of the procedure is to restore the normal length of the ITB and the normal tension in both arms of the released ITB. The alternative technique that has been described is to remove a window of the ITB, which has the disadvantage of essentially removing the function of the ITB. In addition, there may be remaining anterior and posterior portions of the ITB that still require release. The Z-plasty release has the advantage of restoring normal anatomy. It is important to explore the soft tissues beneath the ITB for abnormal bursae tissue and a sensory nerve that represent sources of lateral pain.

POSTOPERATIVE MANAGEMENT

The postoperative rehabilitation protocol is summarized in Table 35-4. This protocol was developed for patients undergoing proximal and distal extensor mechanism realignment procedures, including MPFL reconstruction. Patients are placed into a postoperative long-leg brace for the first 4 weeks. Range of knee motion exercises and patellar mobilization in superior-inferior and medial-lateral directions are begun immediately after surgery to prevent parapatellar contractures. The goal for the first week is to obtain 0 to 90 degrees of motion. Knee flexion is gradually increased to 110 degrees by the fourth week, and then full motion of at least 135 degrees is allowed by the eighth week. This limitation of flexion in the first 4 weeks is designed to protect the suture lines and the repair when a proximal realignment procedure is performed. The therapist should be aware of the potential for a knee motion complication and, if 0 to 110 degrees is not obtained by the end of the fourth week, the patient should undergo a local anesthetic nerve block or a gentle range of motion under anesthesia as previously discussed. The early treatment and avoidance of an arthrofibrotic response to surgery is critical in these cases (see Chapter 38).

Patients are allowed to bear 50% of their body weight for 2 weeks; full weight bearing is allowed by fourth week. When a distal realignment osteotomy has been performed, full weight bearing by 4 to 6 weeks is allowed based on patient control and muscle strength parameters.

CRITICAL POINTS

Postoperative Management

- See Table 35-4
- Postoperative long-leg brace first 4 weeks
- Patellar mobilization begun immediately postoperative
- 0-90 degrees first week, full by eighth week
- Return to strenuous activities dependent on appearance of articular cartilage in the patellofemoral joint

TABLE 35-4 Postoperative Rehabilitation Protocol

	1-4 Weeks	5-8 Weeks	9-12 Weeks	4-6 Months	7-12 Months
Brace:					
Soft postoperative motion	X				
Patellar (optional, symptoms)		X	X	X	X
ROM minimum goals:					
0-90 degrees (weeks 1-2)	X				
0-110 degrees (weeks 3-4)	X				
0-135 degrees		X			
Weight bearing:					
50% body weight (weeks 1-2)	X				
100% body weight (weeks 3-4)	X				
Patellar mobilization	X	X			
Modalities:					
EMS	X	X			
Biofeedback	X	X			
Pain/edema management (cryotherapy)	X	X			
Stretching: hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X
Strengthening:					
Quadriceps isometrics, straight-leg raises	X	X			
Active knee extension	X	X	X		
Closed-chain: gait retraining, toe-raises, wall sits, mini-squats	X	X	X	X	
Knee flexion hamstring curls (90 degrees)	X	X	X	X	X
Knee extension quadriceps (90-30 degrees)	X	X	X	X	X
Hip abduction-adduction, multi-hip		X	X	X	X
Leg press (70-10 degrees)		X	X	X	X
Balance/proprioceptive training: weight shifting, minitrampoline, BAPS, BBS, plyometrics	X	X	X	X	X
Conditioning:					
Upper body weight training, core training	X	X	X	X	X
Upper body cycle	X	X			
Bicycling (stationary)				X	X
Water walking		X	X	X	X
Swimming (kicking)			X	X	X
Walking		X	X	X	X
Ski machine		X	X	X	X
Running: straight			X*	X	X
Cutting: lateral carioca, figure 8s				X*	X
Plyometric training, full sports				X*	X

*Only for patients with normal articular cartilage in the patellofemoral joint.
BAPS, Biomechanical Ankle Platform System (Patterson Medical); *BBS*, Biodex Balance System; *EMS*, electrical muscle stimulation; *ROM*, range of motion; *UBE*, upper body cycle.

Radiographs are taken on the first and the fourth postoperative weeks to ensure adequate position and healing of the osteotomy. Weight bearing may be delayed if problems are detected in bony healing or in quadriceps control. Flexibility exercises, including stretching of the hamstrings, gastrocnemius-soleus, quadriceps, and ITB, are started in the first week. The strengthening program for quadriceps mechanism is begun during the first week and gradually progressed. Straight-leg raises are allowed after the third week. Open kinetic chain exercises are begun between fourth and sixth weeks because there is usually rapid healing of the osteotomy. To initiate a running program, the patient must demonstrate at least 70% of the strength of the noninvolved limb for quadriceps and hamstrings on isometric testing, be at least 3 months postoperative, and have normal articular cartilage surfaces. The return to strenuous activities is markedly dependent on the appearance of the articular cartilage in the patellofemoral joint. Unfortunately, the majority of patients already have deterioration from chronic patellofemoral malalignment. In these patients, the goal of surgery is to return to light, low-impact activities only.

COMPLICATIONS

The common pitfalls related to lateral retinacular release are improper patient selection, incomplete release, excessive or inappropriate release, and inadequate hemostasis. Sectioning of the VLO tendon will cause it to retract, with resultant weakness of quadriceps muscles and patellofemoral imbalance. The ability to evert the patella even at 30 degrees, and certainly at 90 degrees, indicates excessive release of lateral restraints and the VLO tendon insertion and should be avoided to

CRITICAL POINTS

Complications

- Lateral retinacular release pitfalls: improper patient selection, incomplete release, excessive or inappropriate release, inadequate hemostasis
- Proximal realignment: fail if MPFL incompetent, medial plication overtensioned
- Distal realignment: loss of patellar tendon fixation, delayed union or nonunion of the tibial tubercle, fracture of the bony fragment, inadequate correction, overcorrection with iatrogenic medial subluxation, prominent hardware
- Other rare complications: infection, compartment syndrome, neurovascular injury, deep venous thrombosis, pulmonary embolism, hemarthrosis, subcutaneous hematoma, arthrofibrosis, patella baja, complex regional pain syndrome

prevent medial patellar subluxation. A lateral release should also be avoided in a patient with hypermobile patella.

Potential complications related to distal realignment surgery include loss of patellar tendon fixation, delayed union or nonunion of the tibial tubercle, fracture of the bony fragment, inadequate correction, overcorrection with iatrogenic medial subluxation, and prominent hardware. Rapid healing of the tibial tubercle occurs owing to the inherent stability of the step-cut osteotomy and intact medial tissues. If the osteotomy is too superficial through the tibial tubercle, resulting in a thin cortical bony fragment, the potential for fractures, delayed union, or nonunion is increased. At the distal extent of the osteotomy, a hole is drilled through the tibial cortex to prevent the osteotomy from extending distally. Two to three smaller diameter screws are used for tibial tubercle fixation to control rotation of the osteotomized bony fragment. These screws often require removal in the future through a minimal approach.

During the proximal realignment procedure, the three primary sutures should be tied with the knee in 30 degrees of flexion followed by knee flexion-extension to ensure a full range of motion and normal patellofemoral tracking. The MPFL may be incompetent from repeat dislocations or prior surgery. A proximal plication of a thin attenuated MPFL is likely to stretch and fail[6] and should be reconstructed using a QT graft or other tendon graft. Overtensioning of the medial plication or MPFL may produce abnormal patellofemoral contact forces and cartilage deterioration, pain, and limitation of knee flexion.

Parikh and coworkers[135] reviewed complications after MPFL reconstruction in 179 knees in 154 patients aged 6 to 21 years in a single pediatric hospital. The complications included recurrent patellar instability episodes or instability and an osteochondral fracture. A hamstring autograft was looped through bone tunnels in the patella, and the free ends were passed between the medial retinaculum and capsule and then placed in the femoral tunnel and fixed with an interference screw. Eighteen complications were related to improper technique, including recurrent patellar instability or pain (12 knees) or patellar fractures (six knees). In addition, knee motion flexion deficits occurred in eight knees that required a manipulation under anesthesia. Female gender was significantly associated with complications (relative risk, 5.54; $P < .001$). The authors provided several recommendations for resolving the technical problems during surgery, including a single patellar tunnel, radiographic confirmation of an anatomic position of the femoral tunnel, using a gracilis autograft to minimize the size of the patellar tunnel, and checking patellar mobility in extension to avoid overtensioning the graft. It should be noted that suture "docking" of the MPFL tendon graft to the medial patellar MPFL attachment avoids the necessity of patellar tunnels and possibility of a fracture.

Nelitz and associates[118] determined the causes of failure of MPFL reconstruction in 19 patients before revision reconstruction. The primary MPFL procedure had been done with a free gracilis or semitendinosus graft, femoral fixation with an interference screw, and patellar fixation through one or two tunnels. The common causes of failure were severe trochlear dysplasia, increased femoral anteversion that was not corrected, malpositioning of the femoral tunnel, and overtensioning of the graft. Four patients were deemed inappropriate candidates because they did not experience any patellar instability before the operation.

Stephen and colleagues[161] assessed the effect of nonanatomic MPFL reconstructions on patellar tracking and patellofemoral joint contact mechanics in cadaveric knees (aged 46-88 years). The femoral tunnels were placed either at the MPFL anatomic site or 5 mm proximal or distal and tensioned at 2, 10, or 30 N. The investigators reported that anatomically oriented reconstructions with 2-N tension fixed at either 30 or 60 degrees of flexion restored joint contact pressures and tracking to within normal limits. Femoral graft tunnels positioned proximal or distal resulted in significant increases in peak and mean medial pressures and medial patellar tilt ($P < .05$). Grafts tensioned at 10 or 30 N caused significant increases in medial pressure and tilt. These authors previously determined the most isometric femoral attachment site of the MPFL to be (taking the anterior-posterior medial femoral condyle diameter to be 100%) 40% from the posterior, 50% from the distal, and 60% from the anterior border of the medial femoral condyle.[162] Femoral tunnel locations that were 5 mm proximal or distal to this site caused significant changes in lengthening (mean, 6.4 mm; $P = .005$) and shortening (mean, 9.1 mm; $P = .001$), respectively.

Arendt and coworkers[6] evaluated the outcome of MPFL repair and reattachment at its femoral origin in a group of 55 knees in 48 patients with chronic, multiple lateral patellofemoral dislocations. There were 35 women and 13 men whose average age at surgery was 18 years (range, 12-42 years). None of the patients had patella alta or trochlear dysplasia. At 2 years postoperative, 46% had sustained a redislocation injury. In a similar study, Camp and associates[32] reported a 28% failure rate of repair of MPFL tissues in a series of 29 knees that received the operation for chronic recurrent lateral patellar dislocations. The results of these studies highlight the necessity to use an anatomic graft to replace chronically deficient MPFL tissues.

Other postoperative complications should be very rare and include infection, compartment syndrome, neurovascular injury, deep venous thrombosis, pulmonary embolism, hemarthrosis, subcutaneous hematoma, arthrofibrosis, patella baja, and complex regional pain syndrome. The patient should also be informed about the risk of worsening of patellofemoral arthritis symptoms.

CLINICAL STUDIES

Medial Patellofemoral Ligament Reconstruction

A summary of recently published clinical studies on MPFL graft reconstructions is shown in Tables 35-5 and 35-6.[159] A variety of grafts have been used, including the gracilis and semitendinosus tendons, the QT, the patellar tendon, allografts, the adductor magnus, and artificial ligaments, along with different fixation methods. In the majority of studies, the prevention of recurrent dislocation or subluxation episodes was used as a primary outcome factor, along with rating activities of daily living. Typically, fewer than 5% of patients had dislocation or subluxation episodes postoperatively. The most widely used outcome rating instrument was the Kujala score[92] (0-100 points; see Chapter 45), which was designed to rate patellofemoral disorders by measuring the following factors: limp, support, walking, stairs, squatting, running, jumping, prolonged sitting with knees flexed, pain, swelling, knee

TABLE 35-5 Medial Patellofemoral Ligament Reconstruction Study Demographics

	SUBJECTS				GRAFT, FIXATION, CONCOMITANT PROCEDURES		
Study	No. Knees	Mean Age (Range) (yr)	Mean Follow-up (Range) (yr)	F:M	Graft, Procedure	Concomitant Procedures	Clinical Outcome Measures
Siebold et al[150] (2014)	10	19-31	2 (1-4)	5:5	Gracilis tendon	ACI	Kujala, Lysholm, KOOS
Song et al[157] (2014)	20	21 (13-34)	2.9 (2-4.2)	10:10	Hamstring tendon fixed with 2 suture anchors at native patellar site of MPFL	None	Kujala, Lysholm, Tegner
Becher et al[11] (2014)	30	21	2.2 (1.7-3.8)	20:10	*Static:* gracilis tendon fixed at anatomic femoral MPFL insertion and superomedial border of patella. *Dynamic:* gracilis detached at pes anserinus, fixed to proximal patellar margin via tunnel transfer through patella	None	Kujala, Lysholm, Tegner
Berruto et al[16] (2014)	18	19 (15-43)	3	7:9	Bioactive synthetic ligament looped through two patellar tunnels	None	Kujala, IKDC Subjective, KOOS
Enderlein et al[54] (2014)	224	23 (14-46)	1-5	162:78	Gracilis tendon fixed in drill holes in medial edge of patella and screws at femoral MPFL insertion site	Tibial tuberosity transfer in 23%	Kujala
Feller et al[58] (2014)	36	14.3-44.8	3.5 ± 1.6	NA	Gracilis or ST passed through two patellar tunnels, free ends of graft passed into femoral tunnel, fixed with interference screw	Tibial tuberosity transfer in 28%	Authors' questionnaire
Hopper et al[82] (2014)	72	24 (14-46)	2.6 (1.1-6)	50:18	Hamstring tendon passed through patellar tunnel, fixed with interference screw; femoral tunnel placed isometrically, fixed with screw or suture anchor	Tibial tuberosity transfer in 30%	Kujala, Lysholm, Tegner
Li et al[94] (2014)	65	29 ± 6	6.5	37:28	Tibialis anterior allograft fixed in groove in medial margin of patella, sutured to fascia overlying patella, passed through femoral tunnel, fixed with bioabsorbable interference screw	None	Kujala, Lysholm, Tegner
Lippacher et al[97] (2014)	72	18 (14-43)	2.1 (2-3.8)	44:24	Gracilis tendon placed through two converging V-shaped tunnels in patella, placed through femoral tunnel, fixed bioabsorbable interference screw	None	Kujala, IKDC, Tegner, Activity Rating Scale
Matsushita et al[103] (2014)	34	22	3 (1-7.2)	28:6	19 patients TT/TG >20 mm, 15 patients TT/TG <20 mm; MFPL ST, suture anchors patella, doubled tendon passed through femoral tunnel, fixed interference screw	Lateral release in 67% in high TT/TG distance group, 44% control group	Kujala, Lysholm
Kang et al[87] (2013)	82	29.4 ± 5.6	2	50:32	Randomized to Y-graft technique (femoral fixation first with separate tensioning of 2 bundles) or C-graft (patellar fixation first with simultaneous tensioning of two bundles)	Lateral release in 42% of Y-graft group and 38% of C-graft group	Kujala, Lysholm
Wang et al[177] (2013)	70	25 (18-35)	4	35:23	Single-bundle ST (26 knees) or double-bundle STG (44 knees)	VMO advancement in all	Kujala
Goyal[73] (2013)	32	25 (10-48)	3.2 (1-5.7)	22:10	Superficial slip of QT 10-12 mm wide, no patellar tunnel or bony fixation	None	Kujala
Deie et al[39] (2011)	31	22 (12-34)	3.2 (2-5)	24:5	ST, cylindrical bone plug placed at anatomic femoral attachment site	None	Kujala
Han et al[75] (2011)	59	24 (15-41)	5.7 (3.1-7.1)	33:19	ST, double transverse patellar tunnels	None	Kujala, Cincinnati
Panni et al[133] (2011)	51	28 (16-60)	2.7 (2-4.5)	37:11	ST, double transverse patellar tunnels	None	Kujala, Lysholm, Larsen
Ahmad et al[1] (2009)	20	23 (11-43)	2.6 (2-3.2)		Soft tissue grafts, interference screw fixation on femur, docking technique on patella, graft sutured to vastus medialis obliquus	Lateral release in 60%	Kujala, IKDC, Lysholm, Tegner

TABLE 35-5 Medial Patellofemoral Ligament Reconstruction Study Demographics—cont'd

	SUBJECTS				GRAFT, FIXATION, CONCOMITANT PROCEDURES		
Study	No. Knees	Mean Age (Range) (yr)	Mean Follow-up (Range) (yr)	F:M	Graft, Procedure	Concomitant Procedures	Clinical Outcome Measures
Ronga et al[140] (2009)	28	32 (19-40)	3.1 (2.5-4)	7:21	ST or gracilis tendon, double transverse patellar tunnels	None	Kujala, Cincinnati
Sillanpaa et al[152] (2008)	47	20 (19-24)	5-13	0:47	Adductor magnus tenodesis MPFL reconstruction (18) or distal patellar realignment (29)	None	Kujala, Tegner
Christiansen et al[34] (2008)	44	22 (12-47)	1.8 (1-2.7)	29:15	Gracilis tendon autograft, bioresorbable interference screw femoral condyle	Medial tibial tuberosity for severe trochlear dysplasia in 27%	Kujala, KOOS
Gomes[53] (2008)	24	19.3 (16-24)	2.9 (2.5-5.9)		ST graft (12) or pedicled adductor magnus graft (12); ST free graft, fixation: two sutures to lateral retinaculum. Adductor magnus graft: one suture to lateral retinaculum, lateral release	None	ADL Scale
Nomura et al[124] (2007)	24	22.5 (13-48)	11.9 (8.4-17.2)	18:4	Leeds-Keio artificial ligament, staple	Lateral release in 58%	Kujala, Crosby/Insall

ACI, Autologous chondrocyte implantation; *ADL*, activities of daily living; *F:M*, female/male ratio; *IKDC*, International Knee Documentations Committee; *KOOS*, Knee Injury and Osteoarthritis Outcome Score; *MPFL*, medial patellofemoral ligament; *NA*, not available; *QT*, quadriceps tendon; *ST*, semitendinosus; *STG*, semitendinosus-gracilis; *TT/TG*, tibial tubercle/trochlear groove; *VMO*, vastus medialis obliquus.

subluxation, thigh atrophy, and flexion deficiency. Nearly all of the studies reviewed reported statistically significant improvement in this score postoperatively.

Various techniques were used to ascertain patellar stability, including physical examination and stress radiographs.[40,41,108,109] Because most of the study cohorts were followed in the short term postoperatively (mean, <5 years), the percent of patients in whom progression of patellofemoral arthritis occurred after this operation and the survival rate of the procedure in preventing long-term future patellar dislocations or subluxations are unknown.

Two systematic reviews had been published at the time of writing that attempted to determine postoperative activity levels after MPFL procedures. In 2010, Fisher and colleagues[61] reviewed 21 studies (488 patients) and were unable to formulate conclusions regarding return to athletics postoperatively. This was because of the failure of the studies to use outcome measures that assessed sports activity levels or the effect of the knee condition on the ability to return to athletics. More recently, in 2014, Matic and associates[102] assessed 10 articles (402 patients) that included Tegner activity scores. Because only preoperative and follow-up mean scores were reported, the percent of patients who returned to athletics and the levels that were achieved were not provided in six studies. The time to return to sports, provided in three studies, ranged from 4 to 6 months. These investigators found a higher recurrent dislocation rate in patients who underwent MPFL repair compared with reconstruction (27% and 16%, respectively; $P < .0001$).

Bitar and associates[22] conducted a randomized controlled trial of nonoperative versus MPFL reconstruction for acute primary patellar dislocations. Twenty patients (aged 18-38 years) were assigned physical therapy only and 21 patients (aged 12-37 years) underwent MPFL reconstruction with the patellar tendon. The patients were followed from 2 to 5.1 years postoperatively. The mean Kujala score was significantly lower in the nonoperative group compared with the reconstruction group (71 and 89 points, respectively; $P = .001$). The nonoperative group had a 35% rate of recurrent patellar dislocation/subluxation, whereas the reconstruction group had no reports of recurrences.

The effect of femoral tunnel enlargement after MPFL reconstruction was assessed by Berard and colleagues.[15] A gracilis tendon autograft was harvested and folded in half, placed through a femoral tunnel, and secured with a bioabsorbable interference screw. The free ends of the graft were passed through two patellar tunnels. In 55 knees followed a mean of 3 years (range, 1-6 years), tunnel enlargement was noted in 23 (42%) that had a mean cross-sectional area of 105 ± 20 mm^2 compared with 58 ± 11 mm^2 in the other 32 knees. There were no differences between the two groups in patient's age, body mass index, prevalence of trochlear dysplasia, tunnel malposition, recurrent dislocations, or subjective International Knee Documentations Committee (IKDC) scores. However, the mean patellar height was significantly higher in the enlarged tunnel group (1.17 and 1.80; respectively; $P = .03$). The authors concluded that although femoral tunnel enlargement after MPFL reconstruction was common, it did not affect the risk of recurrent instability.

The effect of femoral tunnel placement and trochlear dysplasia on the outcome of hamstring MPFL reconstruction was determined by Hopper and associates in a group of 72 knees.[82] The extent of trochlear dysplasia was rated as grade A or B (low grade) in 89% and grade C or D (high grade) in 11%. All patients in the high-grade group had recurrent dislocations and significantly lower Kujala, Lysholm, and Tegner scores. When these patients were excluded, there were fewer recurrent dislocations and higher clinical scores in knees with anatomically placed femoral tunnels (<10 mm mean distance from anatomic insertion of MPFL to center of femoral tunnel) compared with those of knees with nonanatomically placed tunnels. Recurrent dislocations were associated with increased grade of trochlear dysplasia ($P < .001$) and nonanatomic femoral tunnel placement ($P = .02$). Four knees had postoperative patellar fractures and two had tibial tuberosity avulsion fractures caused by technical errors at surgery. Similar

TABLE 35-6 Results of Medial Patellofemoral Ligament Reconstruction

	KUJALA			LYSHOLM			OTHER			
Study	**Preoperation**	**Follow-up**	***P* Value**	**Preoperation**	**Follow-up**	***P* Value**	**Preoperation**	**Follow-up**	***P* Value**	**Other Findings**
Siebold et al[150] (2014)	60 ± 14	74 ± 25	NS	63 ± 15	74 ± 19	NS	KOOS: 67 ± 15 IKDC: 50 ± 14	74 ± 17 64 ± 22	NS NS	80% cartilage lesions complete fill on MRI
Song et al[157] (2014)	53 ± 12	91 ± 4	<.001	49 ± 11	91 ± 5	<.001				No recurrent dislocations or subluxations; one positive apprehension test, six positive patellar compression tests
Becher et al[11] (2014)	NA	82-84	NA	NA	78-79	NA				No differences between dynamic-static groups; 12 patients in static group and 11 in dynamic group would recommend procedure; one failure (dynamic group)
Berruto et al[16] (2014)	57 ± 8	84 ± 10	<.01				KOOS: 42 ± 4 IKDC: 42 ± 7	83 ± 9 70 ± 4	<.01 .01	Two knees rated fair, no major complications
Enderlein et al[54] (2014)	62 ± 17	80 ± 18	<.001							Predictors of poor outcomes: age >30 yr, female gender, BMI >30, ICRS PF grade 3-4 Redislocation in 4.6%, subjective patellar instability in 39%, revision in 3.2%
Feller et al[58] (2014)										Anterior knee pain 38% in isolated group, 40% in combined group; return to sports: 81% in isolated group, 70% in combined group; higher percent returned to strenuous sports in isolated group
Hopper et al[82] (2014)	NA	Mild group = 79, severe group = 50	.0001	NA	Mild group = 77, severe group = 47	.0001				89% of knees had mild trochlear dysplasia, 11% had severe dysplasia; all patients with severe dysplasia had recurrent dislocations compared with 9% of knees with mild Significantly higher outcome scores in the mild group; return to sport: 56% in mild group, 43% in severe group

Li et al[94] (2014)	53 ± 3	90 ± 6	<.05	47 ± 5	92 ± 6	<.05				No complications, revisions, or recurrent dislocations
Lippacher et al[97] (2014)	66	87.5	<.01				IKDC: 60	80	<.01	All 62 patients who participated in sports before surgery resumed playing, 33 at same level, 29 at lower level Significant factors on outcome: younger age, higher preoperative sports level. Two patients had recurrent dislocations, 5 had subluxations
Matsushita et al[103] (2014)	Increased TT/TG group: 75	92	<.0001	Increased TT/TG group: 79	95	<.0001				No difference in outcome scores between groups at follow-up; no recurrent dislocations; apprehension sign positive in 19% of high TT/TG group and 5% of control group
	Control group: 67	92	<.0001	Control group: 71	92	<.0001				
Kang et al[87] (2013)	Y-graft group: 53	96	<.0001	Y-graft group: 51	92	<.0001				Y-graft had higher scores, but questionable clinical significance; no recurrent dislocations or subluxations
	C-graft group: 52	91	<.0001	C-graft group: 50	88	<.0001				
Wang et al[177] (2013)				NA	Double-bundle = 92, single bundle = 80	<.001				Patellar instability: 27% single bundle, 4.5% double bundle
Goyal[73] (2013)	49 ± 10	91 ± 8	<.001							No dislocations or subluxations
Deie et al[39] (2011)	64	95	<.05							No recurrent dislocations; one patient had positive apprehension sign and required lateral retinacular reconstruction
Han et al[75] (2011)	41	83	<.001				Cincinnati: 51	89	<.001	No recurrent dislocations or subluxations; seven knees had occasional instability sensation; all returned to preoperative levels of athletic participation

Continued

TABLE 35-6 Results of Medial Patellofemoral Ligament Reconstruction—cont'd

	KUJALA			LYSHOLM			OTHER			
Study	**Preoperation**	**Follow-up**	***P* Value**	**Preoperation**	**Follow-up**	***P* Value**	**Preoperation**	**Follow-up**	***P* Value**	**Other Findings**
Panni et al[133] (2011)	57 ± 18	87 ± 14	<.01	58 ± 20	88 ± 16	<.01				No recurrent dislocations; 64% returned to same sports level; 87% satisfied with pain relief
Ahmad et al[1] (2009)	50	88	<.001	50	89	<.001	IKDC: 42	82	<.001	No recurrent dislocations; all returned to preoperative levels of sports
Ronga et al[140] (2009)	45	83	.03				Cincinnati: 52	89	.001	3 (11%) had recurrent dislocation; significant decrease in isokinetic muscle strength at peak torque, total work output, average power (P <.05) compared with contralateral side
Sillanpaa et al[152] (2008)	NA	88 recon, 86 realignment								Recurrent dislocation in 7% of reconstructions and 14% of realignments; radiographic patellar arthritis in 17% of realignments, none in reconstructions
Christiansen et al[34] (2008)	46	84								64% had no pain on ADLs; 59% had no pain with sports; one patient had dislocation, three patients had sensation subluxation; positive apprehension in 41%, patellar pain in 43%; one patellar fracture
Gomes[53] (2008)							ADL: ST 50 ± 4	73 ± 2	NS	ST group had no dislocations, 8 patients played recreational sports; adductor magnus group had one patient with subluxation, 4 patients played recreational sports
							Adductor magnus 51 ± 4	73 ± 1	NS	
Nomura et al[124] (2007)	63	94	<.0001							88% satisfactory clinical results; dislocation/subluxation in two knees, positive apprehension in five knees; x-ray showed slight progression of PF arthritis in five knees and definite progression in two knees

ADL, Activities of daily living; *FU*, follow-up; *ICRS*, International Cartilage Repair Society; *IKDC*, International Knee Documentations Committee; *KOOS*, Knee Injury and Osteoarthritis Outcome Score; *MRI*, magnetic resonance imaging; *NA*, not available; *NS*, not significant; *PF*, patellofemoral; *TT/TG*, tibial tubercle/trochlear groove.

findings were reported by Larson and coworkers[94] with respect to the deleterious effects of nonanatomic femoral tunnel placement on clinical outcomes.

We are currently following patients who received the quadriceps tendon autograft MPFL reconstruction previously described. From our database of 80 patients, there exists a subgroup of 43 patients (44 knees) in whom the patellofemoral joint cartilage was intact at surgery. This subgroup is composed of 30 women and 13 men whose mean patient age at surgery was 20; 77% were less than 20 years old. All of these patients have been followed a mean of 6 years (range, 2-10 years) postoperatively. Before surgery, all patients had either suffered a dislocation injury or had recurrent subluxation episodes and had pain with daily activities. At follow-up, statistically significant improvements were noted in mean Cincinnati Knee Rating scores for pain ($P < .01$), swelling ($P < .01$), partial giving-way ($P < .0001$), full giving-way ($P < .05$), walking ($P < .01$), squatting ($P < .01$), and the patient perception of the knee condition ($P < .0001$). In 41 out of 43 knees (95%), a competent MPFL was present, preventing subluxation and dislocation. Two knees required revisions because of recurrent dislocation episodes. As was discussed previously, this simplified MPFL reconstruction has the advantages of using an autograft rather than an allograft, does not require harvesting a hamstring tendon, and avoids potential complications from patellar drill holes of pain or fracture. Importantly, the soft tissue fixation to the MPFL femoral attachment by sutures with immediate knee motion prevents an abnormally tight medial constraint. The procedure also involves soft tissue balancing and tensioning of the entire medial retinaculum, including the MPFL and MPML tissues.

Outcomes of Procedures for Patellofemoral Articular Cartilage Lesions

Autologous Chondrocyte Implantation

Several clinical outcome studies (Table 35-7)[9,12] and systematic reviews (Table 35-8)[28,50,70,112,113] have been published regarding the use of autologous chondrocyte implantation (ACI) for patellar and trochlear lesions The majority of studies used first generation ACI, implanted as originally described by Brittberg and associates[29] with varying results. Mandelbaum and colleagues[99] followed 40 patients a mean of 4.9 years postoperatively, 28% of whom had a concomitant lateral release or Fulkerson procedure. The investigators reported significant improvement in Cincinnati pain and overall knee condition scores. However, nearly one third of the patients required further surgery for problems related to the ACI and 22% failed. Minas and coworkers[111] reported survivorship rates and outcomes of ACI grafts in 210 patients. The number of patellofemoral ACI grafts was not provided; however, the failure rate was higher for patellofemoral grafts compared with tibiofemoral grafts (70% and 79% at 10 years, respectively). Biant and colleagues[17] reported 10 year outcomes of 36 patellar ACI. Nine grafts (25%) failed, all of whom required further operations.

Text continued on p. 1004

TABLE 35-7 Autologous Chondrocyte Implantation for Patellofemoral Lesions Study Demographics

	SUBJECTS						
Study	No. Knees	Age (yr)	Mean Follow-up (Range) (yr)	F:M	ACI	Concomitant Procedures	Clinical Outcome Measures
Siebold et al[150] (2014)	10	19-31	2 (1-4)	5:5	Cultured chondrocytes implanted arthroscopically as 3-D spheroids	MPFL reconstruction	Kujala, Lysholm, KOOS
Gomoll et al[71] (2014)	110	33 (15-55)	7.5 (4-16)	64:46	1st generation	75 (69%) tibial tubercle osteotomy, 45 (41%) LR, 22 (20%) VMO advancement	IKDC, Cincinnati, WOMAC, SF-36, Knee Society
Minas et al[111] (2014)	NA	NA	≥10	NA	1st generation	NA	Survivorship analysis
Filardo et al[60] (2014)	49	31 ± 10	≥5	16:33	Bioengineered chondrocytes seeded on a hyaluronan-based 3-D scaffold (Hyalograft C)	29 (59%) tibial tubercle osteotomy, 32 (65%) LR	IKDC, Kujala, Tegner
Biant et al[17] (2014)	36	29	≥10	23:13	1st generation, type I/III collagen membrane or periosteum	None	Cincinnati, Stanmore/Bentley
Gillogly & Arnold[68] (2014)	23	31 ± 7	7.6 (5.1-11.4)	12:11	1st generation	Tibial tubercle transfer in all	Cincinnati, IKDC, Lysholm, SF-12
Macmull et al[98] (2012)	48	35 (17-50)	3.3	34:14	1st generation collagen membrane (25) or MACI (23)	None	Modified Cincinnati, Stanmore/Bentley
Vanlauwe et al[172] (2012)	38	30 (14-49)	3.1 (2-6)	25:12	ACI characterized chondrocytes, covered with collagen membrane	12 (31%) Fulkerson	KOOS

Continued

TABLE 35-7 Autologous Chondrocyte Implantation for Patellofemoral Lesions Study Demographics—cont'd

	SUBJECTS						
Study	No. Knees	Age (yr)	Mean Follow-up (Range) (yr)	F:M	ACI	Concomitant Procedures	Clinical Outcome Measures
Bentley et al[14] (2012)	24	NA	10	NA	1st generation collagen membrane or periosteum (20), mosaicplasty (4)	None	Survivorship analysis
Vasiliadis et al[173] (2011)	92	35 (14-57)	12.6	NA	1st generation	21 tibial tubercle transfer + medial plication MPFL + VMO + LR; 8 EMM reconstruction; 1 medial plication + trochleaplasty; 1 LR + trochleaplasty; 4 tibial osteotomy	Lysholm, Tegner
Pascual-Garrido et al[136] (2009)	52	32 (16-49)	4 (2-7)	26:26	1st generation	28 Fulkerson; 4 LR; 2 lateral meniscus allograft; 1 osteochondral autograft transfer MFC	Lysholm, IKDS, KOOS, Cincinnati, Tegner, SF-36
Gobbi et al[69] (2009)	34	31 (15-55)	6.3 (5-8.7)	11:23	ACI seeded on hyaluronan scaffold	10 patellar realignments; 5 meniscectomy; 1 ACL reconstruction	IKDC, Tegner
Gigante et al[67] (2009)	12	31	3	6:6	MACI	Fulkerson in all	Kujala, Lysholm, Cincinnati, Tegner
Niemeyer et al[121] (2008)	70	34	3.2 (1.1-5.3)	NA	First generation or seeded on 3-D PLGA fleece	None	IKDC, Lysholm, Cincinnati Sports Activity Scale
Mandelbaum et al[99] (2007)	40	37 (16-48)	4.9 (2-7)	12:28	1st generation	28% LR or Fulkerson, 15% fragment reattachment or removal, 13% meniscus repair or meniscectomy	Cincinnati
Kreuz et al[91] (2007)	118	34 (18-48)	3	49:69	1st generation	None	Cincinnati Sports Activity Scale
Steinwachs & Kreuz[160] (2007)	63	32 (18-50)	3	32:31	1st generation, type I/III collagen membrane	None	Cincinnati
Farr[55] (2007)	38	31 (14-50)	3 (0.5-5.1)	17:21	1st generation	28 anteromedialization; 2 lateral meniscus transplants, 2 LR; 1 MPFL recon; 1 ACL reconstruction; 1 medial release	Cincinnati, Lysholm
Henderson & Lavigne[80] (2006)	44	14-56	0.7-4.6	23:21	1st generation	22 proximal-distal realignments	IKDC, Cincinnati, SF-36
Minas & Bryant[110] (2005)	45	36 (15-54)	3.9 (2-7)	18:27	1st generation	21 tibial tubercle osteotomy; 7 tibial tubercle osteotomy + high tibial osteotomy; 1 high tibial osteotomy	SF-36, WOMAC, Cincinnati

ACI, Autologous chondrocyte implantation; *ACL*, anterior cruciate ligament; *EMM*, extensor mechanism malalignment; *F:M,* female/male ratio; *IKDC*, International Knee Documentations Committee; *KOOS*, Knee Injury and Osteoarthritis Outcome Score; *LR*, lateral release; *MACI*, matrix-assisted chondrocyte implantation; *MFC*, medial femoral condyle; *MPFL*, medial patellofemoral ligament; *NA*, not available; *PLGA*, poly-lactic-co-glycolic acid; *SF-36*, Medical Outcomes Study Short-Form 36-item questionnaire; *VMO*, vastus medialis obliquus; *WOMAC*, Western Ontario and McMaster Universities.

TABLE 35-8 Results of Autologous Chondrocyte Implantation for Patellofemoral Lesions

	IKDC			CINCINNATI			LYSHOLM			OTHER			
Study	**Preop**	**Follow-up**	***P* Value**	**Preop**	**Follow-up**	***P* Value**	**Preop**	**Follow-up**	***P* Value**	**Preop**	**Follow-up**	***P* Value**	**Other Findings**
Siebold et al[150] (2014)	50 ± 14	64 ± 22	NS				63 ± 15	74 ± 19	NS	KOOS: 67 ± 15	74 ± 17	NS	80% cartilage lesions complete fill on MRI
										Kujala: 60 ± 14	74 ± 25	NS	
Gomoll et al[71] (2014)	40	69	<.0001							WOMAC: 50	28	<.0001	84% felt improvement, 92% would have operation again; 8% failed, 16% did not improve
										Knee Society Knee: 61	85	<.0001	
										Knee Society Function: 58	72	<.0001	
Minas et al[111] (2014)													Survivorship: 70% at 10 and 15 yr
Filardo et al[60] (2014)	38 ± 14	77 ± 18	<.001							Kujala: 48 ± 15	85 ± 14	<.001	Trochlear lesions had better clinical outcomes compared with patellar lesions; no revisions; 6% no improvement
Biant et al[17] (2014)				Patients with intact grafts at 10: 63% excellent, 30% good, 7% fair									25% failed at mean 5.8 yr (1-8 yr)
Gillogly and Arnold[68] (2014)	43	76	<.0001				40	79	<.0001				83% reported good to excellent outcomes, 91% felt knee improved; 33% reoperation for periosteal hypertrophy; 1 failure
Macmull et al[98] (2012)				ACI group: 42	48								Patients symptomatic mean 7.5 yr before surgery
				MACI group: 48	61								

Continued

TABLE 35-8 Results of Autologous Chondrocyte Implantation for Patellofemoral Lesions—cont'd

	IKDC			CINCINNATI			LYSHOLM			OTHER			
Study	**Preop**	**Follow-up**	***P* Value**	**Preop**	**Follow-up**	***P* Value**	**Preop**	**Follow-up**	***P* Value**	**Preop**	**Follow-up**	***P* Value**	**Other Findings**
Vanlauwe et al[172] (2012)										KOOS: 64	73	.0001	MRI hypertrophic filling defect in 26%, complete filling in 26%; 18% arthrofibrosis (transient) 16% F/U scope for clicking or pain
Bentley et al[14] (2012)													Failure rates: 5% ACI, 25% mosaicplasty
Vasiliadis et al[173] (2011)							70	79	NS				93% would undergo operation again; 5% failed and were revised; 29% periosteal hypertrophy, 8% arthrofibrosis
Pascual-Garrido et al[136] (2009)	31	57	<.001	43	63	<.001	37	63	<.001	All KOOS scales		<.001	82% completely satisfied, 72% would undergo operation again; ACI combined with anteromedialization had better outcomes than ACI alone; 8% failed; 25% patients had F/U scope for periosteal graft hypertrophy
Gobbi et al[69] (2009)	46	77	<.001							IKDC objective 91% normal/ nearly normal			Decrease in Tegner scores between 2- and 5-year evaluations; patients with concomitant realignment had lower scores and deterioration in scores between 2- and 5-year evaluations; 1 failure
Gigante et al[67] (2009)							55	92		Kujala: 52	88.5	NA	All patients returned to sports, all but one satisfied
Niemeyer et al[121] (2008)	NA	62 ± 21					NA	73 ± 22					83% returned to preinjury sports activity level; 84% knee condition improved; 81% would undergo operation again

Mandelbaum et al[99] (2007)				Pain score: 2.6 ± 1.7	6.2 ± 2.4	<.0001						No effect of concurrent procedures on outcome; F/U scope in 28% for adhesions, periosteal flap detachment, loose bodies, fibrotic tissue, decreased knee motion; 22% failed
				Overall condition 3.1 ± 1.0	6.4 ± 1.7	<.0001						
Kreuz et al[91] (2007)												By 3 years, 96% returned to preinjury sports activity level; 4% patients who had surgery for periosteal hypertrophy decreased activity level; patients in highest activity level (I) had better clinical and MRI outcomes than those in lower levels
Steinwachs and Kreuz[160] (2007)												85% had normal/nearly normal ICRS rating; no effect on location of lesion and outcome; 5% revised
Farr[55] (2007)				80% rated knee good, very good, or excellent			56	86	<.0001			F/U 66%: 18% major mechanical symptoms, 13% arthrofibrosis, 8% substantial pain
Henderson and Lavigne[80] (2006)	42 ± 17	68 ± 23	<.05									14% had poor results; patients with realignment had higher scores in all categories
Minas and Bryant[110] (2005)										WOMAC:39	23	<.0001	71% rated outcomes as good/excellent, 22% as fair, 7% as poor; 18% failed
										Knee Society Pain: 54	79	<.0001	
										Knee Society Function: 65	78	<.0001	

ACI, Autologous chondrocyte implantation; *F/U*, follow-up; *ICRS*, International Cartilage Repair Society; *IKDC*, International Knee Documentations Committee; *KOOS*, Knee Injury and Osteoarthritis Outcome Score; *MRI*, magnetic resonance imaging; *MACI*, matrix-assisted chondrocyte implantation; *WOMAC*, Western Ontario and McMaster Universities.

Gillogly and Arnold[68] followed 25 knees a mean of 7.6 years after ACI for isolated patellar defects. Significant improvements were noted for IKDC, Cincinnati, and Lysholm scores. However, 40% required a reoperation, mostly because of periosteal hypertrophy. The authors have modified their surgical technique by using an absorbable collagen membrane in place of the periosteal graft.

Gobbi and colleagues[69] followed 34 patients who received a second-generation ACI Hyalogaft-C (Fidia Advanced Biopolymers), a tissue-engineered graft composed of autologous chondrocytes grown on a hyaluronan-based 3-dimensional scaffold, for isolated defects in the patellofemoral joint. Ten patients also underwent a patellar realignment. At follow-up, a mean of 6.3 years postoperatively, significant improvement was noted in the mean IKDC subjective score ($P < .001$). On the IKDC objective knee evaluation, 91% were rated as normal or nearly normal. However, patients who underwent concomitant realignment procedures had lower scores and a deterioration in scores between the 2- and 5-year evaluations.

Filardo and colleagues[60] reported on 49 patients who underwent implantation of autologous chondrocytes seeded on a hyaluronan-based 3-dimensional scaffold (Hyalograft C, Fidia Advanced Biopolymers Laboratories). Thirteen patients also had a lateral release, and six had a realignment procedure. Five years later, significant improvements were found in mean IKDC subjective and Kujala scores. Patients who had trochlear lesions had better outcomes than those with patellar lesions; the latter underwent more combined procedures (lateral release, tibial tubercle osteotomy).

Other investigators reported that patients who had combined ACI-realignment procedures had results that were either superior or comparable with those who underwent ACI alone.[55,80,173] For example, Vasiliadis and colleagues[173] followed 92 patients that underwent ACI, of whom 38 had some type of realignment procedure. At a mean of 12.6 years postoperatively, the group demonstrated improvements in Lysholm rating, and 93% indicated they would undergo the operation again. The clinical rating results in patients who underwent realignment procedures were not significantly different than those who had an isolated ACI. In addition, realignment procedures were associated with a decreased incidence of periosteal hypertrophy compared with isolated ACI (16% and 39%, respectively; $P = .01$). However, realignment procedures resulted in a higher incidence of complications compared with isolated ACI (29% and 13%, respectively; $P = .05$), such as arthrofibrosis and delamination.

Trinh and associates[169] conducted a systematic review to determine if a difference existed in outcomes between combined ACI and realignment procedures compared with ACI alone. Eleven studies were included comprising 366 subjects, 84 (23%) of whom also underwent concomitant tibial tubercle osteotomy. Both first- and second-generation ACI studies were included. The authors reported significant improvements in clinical outcomes (IKDC subjective, Cincinnati, Lysholm, Knee and Osteoarthritis Outcome Score [KOOS], Tegner, Short Form Health Survey [SF-36]) for both groups, with a higher level of improvement noted in patients who had combined procedures from three studies that directly compared these groups. The overall complication rate was 15.2%; the majority were related to periosteal patch hypertrophy or extrusion. Ten of the eleven studies in this review were level III or IV, and there was noteworthy heterogeneity in the lesions, subjects, prior surgery performed, and length of follow-up.

The use of particulated juvenile articular cartilage allografts (Denovo NT Natural Tissue Graft; Zimmer) for patellar defects in a small case series was described by Tompkins and associates.[167] Fifteen knees were followed for a mean of 28.8 ± 10.2 months, 10 of whom underwent various concomitant extensor mechanism procedures. MRI at follow-up revealed normal or nearly normal ICRS cartilage repair score in 11 knees, and all but three showed 90% or greater fill of the defect surface area. Five patients returned to their presymptomatic activity levels; however, seven reported anterior knee pain with stair climbing or prolonged sitting. Three patients required subsequent surgery for graft problems. Farr and colleagues[56] also performed this procedure in 11 knees with trochlear defects along with 18 other knees that had femoral condylar defects. The results were presented for all knees combined and therefore the outcomes of this operation for trochlear defects is unknown.

Osteochondral Autograft Transfer

Few data have been published regarding osteochondral autograft transfer for patellofemoral defects.[7,13,59,76-78,120] Hangody and colleagues[78] summarized the results of 1097 osteochondral autograft transfer procedures, 137 of which were done for lesions located in the patellofemoral joint. The majority of patients (percentage unknown) underwent concomitant patellar realignment procedures. The results were assessed with a variety of scoring systems (modified Hospital for Special Surgery, modified Cincinnati, Lysholm) from 1 to 10 years postoperatively. The clinical scores demonstrated "good to excellent" results in 74% of this subset of patients, which were the only data reported. Hangody and associates[76] also reviewed the outcome of this operation in 383 professional athletes. Twenty-six patients received the procedure for patellar or trochlear defects. The only data reported specifically for patellofemoral procedures were mean Hospital for Special Surgery scores, which were not significantly improved compared with the preoperative condition.

Astur and associates[7] evaluated 33 patients who had an osteochondral autograft transfer for full-thickness patellar lesions 1 to 2.5 cm in diameter. Twenty-eight knees had one plug, and five knees required two plugs. At a mean of 2.5 years postoperatively, significant improvements were reported in Lysholm, Fulkerson, Kujala, and SF-36 scores ($P < .05$). MRI performed 6 months after surgery showed that 83% of the plugs had complete osseous integration, which increased to 100% at 1 year. Three patients had arthrofibrosis postoperatively that was successfully treated with an arthroscopic release.

Nho and colleagues[120] assessed clinical and MRI outcomes of osteochondral autograft transfer procedures for patellar lesions in 22 patients a mean of 2.4 years (range, 1.5-4.8 years) postoperatively. There were 12 men and 10 women whose mean age at surgery was 30 years (range, 15-57 years). The mean number of plugs used was 1.8 (range, 1-7); 20 patients had 1 to 2 plugs implanted. Nine patients underwent a concomitant distal realignment. The mean IKDC score improved from 47 ± 14 before surgery to 74 ± 12 at follow-up ($P < .05$), and the mean Activities of Daily Living score improved from 60 ± 17 before surgery to 85 ± 8 at follow-up ($P < .05$). MRI demonstrated 67% to 100% repair fill and 64% had fissures smaller than 2 mm at the articular cartilage interface. There was one failure in a patient who required four plugs.

Figueroa and associates[59] reported their results of this operation in 10 men aged 15 to 38 years who were followed a mean of 3.1 years postoperatively. Additional procedures to treat patellar instability and malalignment were required in each patient. The investigators reported improvements in the Lysholm score and a mean postoperative IKDC subjective score of 93.6 (range, 92-96). MRI obtained 6 to 10 months postoperatively demonstrated ICRS normal or nearly normal ratings in the graft and peripheral chondral tissue.

Our Studies of Procedures for Patellofemoral Articular Cartilage Lesions

We have prospectively followed all patients in whom a patellar osteochondral autograft transfer procedure was performed at our center.

Between July 1996 and February 2010, a total of 53 osteochondral autograft transfer procedures were done in 43 knees for isolated patellar lesions. Twenty-three of these had failed at the time of writing, leaving 30 procedures that have been followed a mean of 5.6 years (range, 2.3-10.1 years). The 23 procedures that failed occurred in 18 women and five men whose mean age at the time of surgery was 35.5 years (range, 26-50 years). The average time from surgery to the failure (defined as a revision osteochondral autograft transfer, total knee arthroplasty, patellectomy, patella allograft, or patient designated as requiring any of these procedures) was 3 years (range, 0.4-10 years). All but six of these patients had sustained an injury to their knee—during daily activities in eight, during work activities in six, and during sports in three. An average of 9 years had elapsed (range, 0.2-27 years) between the injury or onset of symptoms and the osteochondral autograft transfer procedure.

The 30 patellar osteochondral autograft transfer procedures that had survived at the time of writing were performed in 23 females and seven males. The mean age at the time of the procedure was 33 years (range, 14-45 years). Sixteen patients sustained an injury, and 14 patients had a gradual onset of symptoms without an injury. The mean time from the injury or onset of symptoms to the operation was 7.7 years (range, 0.6-23.6 years). At the most recent follow-up (data available for 25 patients a mean of 5.6 years [range, 2.3-10.1 years]), 11 patients rated their knee condition as very good, 8 as good, 4 as fair, and 2 as poor. Eighteen patients were able to participate in low-impact athletic activities without problems. Three patients were able to perform daily activities without problems, and four patients had moderate problems with daily activities. Seven of these patients received a functional rating as failed because their pain score had not improved compared with the preoperative rating.

We conducted a systematic review to determine the outcomes of operations performed for large (≥4 cm^2), symptomatic lesions in the patellofemoral joint in patients aged 50 years or younger.[126] Eighteen articles encompassing 840 knees were included. There were 613 knees that underwent ACI, 193 knees that had patellofemoral arthroplasty, and 34 knees that underwent osteochondral allografting. Long-term follow-up was only available in four studies, and 21 different outcome instruments were used to determine knee function. When taking into account knees that either failed or had fair or poor function, the percent of patients who failed to achieve a benefit averaged 22% after patellofemoral arthroplasty, 33% after osteochondral allografting, and ranged from 8% to 60% after ACI (Fig. 35-20). The results of this review demonstrated that in younger patients with large patellofemoral lesions, all three procedures had unpredictable results. Accordingly, patients with patellofemoral cartilage damage undergoing cartilage restoration procedures are advised that these procedures may or may not relieve arthritis-related symptoms. In middle-aged patients, there is increase use of a patellofemoral arthroplasty as described in Chapter 37.

Outcomes of Trochleoplasty Procedures

A recent systematic review of 11 studies encompassing 339 knees that underwent trocheoplasty procedures found significant improvements in clinical rating scales (Kujala, IKDC, KOOS) and an overall complication rate of 13.4%.[156] Problems related to increased pain were reported in 29 knees, loss of knee motion in 12 knees, and redislocated patella in 3 knees.

Blond and Haugegaard[24] followed 37 knees in 31 patients for 1 to 4.7 years after their modified arthroscopic Breiter trochleoplasty procedure and MPFL reconstruction (Table 35-9). These investigators reported that 87% had acceptable results with no further surgery required, and none had a recurrent patellar dislocation. These authors hypothesized that this combined procedure would reduce joint forces, pain, and subsequent cartilage wear compared with an MPFL reconstruction alone; however, the study was unable to address this theory.

Outcomes of the Dejour technique were assessed in a group of 31 knees a mean of 7 years postoperatively.[129] All patients underwent additional procedures as required such as tibial tuberosity distalization or medialization. No patient had a subsequent patellar dislocation, and patellar tracking was normal in all cases at follow-up. There was no

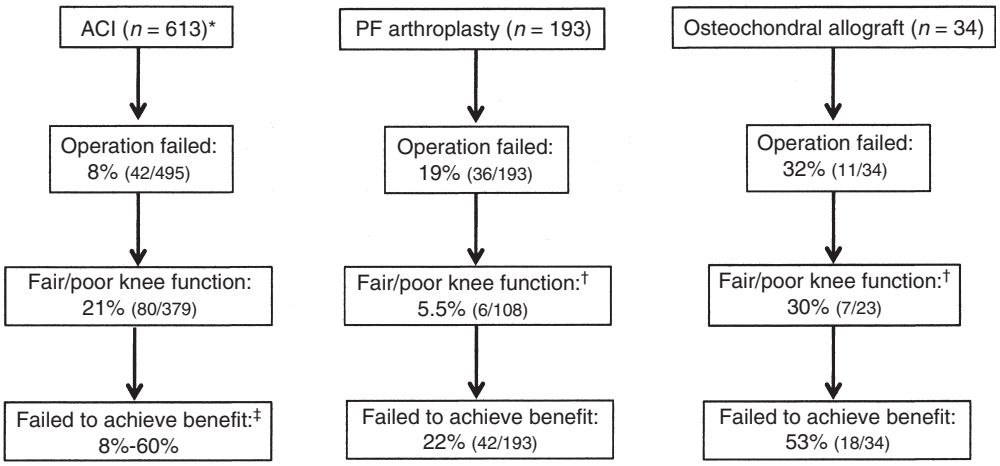


FIG 35-20 Rates of patients who failed to achieve a benefit from their operation. *For ACI, the rate of failure was not provided in one study, and fair or poor knee function could not be determined in three studies. †For PFA, fair or poor knee function could not be determined in one study. ‡An average value for this rate could not be accurately calculated in some studies because it was unclear whether patients in whom the operation failed were also included in the fair and poor knee function categories. For all other PFA studies and all allograft studies, fair or poor knee function was determined in patients in whom the prosthesis or allograft had survived. *ACI*, Autologous chondrocyte implantation; *PFA*, patellofemoral arthroplasty. (From Noyes FR, Barber-Westin SD. Advanced patellofemoral cartilage lesions in patients younger than 50 years of age: is there an ideal operative option? *Arthroscopy*. 2013;29:1423-1436.)

TABLE 35-9 Clinical Outcomes of Trochleoplasty for Severe Trochlear Dysplasia

	SUBJECTS						OUTCOMES			
Study	No. Knees/ Patients	Follow-up (yr)	Prior PF Procedures	Age (Range) (yr)	F:M	Operative Procedure	Complications	Redislocation Rate (%)	Rating Scales (2014)	Satisfaction, Return to Activity Rates
Blond & Haugegaard[24] (2014)	37/31	1-4.7	16 prior PF surgery	19 (12-39)	21:10	Modified Bereiter (arthroscopic); MPFL reconstructed with gracilis tendon	Two subsequent tibial tubercle medialization, three lateral release	0	Kujala preoperative 64 (range, 12-90), F/U 95 (range, 47-100) KOOS pain preoperative 86 (range, 42-97), F/U 94 (range, 53-100) KOOS sports preoperative 40 (range, 0-95), F/U 85 (range, 20-100)	93% satisfied; 55% resumed sports/maximal activities
Banke et al[8] (2014)	18:17	2-3.3	4 prior PF surgery	22 ± 5	11:6	Bereiter; MPFL reconstructed with gracilis tendon	Two arthroscopic lysis adhesions, one overtight MPFL revised	0	Kujala preoperative 51 (range, 7-86), F/U 88 (range, 59-103) IKDC preoperative 49 (range, 11-82), F/U 82 (range, 49-99)	94% satisfied
Ntagiopoulos et al[129] (2013)	31:27	2-9	No prior PF surgery	21 (14-47)	13:14	Dejour; all had combined procedures	Two removal broken staples, one DVT	0	Kujala preoperative 59 (range, 28-81), F/U 87 (range, 49-100) IKDC preoperative 41 (range, 25-80), F/U 82 (range, 40-100)	94% satisfied; 87% returned to prior activity level
Dejour et al[42] (2013)	24:22	2-15.9	All prior PF surgery	23 (14-33)	1:33	Dejour; all had combined procedures	One removal of broken staples	0	Kujala preoperative 44 (range, 25-73), F/U 82 (range, 61-100) IKDC preoperative 51 (range, 23-75), F/U 77 (range, 53-100)	All patients satisfied; 95% returned to prior activity level
Nelitz et al[115] (2013)	26:23	2-3.5	13 prior PF surgery	19 (15-23)	9:14	Bereiter; MPFL reconstructed with gracilis tendon	None	0	Kujala preoperative 79 (range, 21-100), F/U 96 (range 74-100) IKDC preoperative 74 (range, 32-95), F/U 90 (range, 65-98)	All returned to sports, 6 at a lower level; 10 very satisfied, 12 satisfied with results

Fucentese et al[63] (2011)	44:38	2-7.8	13 prior PF surgery	18 (14-40)	28:10	Bereiter	Two subsequent stabilization procedures, one transient femoral nerve palsy, one wound-healing problem, one CRPS	2	Kujala preoperative 68 (range, 29-84), F/U 90 (range, 42-100)	6 instability with daily activities, 7 would not have surgery again; authors now perform concurrent MPFL reconstruction
Thaunat et al[166] (2011)	19:17	1-5.9	7 prior PF surgery	23 (18-45)	9:8	Goutallier; all had additional procedures	One lysis adhesions, two procedures for tibial tubercle pseudarthrosis, eight removal anterior tibial screws, one dislocation traumatic injury	5; two patients failed, treated conservatively	Kujala F/U 80 (range, 33-98) KOOS F/U 70 (range, 23-96) IKDC F/U 67 (range, 21-92)	31% very satisfied, 63% satisfied with outcome
Utting et al[171] (2008)	42:40	1-4.8	16 prior PF surgery	21 (14-33)	NA	Bereiter; associated procedures in 29 knees	One manipulation, one dislocation traumatic injury	0	Kujala preoperative 62 (range, 29-92), F/U 76 (range, 26-100) IKDC preoperative 54 (range, 26-89), F/U 72 (range, 23-100)	93% satisfied; 67% resumed sports/maximal activities
Donell et al[48] (2006)	17:15	1-9	6 prior PF surgery	25 (15-47)	12:3	Dejour	Five lysis adhesions, one patellar chondroplasty, one remedial reefing, one removal loose screw; six marked painful crepitus	0	Kujala preoperative 48 (range, 13-75), F/U 75 (range, 51-98)	41% very satisfied, 41% satisfied, 18% disappointed
von Knoch et al[176] (2006)	45:38	4-14	15 prior PF surgery	22 (15-31)	22:16	Bereiter	One distal realignment, one patella infera; pain increased in 33%	0	Kujala F/U 95 (range, 80-100)	100% satisfied; all but one returned to higher sport levels
Verdonk et al[175] (2005)	13:12	0.7-2.8	19 prior PF surgery	27 (14-39)	9:3	Dejour	Five arthrofibrosis, two persistent pain, one total knee arthroplasty	0	Larsen-Lauridsen: 3 good, 3 fair, 7 poor	77% satisfied
Schottle et al[144] (2005)	19:16	2-4	5 prior PF surgery	22 (17-40)	13:3	Bereiter	Four persistent apprehension, five medial parapatellar tenderness, two increased pain	0	Kujala preoperative 56 (range, 27-67), F/U 80 (range, 43-99) Drez subjective score: 10 excellent, 6 good, 1 fair, 2 poor	NA

CRPS, Complex regional pain syndrome; *DVT*, deep venous thrombosis; *F:M*, female/male ratio; *F/U*, follow-up; *MPFL*, medial patellofemoral ligament; *NA*, not available; *PF*, patellofemoral.

evidence of patellofemoral arthritis on axial radiographs. None of the patients in this series had undergone previous patellofemoral surgery, the mean age was 21 years, and 90% had ICRS cartilage grades of I or II (normal or nearly normal) on the trochlea.

In another series of 24 knees that had undergone prior failed patellofemoral procedures, Dejour and colleagues[42] reported no major complications and a 100% satisfaction rate a mean of 5.5 years postoperatively. However, a positive apprehension sign was still present in 25%, and pain remained unchanged or increased in 28%.

The outcome of the Bereiter technique, combined with a gracilis tendon MPFL reconstruction, was examined by Banke and colleagues[8] in a cohort of 17 patients (18 knees) whose mean age was 22 ± 5 years. At a mean of 2.5 years postoperatively, all patients but one were satisfied, and no recurrent patellar dislocations had occurred. None of these patients had degenerative changes in the patellofemoral compartment at surgery, and none had undergone prior major operative procedures. Two patients required an arthroscopic lysis of adhesions for early arthrofibrosis and one patient required a revision MPFL reconstruction.

Poorer results were reported after the Bereiter technique by Fucestese and associates,[63] who did not perform a concurrent MPFL reconstruction. In a group of 44 knees followed a mean of 4 years, two patients required further stabilization procedures and 6 others had a sensation of instability with daily activities. Deterioration of cartilage on the lateral trochlear facet was noted on MRI in 16 knees. These authors now perform MPFL reconstructions with this trochleoplasty technique.

ILLUSTRATIVE CASE

Acute Patellar Tendon Rupture. A demonstration of the surgical technique for an acute patellar tendon rupture is shown in Figure 35-21. In Figure 35-21, *A*, the preoperative photograph shows subcutaneous hemorrhage along the anterior aspect of the knee in a patient who sustained a fall and acute rupture of the patellar tendon. The preoperative MRI showed extensive disruption throughout the entire patellar tendon. In Figure 35-21, *B*, the initial exploration shows a "mop-end" appearance to the midsubstance patellar tendon rupture. Figure 35-21, *C* and *D* show the method of repair with interrupted baseball locking sutures from the distal tendon to the proximal tendon or through the patellar tunnel based on the site of the tendon rupture. In this case, a tendon-to-tendon repair was performed. Two wire sutures were placed through the tibial tubercle and distal one third of the patella. One wire suture was placed through the tibial tubercle and distal quadriceps patellar attachment to function as a tension band. The use of wire fixation does involve the need for later removal; however, it provides a firm fixation of low cross-sectional area, which is an advantage over synthetic tape. The length of the repaired patellar tendon is adjusted at surgery and verified by fluoroscopy to be equal to the opposite lateral knee preoperative radiograph. It is important that the immediate range of motion from 0 to 90 degrees be initiated within the first 2 weeks after surgery, along with quadriceps muscle exercises to prevent a patella infera. The wire fixation allows initial weight bearing with the knee in extension. A semitendinosus-gracilis graft augmentation was not required in this case but may be indicated if the patellar tendon is severely disrupted, preventing primary tendon suture. This patient had a successful result and was weaned from crutches at 8 weeks postoperatively, regained a normal range of knee motion, and had a normal patellar height equal to the opposite knee. He was cautioned to avoid full weight bearing on the operative limb in ascending and descending stairs until 20 weeks from surgery and to not participate in sporting activities until 6 months after surgery.

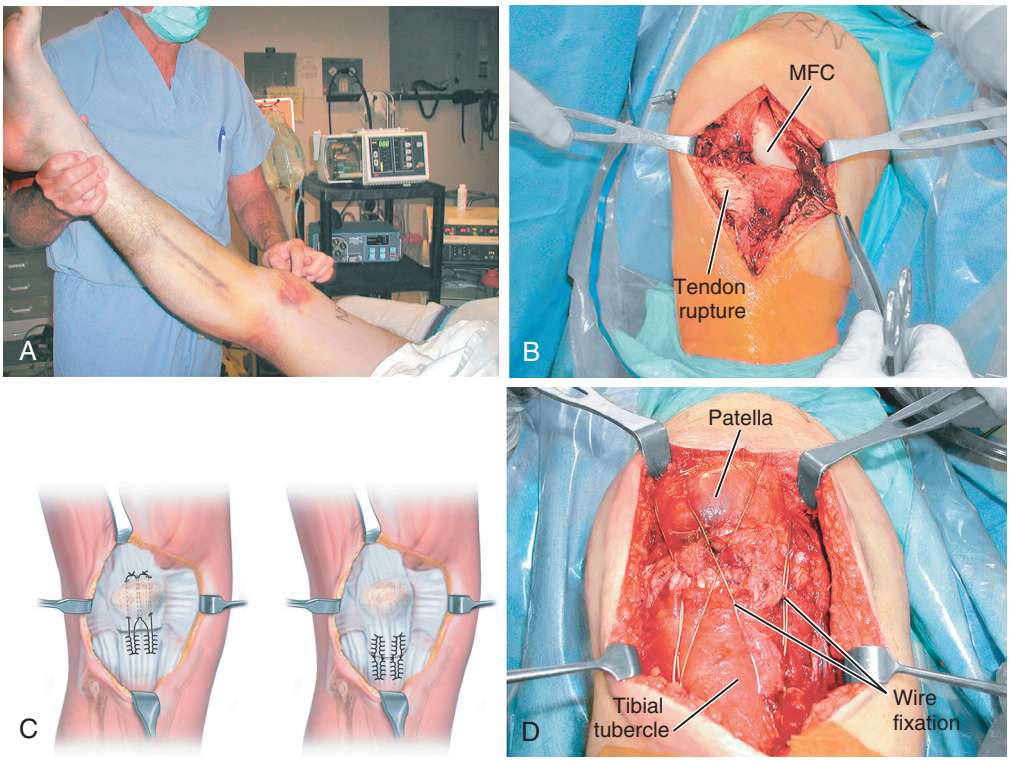


FIG 35-21 Repair of acute patellar tendon rupture. *MFC,* Medial femoral condyle.

Video Content

Video 1-1
Video 35-1
Video 35-2
Video 35-3
Video 36-1

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Patellofemoral Disorders: Correction of Rotational Malalignment of the Lower Extremity

Robert A. Teitge

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INTRODUCTION

What is Rotational Malalignment?

The geometry of bones is normally viewed in the three cardinal planes: frontal (coronal), sagittal, and transverse (horizontal, Fig. 36-1). The mechanical axis of the lower extremity from the femoral head center to the talus center (sometimes referred to as the hip-knee-ankle [HKA] axis) needs to be viewed in each of the three planes to define alignment. In the frontal plane, angular deviations from the normal straight line are referred to as varus-valgus, in the sagittal plane as flexion-extension, and in the horizontal plane as anteversion-retroversion (or antetorsion-retrotorsion). Just as varus or valgus deformity observed in the frontal plane causes abnormal joint loading, excess anteversion or retroversion observed in the horizontal plane causes abnormal joint loading.

Anterior knee pain, patellar instability, and patellar arthritis/chondromalacia are three different conditions that may be causally related to an abnormal limb alignment in the transverse plane. This chapter reviews the concept of torsional malalignment of the lower limb and its effect on the patellofemoral (PF) joint.

Limb alignment determines where and in what direction the tibiofemoral joint and patellofemoral joint (PFJ) are loaded. The geometry of the skeleton determines the direction of the load application on the PFJ. The PF ligaments acting against the patella in the trochlea are responsible for stability. Articular cartilage reduces friction to conserve energy and to transmit the force generated by a combination of body mass, momentum, gravity, and muscles. The musculotendinous units move the skeleton, stop it from moving, or hold it against gravity but are not normally responsible for preventing joint dislocation or subluxation. The total load depends on a variety of variables, including body mass, muscle activity, gravity, lever arm length, rate and direction of body motion, and so on. Femoral and tibial torsion both alter the position of the trochlea in space, thus where PF forces are centered. These forces may be changed by rotational osteotomy of the femur or tibia.

"Does Lower Limb Torsion Matter?" was the title of a keynote address at the 2012 European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA) meeting. The question importantly opens the door to a multitude of related queries. What is torsion? What is rotation? How is torsion measured? Is there validity to the torsion measurement? What is normal torsion? What is the mechanical effect of altered torsion? Does abnormal torsion cause symptoms? Does abnormal torsion cause pathology? Where is abnormal torsion located? Are femoral and tibial torsions equally important? Are femoral and tibial torsions compensatory? Can abnormal torsion be corrected? Are femoral and tibial torsions the only causes of abnormal limb torsion? Is corrective osteotomy beneficial? There are an endless variety of additional questions, none of which has been adequately studied.

Maquet, in his masterpiece *Biomechanics of the Knee*,[29] drew a strong relationship between the location of the resultant vector sum of all of the forces that produce knee joint loading and the location of the mechanical axis. Although he is often remembered for his anterior displacement osteotomy of the tibial tuberosity, Maquet emphasized an understanding of limb alignment in the coronal plan. Missing from the complete picture has been a similar analysis of the forces as seen in the transverse or horizontal plane.

The term *miserable malalignment* was apparently first introduced by Stan James.[15] His classic description of limb maltorsion is highly recommended reading.

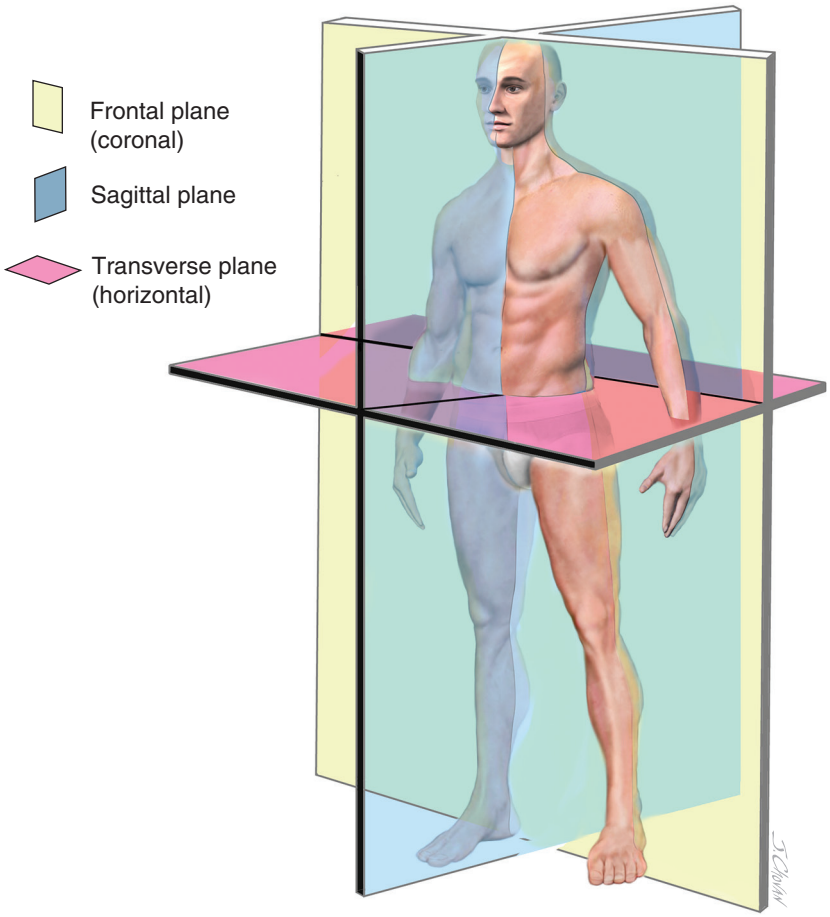


FIG 36-1 The geometry of bones is normally viewed in the three cardinal planes: frontal (coronal), sagittal, and transverse (horizontal).

The essence of this chapter is that during normal gait, the knee joint axis moves forward in the direction the body is moving. When the knee joint axis is twisted away from the direction the body is moving, the loading vectors are directed obliquely, resulting in abnormal PFJ shear forces. This is common with abnormal torsion of either the femur or the tibia. For example, a patella dislocates when the combined stabilizing elements of trochlear geometry and PF ligaments are overcome by an excessive dislocating force. The excessive dislocating force is often caused by a knee joint pointing inward because of abnormal femoral anteversion or abnormal increase in external tibial torsion. Corrective osteotomy has no effect on the trochlear geometry or the integrity of the PF ligaments, but it does change the displacement force.

Normal alignment is presumed to be normal because it is the optimal limb geometry for the transfer of the body mass to the ground. Abnormal geometry results in unusual force transmissions through the PF joint during gait. It is rare to see published PF clinical studies that have reviewed limb alignment adequately. The precise variation from the normal skeleton is generally not specified, ranges of motion of all joints in all planes of the lower extremity have not been adequately recorded, and ligamentous stability is not measured.

The literature on patellar malalignment is quite confusing because many terms are commonly interchanged and not precisely defined. John Insall in 1976 defined *patellar malalignment* as being either an increased Q-angle or a high-riding patella.[13] No other options were considered. In addition, he observed that "an increased Q-angle is usually associated with increased femoral anteversion and external tibial torsion. In the presence of these abnormalities, when the hip and ankle joints are normally aligned, the patella faces inward and motion of the knee occurs about an axis that is rotated medially compared with the axes of the hip and ankle joints." He then recommended a medial tibial tubercle transfer or "patellar realignment" to treat this torsional malalignment, and it is no surprise that he reported that 61% of the patients remained symptomatic. Clearly the underlying pathoanatomy had not been measured nor addressed. Subsequent biomechanic studies suggest the recommended treatment is inappropriate. Tibial tubercle transfer has been shown to cause external rotation of the tibia on the femur rather than pull the patella medially into the trochlea[17] and has been shown to increase medial compartment loading[20] and medial facet loading. I believe the terms *patellar malalignment* and *patellar realignment* lack precise definition and therefore should never be used. The term *malalignment* should refer only to a limb that deviates from a neutral (normal) mechanical axis, and the deviation must be defined in each plane. Skeletal alignment is a direct result of the shape of the bones in the limb, but limb malalignment may also be caused by a joint with acquired cartilage or ligament loss.

More than 50 different factors have been associated with anterior knee pain, chondromalacia patellae, patellar instability, or patellar malalignment (Table 36-1). Although these factors may be very important, objective measurement tools are lacking. No study has ever tried

TABLE 36-1 Cited Contributions to Patellofemoral Dysfunction

Genu valgum	Genu varum
Femoral anteversion	Femoral retroversion
Excess external tibial torsion	Excessive internal tibial torsion
Outerbridge ridge	Trochlear dysplasia
Shallow trochlea	Short lateral trochlea
Increased Q-angle	Decreased Q-angle
Excessive lateral quadriceps pull	Insufficient vastus medialis obliquus
Decreased patellar surface contact area	Abnormal patellar spin
Patellar dysplasia	Patella alta
Patella baja (infera)	Meniscectomy
Laxity of ACL, PCL, MCL, or FCL	Rotatory instability
Iliotibial band contracture	Quadriceps contracture
Achilles contracture	Retinacular contracture
Retinacular laxity	Hyperpronation
Pes planus	Tibial tubercle–trochlear groove distance (TT/TG)
Patellar malalignment	Patellar instability
Patellar subluxation	Medial patellar dislocation
Lateral patellar dislocation	Chondral softening
Genu recurvatum	Patellar tilt
Patellar shift	Abnormal (mal) tracking
VMO dysplasia	J sign
A sign	Bayonet sign
Crossing sign	Trochlear bump
Patellar thickness	Knee flexion contracture
Infrapatellar contracture	VMO/VLO ratio
Rearfoot varus	Patellar glide
Quadriceps tendon width	Flexor hallucis longus tendon entrapment
Flexor hallucis dysfunction	Increased lumbosacral instability
Hip flexion contracture	Abdominal oblique: rectus femoris + psoas imbalance
Quadriceps atrophy	Pelvic abductor weakness
Increased thoracolumbar extension	Inward pointing knee
Female gender	

ACL, Anterior cruciate ligament; *FCL*, fibular collateral ligament; *MCL*, medial collateral ligament; *PCL*, posterior cruciate ligament; *VLO*, vastus lateralis obliquus; *VMO*, vastus medialis obliquus.

to assess all of these variables in a single cohort of patients, and even if this were undertaken, the lack of objective measurement techniques would make the study invalid. If these variables are indeed important, then any study would need to incorporate accurate measurements of each. The relative importance of each needs to be developed. Without this, clinicians are left with a realization that data do not exist to guide in the knowledge of pathomechanics, diagnosis, and treatment and that we depend only on unrelated clinical observations and some very basic laboratory studies. Thus, the complete validation of the importance of limb torsion in contributing to PF pain and dysfunction may always be challenged.

Anterior Knee Pain, Patellar Instability, and Patellar Chondropathy

All three of these disorders are often the result of excessive mechanical force. This excessive force is often the result of a twisting of the knee out of normal alignment. These three disorders may or may not be related and may coexist. It is useful in the evaluation of PF symptoms to consider each independently.

Anterior knee pain may have many causes as suggested in Table 36-1. Abnormal soft tissue strain caused by twisting of the knee out of normal plane is a likely contributing cause. No studies linking the prevalence of abnormal femoral or tibial torsion with anterior knee pain have been published.

Patellar instability results from a loss of the patellar stabilizers when subjected to an excess of displacement forces. The patellar stabilizers are the trochlear groove and both the medial and lateral PF ligaments and the medial and lateral meniscopatellar ligaments. As early as 1964, Brattström[2] demonstrated that in recurrent dislocation of the patella, a flattening or dysplasia of the trochlear groove is nearly always present. Dejour and colleagues[6] demonstrated that this dysplasia is often in the proximal portion of the trochlea not seen on an axial PF radiograph but measureable on a true lateral knee radiograph by recognizing the floor of the groove and the anterior projections of the medial and lateral condyles. For lateral patellar dislocation to occur, the medial patellofemoral ligaments (MPFLs) must have been injured. A number of authors, including Christoforakis and colleagues[4] and Desio and associates,[8] have demonstrated in the laboratory that the lateral retinaculum provides up to 19% of the resistance against lateral displacement; thus the patella is usually more unstable after lateral retinacular release. Medial dislocation is a distinct possibility, and I reported 70 cases confirmed with stress radiography at the annual meeting of the American Association of Orthopaedic Surgeons in 1990. The diagnosis of instability requires a force and displacement examination, and stress radiography[46] may provide documentation as shown in Figures 36-2 and 36-3, in which unstressed radiographs were normal but stress application demonstrates obvious excessive displacement.

A necessary contributing cause of patellar dislocation is the existence of an abnormally high displacement force. This most often occurs when the direction of the lateral quadriceps vector is increased and commonly occurs when the femur twists medially out from under the patella. This is usually caused by some torsional abnormality of the lower limb (Fig. 36-4). In the face of such excess displacement forces, a PF ligament reconstruction may fail. No studies accurately correlating femoral and tibial torsion with the incidence of patellar instability have been published.

Arthrosis or chondromalacia exists when articular cartilage fails as the force per unit area exceeds biological tolerance. For acute fractures of articular cartilage, this may be in the range of 20 MPa. Chronic overload caused by a too small articular surface area or too much body weight, muscle loading, or long lever arms with chronic pressure exceeding 5 MPa may lead to arthrosis. Articular cartilage fractures exist nearly 100% of the time after acute patellar dislocation.[32] Although magnetic resonance imaging (MRI) is often used to demonstrate articular cartilage lesions, its sensitivity is still limited. Double-contrast computed tomography (CT) arthrography is seldom used but may offer increased resolution as seen in Figure 36-5. No studies correlating specific articular cartilage lesions with limb torsion have been completed.

HOW DOES LONG BONE TORSION AFFECT THE PATELLOFEMORAL JOINT?

The knee joint axis moves straight forward during gait with a small (<10 degrees) turning inward and outward.[27] The foot also tends to move in a fairly constant direction (foot progression angle).[28,38] The geometry of the lower extremity skeleton largely determines the direction of load application at the PF joint, with the amount of load depending on the body mass, the length of the lever arms, the surface

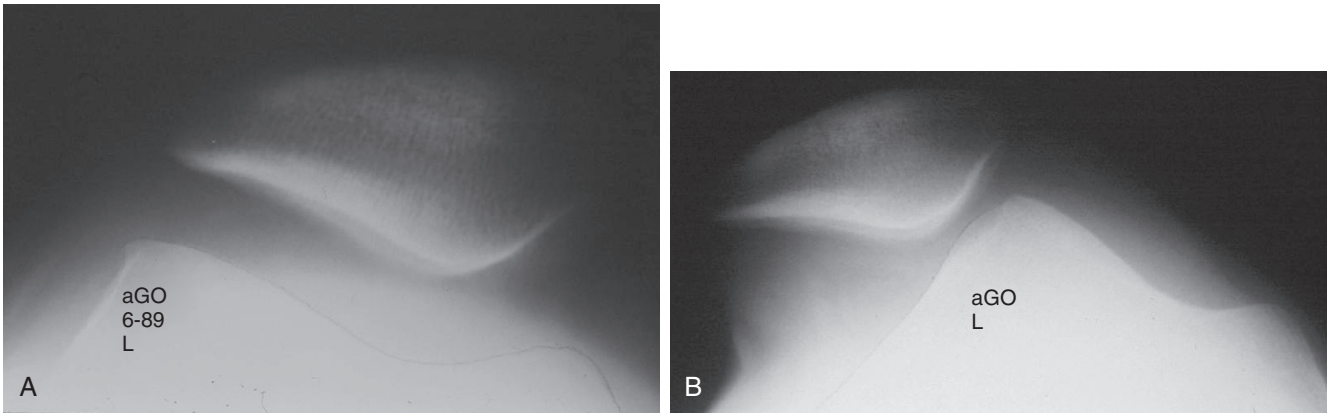


FIG 36-2 **A,** An 18-year-old patient complained of anterior knee pain and giving way, without a history of dislocation. Radiographic parameters are normal. **B,** Stress application was necessary to demonstrate dislocation.

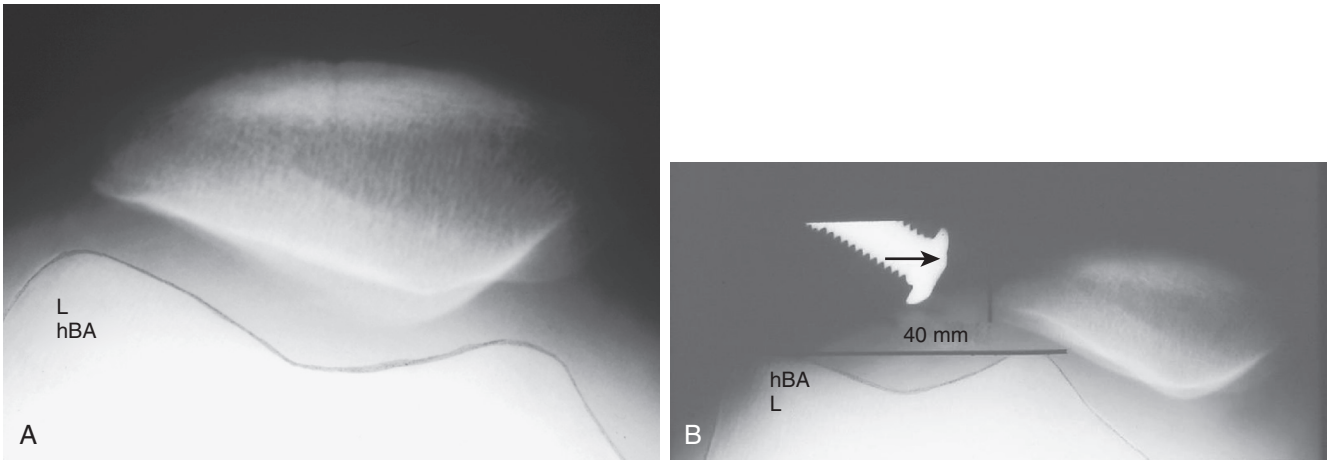


FIG 36-3 **A,** Radiograph of a 38-year-old woman with anterior knee pain after a dashboard injury. Symptoms worsened after a lateral retinacular release. Radiographic parameters were normal. **B,** Stress radiographs demonstrated medial dislocation.

area of the PFJ, and the velocity of the moving system. If the knee joint axis is twisted out of its normal plane of flexion and extension while the quadriceps is contracting, a side-directed force is created that acts on the patella, attempting to displace it. This causes an increased strain on the PF ligaments and retinaculum and an imbalanced direction of force on the PF articular surface.

If these side-directed vectors exceed biological tolerance, either instability or arthrosis may result. For example, an inward pointing of the knee increases the lateral direction of pull of the quadriceps. Therefore the pull on the MPFL (and medial retinaculum and medial meniscopatellar ligament) is increased and the direction of pressure on the patella is altered, creating an increase on the lateral facet and a decrease on the medial facet (Fig. 36-6). The radiographic appearance of subchondral density under the patellar facets is a useful clue to the mechanical environment (Fig. 36-7).

Maximum energy conservation during gait is caused by precise anatomy and joint kinematics.[35] Abnormalities in normal bony anatomy or joint motions distort the normal force vectors needed to transfer the body mass to the ground. Deviations in normal limb alignment may result in the knee joint flexion-extension axis advancing sideways while the body moves forward. Causes of a knee joint axis pointing out of the direction include weakness of hip musculature, femoral anteversion or retroversion, excess internal or external tibial torsion, genu valgum or varus, foot hyperpronation, and Achilles contracture.

The *foot progression angle* (FPA) is generally defined as the angle between the long axis of the foot and the direction of body progression and averages between 10 to 15 degrees.[28,38] It has been shown that the FPA remains similar despite differences in the torsion of the tibia or femur.[38] It is likely that this is because proper ankle dorsiflexion cannot occur during gait if the ankle joint axis is not aligned with the direction of forward movement or because this presents the most stable position of the foot on the ground. Hip rotation must vary if there are changes in the torsion of the long bones and the FPA stays constant. Alterations in both femoral and tibial torsion changes the effective lever arm of the hip stabilizers[1] and may account for the frequency of soft tissue complaints around the hip and pelvis, as well as the increased pelvic tilt and lumbar lordosis seen in these patients. Examples of the change

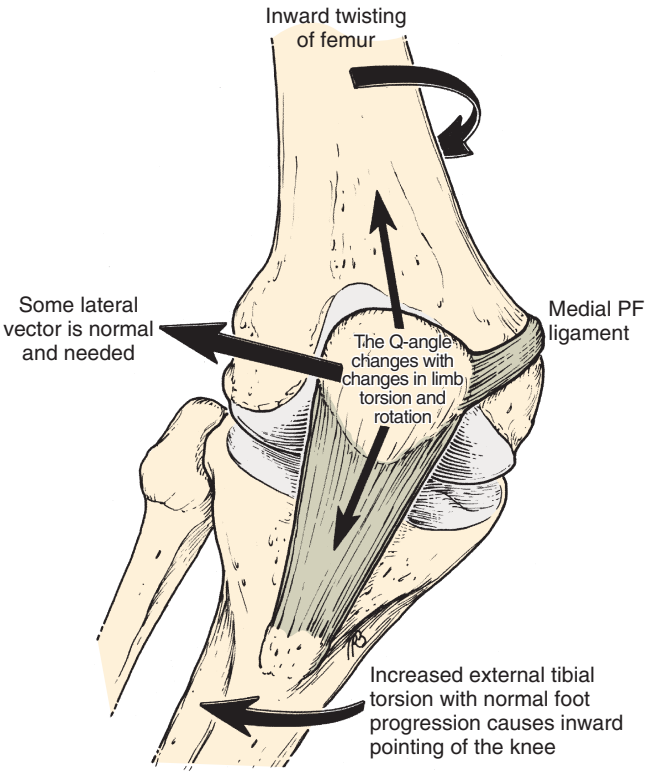


FIG 36-4 If the knee joint twists inward because the femur twists inward, the lateral pull on the quadriceps is increased, the lateral displacement pull on the patella is increased, the strain on the medial patellofemoral (PF) ligament is increased, the compression on the lateral patellar facet is increased, and the compression on the medial patellar facet is decreased. The treatment must be to decrease the inward twist on the knee joint, not to move the tubercle medially. A similar increase of inward pointing of the knee joint occurs in the presence of excess external tibial torsion when the foot is pointed forward.

in the position of the hip and knee with a constant foot progression angle and changes in femoral and tibial torsion are seen in Figures 36-8 to 36-12.

Figures 36-8 to 36-12 are drawn with a foot progression angle of 13 degrees (Seber average) for a normal male torsional alignment (Fig. 36-8), a normal female torsional alignment (Fig. 36-9), a female with 30 degrees of excess external tibial torsion (Fig. 36-10), a female with 30 degrees of excess femoral anteversion (Fig. 36-11), and a female with both 30 degrees of excess tibial external torsion and 30 degrees of excess femoral anteversion (Fig. 36-12). One may study the variations in knee joint progression with these common abnormal patterns. Yoshioka and associates[50-52] found identical femoral anteversion and genu valgus in both males and females but an increase in external tibial torsion and an increase in foot external rotation in females over males. This increase in external foot rotation may account for the apparent increased genu valgus in females, for the increased incidence in PF symptoms in females, and even for the increased incidence of anterior cruciate ligament (ACL) tears in females.

BIOMECHANIC EVIDENCE RELATING LIMB TORSION WITH PATELLOFEMORAL INSTABILITY AND PAIN

A change in PF contact areas and pressures were noted after alteration of femoral or tibial torsion or rotation by Lee and coworkers,[22-24] Hefzy and associates,[12] and vanKampen and Huiskes.[48] Kiljowski and colleagues[18] (unpublished data) placed lower limbs (femoral head to foot) in a frame with a clamp, attaching the femoral head to a vertical post that allowed the knee flexion to be altered by sliding the femoral head up and down the post. The foot was held in a position of normal FPA and an osteotomy was performed in the shaft of the femur, allowing rotation. PF contact pressures and MPFL strain were measured while the osteotomy changed the femoral torsion 15 degrees and 30 degrees, both inward and outward. At 30 degrees of knee flexion, lateral facet pressure increased an average of 30%, with a 30 degrees increase in

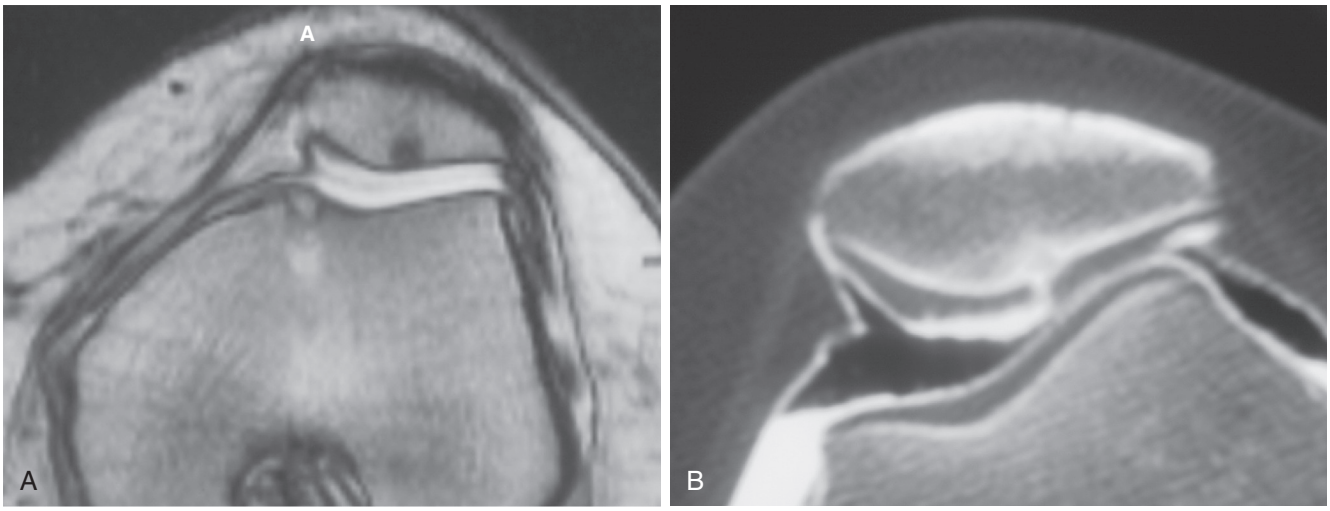


FIG 36-5 **A,** Magnetic resonance imaging read as focal osteonecrosis. **B,** Contrast computed tomography arthrogram clearly shows a split in the articular cartilage extending down to the cystic lesion with damaged articular cartilage medial to the cartilage split. Most likely, there was an acute subluxation episode that compressed the articular cartilage until it failed with a split relieving ligament tension, with further lateral subluxation damaging the medial articular cartilage into which the contrast dye now moves. *A,* Anterior.

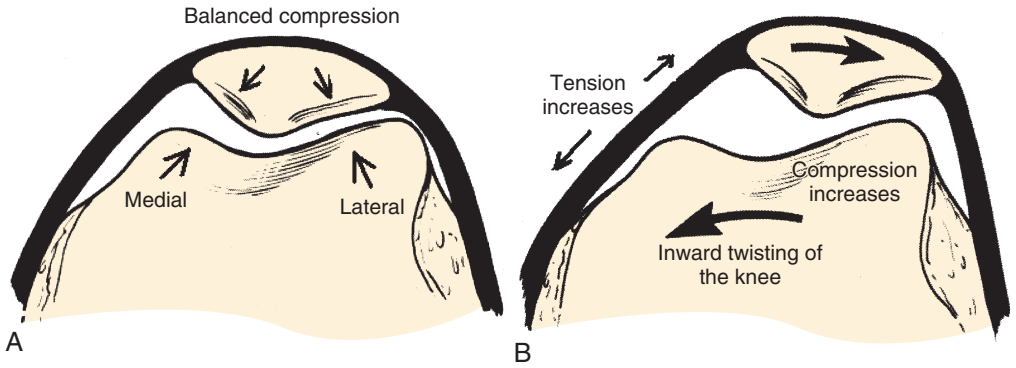


FIG 36-6 A, If the knee joint moves forward, the compression on the patellofemoral joint and ligaments tensioned are balanced. **B,** If the knee joint twists inward from beneath the patella, the medial patellofemoral ligament is placed under increased tension, the compression beneath the lateral facet increases, and the compression beneath the medial facet decreases.

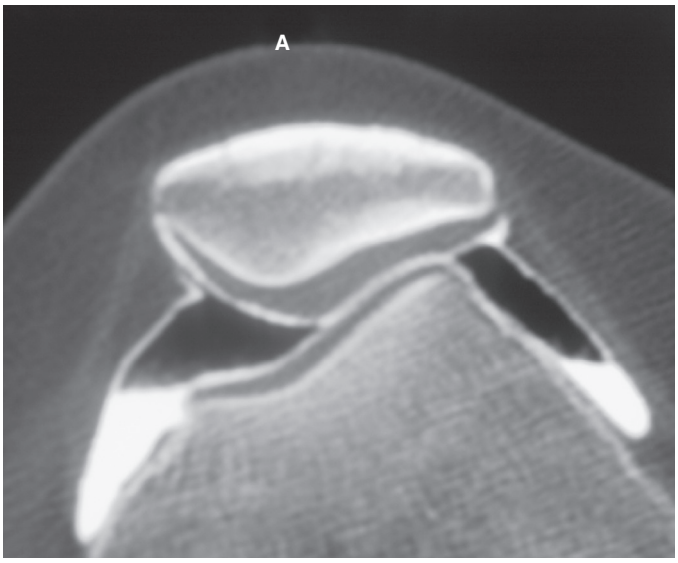


FIG 36-7 As the femur rotates internally beneath the patella, the lateral patellar articular cartilage is compressed. The increased crescentric density in the lateral patellar subchondral bone is indicative of chronic localized pressure. *A,* Anterior.

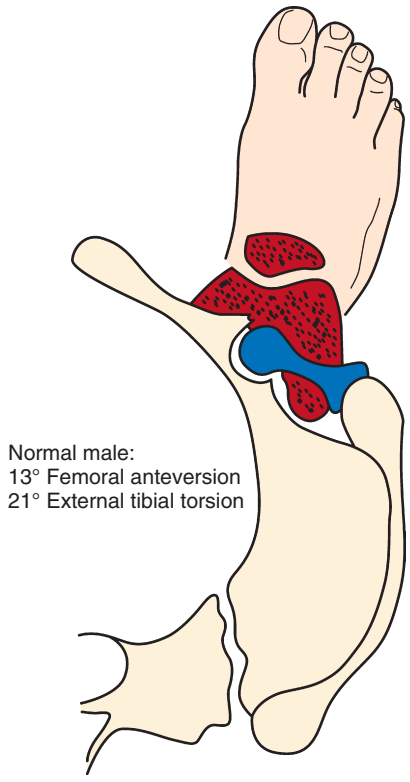


FIG 36-8 Normal male with femoral anteversion of 13 degrees and external tibial torsion of 21 degrees. Note that with a foot progression angle of 13 degrees, the knee joint faces slightly outward.

femoral anteversion, while medial facet pressures were decreased. Strain in the MPFL increased 57% after a 30 degrees increase of internal femoral torsion. Fujikawa and coworkers[11] in a biomechanic study measuring PF contact pressures concluded that if an angular deformity and a torsional deformity coexist, the rotatory component causes the greater PF changes. These authors also noted that when a varus deformity was created, the greater the varus deformity, the less the PF congruence.

CLINICAL EVIDENCE RELATING LIMB TORSION TO PATELLOFEMORAL INSTABILITY AND PAIN

Brattström[2] in 1964 measured trochlear depth in a group of patients with recurrent dislocation of the patella and confirmed that a shallow trochlea was always present. Brattström also defined the Q-angle and pointed out the change in Q-angle as a result of changes in limb rotation. Brattström reviewed the literature on the rotational femoral osteotomy as described by Graser (1904), Fürmeier (1953), Kiesselbach (1956), and Vinditti and Forcella (1958) and concluded that "femoral osteotomy is a big operation that demands prolonged after treatment. I have not encountered any instance of recurrent dislocation of the patella that justified my suggesting an operation of this nature to the patient." Takai and associates[42] measured femoral and tibial torsion in patients with unicompartmental arthrosis in either the medial, lateral, or PF compartment and found the highest correlation to be that of PF arthrosis with increased femoral anteversion (23 degrees of anteversion in the osteoarthritis group versus 9 degrees of anteversion in the control group). Janssen[16] found a high correlation between patellar dislocation and an increase in *internal femoral torsion* and speculated that *internal femoral torsion* was also responsible for the development

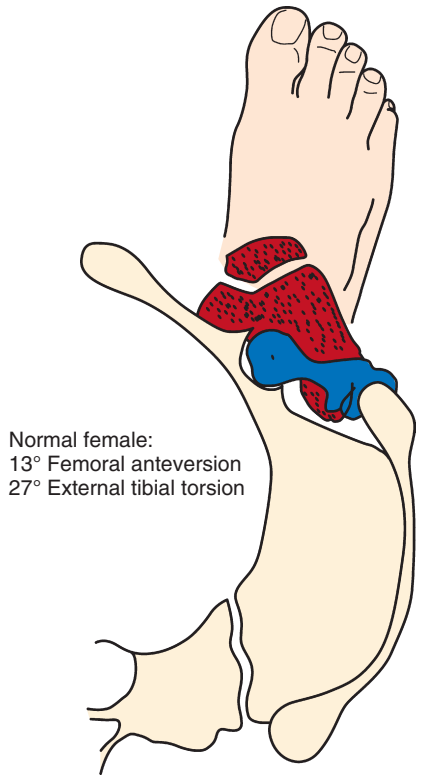


FIG 36-9 Normal female with femoral anteversion of 13 degrees and external tibial torsion of 27 degrees. Note that the knee joint is pointing slightly more inward and the greater trochanter is slightly more anterior than the normal male.

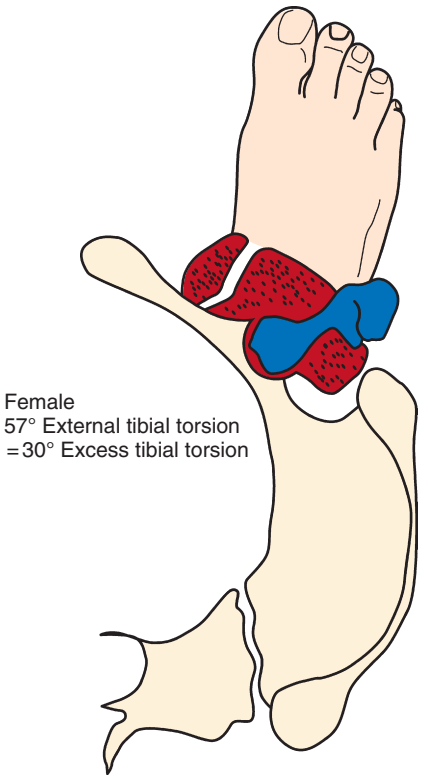


FIG 36-10 Female with a 30 degrees of increase in tibial torsion. To keep the foot progression angle normal, the knee joint axis points inward nearly 30 degrees, causing increased strain on the knee. The hip appears markedly internally rotated with the greater trochanter pointing somewhat anteriorly.

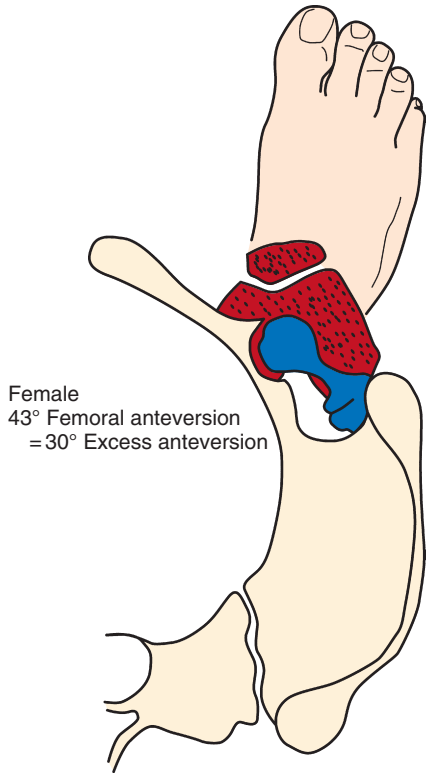


FIG 36-11 Female with 30 degrees of increase in femoral anteversion. The knee joint points in the same direction, slightly inward, as in the normal female, but the greater trochanter points posteriorly, giving a poor mechanical advantage. At some point, the hip cannot externally rotate enough to keep the knee joint pointed forward. With fatigue of the hip abductors, the knee points more inward to compensate for hip collapse, placing greater stress on the knee.

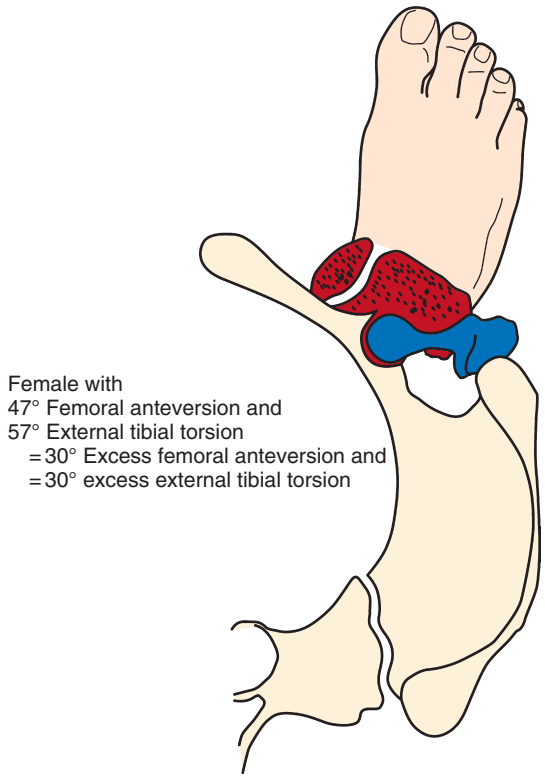


FIG 36-12 Female with a 30 degrees of increase in both femoral anteversion and external tibial torsion. Note the trochanter is pointed more anterior than normal, and with the foot progression angle normal, the knee joint axis points markedly inward.

of trochlear dysplasia. Lerat and colleagues[25,26] noted a significantly increased association of *internal femoral torsion* with both patellar instability ($P < .0001$) and patellar chondropathy ($P < .001$). Stroud and coworkers[41] followed 92 patients who, at age 5 years, showed 30 degrees greater *internal* hip rotation (measured in extension) than *external* rotation. At age 24 years, PF pain was noted by 30% in the increased *internal* rotation group compared with only 8% in the control group ($P < .001$). Winson and associates[49] found that 70% of adolescents undergoing arthroscopy for anterior knee pain had an increased *internal femoral torsion* compared with only 33% or those undergoing arthroscopy for a meniscal or cruciate injury. Turner[47] noted increased *external tibial torsion* in patients with PF instability (25 degrees vs. 19 degrees). Of perhaps great significance to those who believe that muscle strengthening is the key to treating PF symptoms, Nyland and colleagues[33] found a significant decrease in vastus medialis and gluteus medius electromyogram amplitude in athletes with clinically increased *internal femoral torsion*. Arnold and coworkers[1] noted that an increase in femoral anteversion of 30 to 40 degrees and decreased abduction moment arm strength by 40% to 50%, was enough to impair normal walking. Therefore those individuals required turning the knee inward to keep the hip from collapsing. This inward pointing of the knee creates high shearing force on the PFJ.

FEMORAL AND TIBIAL TORSION MEASUREMENTS LACK STANDARDS

Femoral anteversion has been measured by a variety of techniques by many authors[50,51] (Fig. 36-13). To measure limb alignment in the horizontal (transverse) plane, a CT rotational study is obtained. This is a CT scan that overlaps cuts from the femoral head, base of the femoral neck or lesser trochanter, the knee joint (either tangent to the posterior condyles or between the medial and lateral epicondyles), the proximal tibia at the joint, the tibial tuberosity, and the ankle joint (Fig. 36-14). These cuts allow measurement of femoral torsion, tibial torsion, knee torsion, and the tibial tubercle-trochlear groove (TT/TG) distance. CT also allows for the observation of trochlear depth or dysplasia, the position of the patella in the trochlea (unstressed), patellar tilt and shift, and the density of the subchondral trabeculae. Axial MRI with overlapped images may provide similar measurements, but no standards have yet been established.

To measure torsion of the femur, the recommendations of Murphy and coworkers[31] and Yoshioka and Cooke[50] are followed; these superimpose the CT cuts through the center of the femoral head and the base of the femoral neck where the circular nature of the femoral shaft becomes apparent (see Fig. 36-14, *A* to *C*). A line drawn through the center of these two proximal femoral locations becomes the proximal sreference line. A CT cut through the distal femur, where the anteroposterior (AP) dimension of the medial and lateral condyles is greatest allows a line to be drawn tangent to the posterior condylar surface. A second line can be drawn through the medial and lateral epicondyles. Yoshioka and Cooke[50] measured femoral torsion (anteversion) directly from the bone in a series of 32 femora and noted an average anteversion of 13.1 degrees in both males and females when the distal measurement was the tangent across the posterior femoral condyles and 7.4 degrees when measured across the epicondyles (standard deviation [SD], 8 degrees; range, –11 to +22 degrees). It is useful to measure both epicondylar axes and posterior condylar axes to help avoid an error if dysplasia of the lateral femoral condyle with a short AP distance is present. Yoshioka and Cooke[50] reviewed the literature that measured femoral anteversion using a variety of different techniques and noted that 12 of the 18 reviewed papers reported normal values between 8 and 16 degrees. I have arbitrarily chosen Yoshioka's 13 degrees as the goal for surgical correction. Kuo and colleagues[19] examined various measurement techniques and concluded that CT was accurate but

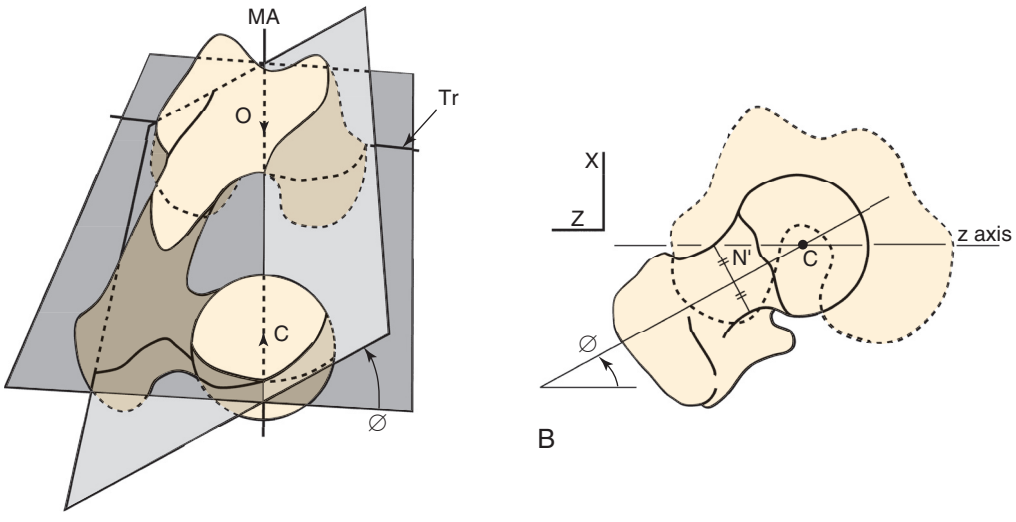


FIG 36-13 **A,** Femoral anteversion or antetorsion (angle Ø) may be measured along the center of the femoral neck from the center of the femoral head to the center of the femoral shaft at the base of the neck and distally either along the transepicondylar axis 7.4 degrees or the tangent of the posterior femoral condyles 13.1 degrees. These differ by about 6 degrees, with a range of 11 degrees retroversion to 22 degrees of anteversion. **B,** This measurement by Yoshioka and Cooke[50] is taken directly off the bone. Murphy and coworkers validated a computed tomographic measurement along these same lines. *C,* center of hip; *MA,* mechanical axis; *O,* origin of coordinate system, the attachment of the posterior cruciate ligament; *Tr,* transverse axis. (***A,*** From Yoshioka Y, Cooke TDV. Femoral anteversion: assessment based on function axes. *J Orthop Res* 1987;5:86-91. ***B,*** From Yoshioka Y, Siu D, Cooke TDV. The anatomy and functional axes of the femur. *J Bone Joint Surg Am* 1987;69:873-80.)

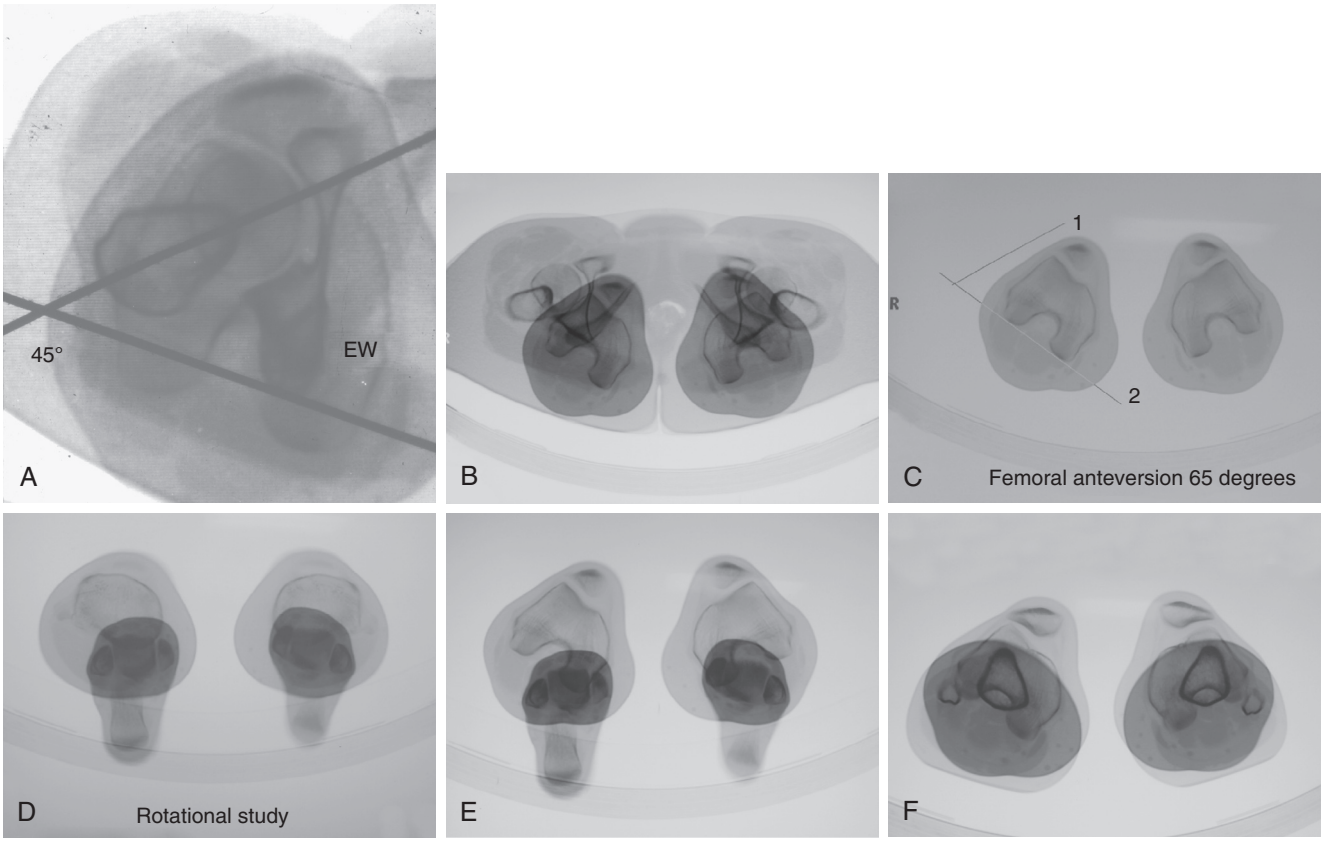


FIG 36-14 **A,** For measuring femoral torsion (anteversion), computed tomographic slices taken through the femoral head, the inferior greater trochanter, and the knee joint are superimposed. One line is drawn from the center of the femoral head through the greater trochanter and a second is tangent to the posterior femoral condyles at the knee joint. **B,** Hip and knee overlapped, allowing references lines seen in **C** to be drawn. **C,** *Reference line* 1 is taken from the center of the femoral head to the center of the femur at the level of the lower greater trochanter. *Reference line* 2 is a tangent to the posterior surface of the femoral condyles. The epicondyles are also readily seen and can be used as a second reference. There is generally a 6-degree difference between these two choices of reference. **D,** Tibial torsion can be measured between the axis of the tibial plateau and the ankle joint axis. **E,** The angle between the epicondylar axis of the femur and the ankle joint axis can be used as a measure of tibial torsion. **F,** The distance between the tibial tubercle and the center of the trochlear groove is also provided in the rotational study. Dejour and colleagues[6] stated that a distance greater than 20 mm is abnormal and correlates with objective patellar instability.

plane radiographic techniques were not. It is often stated that a patient with increased femoral anteversion has a compensatory external tibial torsion. Pasciak and coworkers[34] found this not to be the case and reported no relation between femoral anteversion and tibial torsion. In a review of over 300 CT rotational studies, we found that with increased femoral anteversion, tibial torsion may be normal, increased external, or increased internal.

The measurement of tibial torsion by CT has not been standardized. Jakob and coworkers[14] described a common sense method superimposing cuts across the proximal tibia and distal ankle joint. I have attempted to use the anatomic measurements of the tibia described by Yoshioka and colleagues[52] as a basis for measuring the proximal tibial reference line (Fig. 36-15). Blinded repeat measurements made by an orthopedic radiologist produced a measurement variation of less than 1 degree, indicating that reproducible measurements are possible. Yoshioka and colleagues'[52] anatomic study reported a lateral torsion of 21 degrees in males and 27 degrees in females, a significant difference. This was the only difference in geometry noted between males and females in both the tibia and the femur. In addition, these authors noticed a difference of 16 degrees between the transverse axis across the tibial plateau and the center of the foot. If this observation is confirmed, it is of major importance because it may explain the widely quoted difference between men and women in the frequency of PF disorders. It may also explain the reported increased incidence of ACL tears in women. Le Damany[21] reported 23.7 degrees to be normal tibial torsion. Seber and associates[38] calculated external tibial torsion to be 30 degrees (range, 16 to 50 degrees) in a group of 50 "normal" (asymptomatic) men, but their measurement technique was unique in selecting the location for drawing the proximal tibial reference. Eckhoff and coworkers[9] noted variations between 15 and 30 degrees. Turner[47] found 19 degrees (SD, 4.8 degrees) in a control group and 24.5 degrees (SD, 6.3 degrees) in a group with unstable patella. The CT measurements of Sayli and coworkers[36] averaged 30 to 35 degrees. Siston compared the selection of the transverse axis across the top of the tibial plateau by 11 different knee surgeons and reported a range of 90 degrees from 44 degrees of internal rotation to 46 degrees of external rotation and a standard deviation of 28.1 degrees.[53] This wide variation in selecting the location of a critical axis suggests that a more accurate and reproducible method is needed before we can answer important questions. Tamari and associates[43] demonstrated a lack of reliability

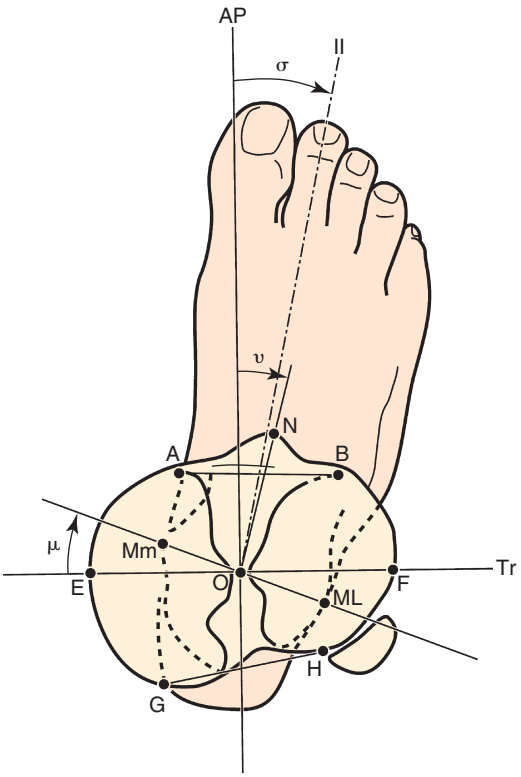


FIG 36-15 The tibial torsion may be measured as the angle μ, which is between the widest distance on the tibial plateau (E-F) and the line connecting the malleoli (Mm-ML). Males = 21 degrees, females = 27 degrees. Angle σ is the "foot rotation," the outward deviation of the foot in reference to the tibial plateau transverse axis (E-F). Males = –5 degrees, females = +11 degrees. *A,* Anterior margin of articular cartilage medial tibial plateau; *AP,* anterior-posterior axis; *B,* anterior margin of articular cartilage lateral tibial plateau; *N,* anterior point of tibial tuberosity; *ML,* tip of lateral malleolus; *Mm,* tip of medial malleolus. (From Yoshioka Y, Siu DW, Scudamore RA, Cooke TDV. Tibial anatomy and functional axes. *J Orthop Res.* 1989;7:132-137.)

among measurement methods and this remains a major stumbling block in answering the question of how much of an influence altered tibial torsion plays in PF instability and when osteotomy may be useful.

In addition to using the tangent to the posterior tibial cortex, Cobb's axis, and Yoshioka's anatomic measurements, I also use the femoral epicondylar axis as the proximal reference for tibial torsion. This is because of the interest in the relationship of the knee joint axis to the ankle joint axis and the problem incurred in selecting a line across an ovalshaped tibial plateau. A rotation of the tibia on the femur must not be present if a distal femoral axis compared with the angle joint axis is used as to measure tibial torsion.

INDICATIONS

Any variation from optimal skeletal alignment may increase the vector forces acting on the PF joint, causing either PF ligament failure with subsequent subluxation or cartilage failure as in chondromalacia or arthrosis or both ligament and cartilage failure. Anterior knee pain may result from these abnormal forces or their consequences (Fig. 36-16).

An inward-pointing knee attributable to any cause will increase the lateral displacement force on the patella (Figs. 36-17 to 36-19). If this force is great or if the trochlear support is reduced from dysplasia or



FIG 36-16 Miserable malalignment. The patient often presents with medial parapatellar pain with no localizing findings or images indicating pathology. Later instability or arthrosis may develop.

fracture, the medial ligaments may fail, resulting in lateral patellar instability. The converse is also true. Pain in the medial retinaculum is a common symptom caused by this increased stress. If the trochlear support is normal, the ligament may not fail, but the articular load may increase, causing arthrosis. This increased force may be the result of abnormal femoral torsion, abnormal tibial torsion, genu valgum, hyperpronation, Achilles contracture, or other conditions. The choice for surgery depends on the relative size of the deformity and the relative surgical risk and morbidity.

The MPFL is a rather small structure. This is because a large ligament is not needed to restrain the patella from leaving the center of the trochlea if the limb is straight, the knee joint axis points forward, the quadriceps vector is in the frontal plane, and the trochlea is normal. If the trochlea is dysplastic (shallow), the ligament may not be strong enough to withstand the normal lateral pull of the quadriceps. If there is an abnormal limb torsion (so the knee joint does not move forward in the direction the body is moving), the side-displacing force is increased, and the ligament is more likely to be overcome, leading to patellar instability. An MPFL reconstruction may be useful to restore patellar restraint, but in the face of continued increased displacement forces caused by a torsional limb malalignment, such a reconstruction may fail. Conversely, in the face of normal limb torsion, the side-directed force may not be sufficient to displace the patella even with insufficient ligaments. The clinical presentation may be pain, instability, arthrosis, or a combination of these problems.

SURGICAL STRATEGY

The goal of operative treatment is to normalize the biomechanics through restitution of normal anatomy.[44,45] The morbidity of surgery may dictate otherwise. When multiple anatomic abnormalities exist, it is not known which may be more important. If a patient has recurrent



FIG 36-17 A 17-year-old student with rapid onset of pain and abnormal gait. It is likely that progressive overload caused by torsional malalignment resulted in progressive increased foot pronation with loss of foot and ankle stability and secondary weakness of the lateral hip musculature. **A,** When standing anteroposterior, the squinting patella on the right is well seen. Both femurs have 50 degrees greater than normal anteversion. **B,** What the patient sees looking down her legs. **C,** If the knee faces forward, the foot turns out. **D,** The dynamic picture is much worse because the anteversion puts the greater trochanter pointing posteriorly so there is no hip abduction power, and the pelvis collapses. In an attempt to increase hip power and put the foot forward, the knee joint must point inward, even more when there is an increase in hyperpronation.

patellar lateral subluxation, articular cartilage damage, trochlear dysplasia, patella alta, an Achilles contracture, a femoral anteversion of 45 degrees, an external tibial torsion of 55 degrees, and a genu valgum of 10 degrees, is it best to perform a varus, external rotational femoral osteotomy, a distalization of the tibial tuberosity, a reconstruction of the MPFL, a trochlear osteotomy, an internal rotation osteotomy of the tibia, or an Achilles lengthening? These abnormal findings are often quite subtle, but combinations are surprisingly common. The surgical approach to correct all abnormalities may be quite logical from a biomechanic view but excessive from a surgical morbidity standpoint. A biomechanic solution with osteotomy may mean that the ligament reconstruction is not necessary because the displacing forces are reduced. A cartilage restoration is not necessary because the compressive forces are reduced and changed in direction. As yet, no biomechanic studies indicate which surgery alters biomechanics the most.

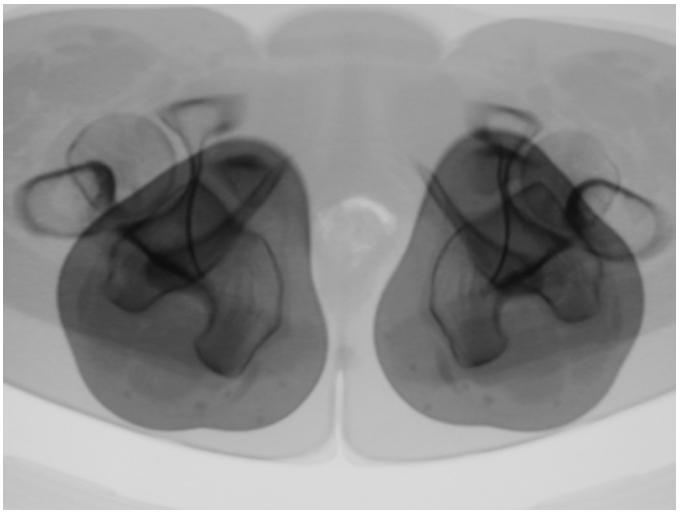


FIG 36-18 Computed tomography rotation study of the same patient yields anteversion of 67 degrees. The hip cannot be rotated externally enough for the knee joint to face forward.



FIG 36-19 Six weeks postoperative, the patient shows 50 degrees of external rotational intertrochanteric osteotomy on the right hip. The right foot is less pronated than the left foot, and the left knee joint is pointed slightly more inward than the right. Gait has already improved, and knee pain diminished immediately after surgery.

Experience suggests surgery is indicated for most cases with torsion of the femur or tibia exceeding 30 degrees from normal. For cases with torsion exceeding 20 degrees from normal, surgery is thought to be beneficial. For cases with abnormality less than 20 degrees, the accuracy of surgery or the morbidity may not justify surgery for small biomechanical changes. Turner's [47] data found 19 degrees average external torsion in a control group and 24.5 degrees in a patellar instability group. Takai and associates[42] found 9 degrees average femoral anteversion in a control group and 23 degrees average in a PF arthrosis group. Therefore it is possible that small limb torsional differences are significant.



FIG 36-20 Postoperative radiograph of a femoral rotational osteotomy produced with an intramedullary saw. Rotation changes the anterior bow of the femur to a corkscrew shape that does not allow the nail to pass congruently, resulting in splitting of the distal fragment.

SURGICAL TECHNIQUE

To correct an excess of internal femoral torsion that is not associated with a genu varus or valgus, an intertrochanteric osteotomy has been used since the late 1980s. Before that, I used the technique of closed intramedullary saw and fixation with an intramedullary nail. This technique is generally good for treating fracture malunion. However, with congenital maltorsion the normal antecurvatum of the femoral shaft is destroyed when the femur is cut in mid-diaphysis. The two antecurved fragments are rotated, and commonly a curved intramedullary nail can split the distal fragment (Fig. 36-20). In my original series of patients, osteotomizing the femur with an intramedullary saw and using an intramedullary nail for fixation resulted in poorer bone stability compared with rigid internal plate fixation. There were more postoperative pain, blood loss, and delayed union, and one death resulted from an apparent fat embolism. Consequently, the technique was abandoned, and I currently prefer rigid fixation with an AO 95-degree condylar blade plate (Figs. 36-21 and 36-22). The intertrochanteric location was chosen to minimize damage to the quadriceps, avoid scaring that may occur between the distal quadriceps and the supracondylar femur, and theoretically reduce the abrupt angular change the quadriceps would make with a supracondylar location. It should be noted these decisions are without scientific evidence. If a genu varum or genu valgum is associated with a torsional abnormality and the tibiofemoral angle is abnormal, this deformity must be corrected in the supracondylar region.

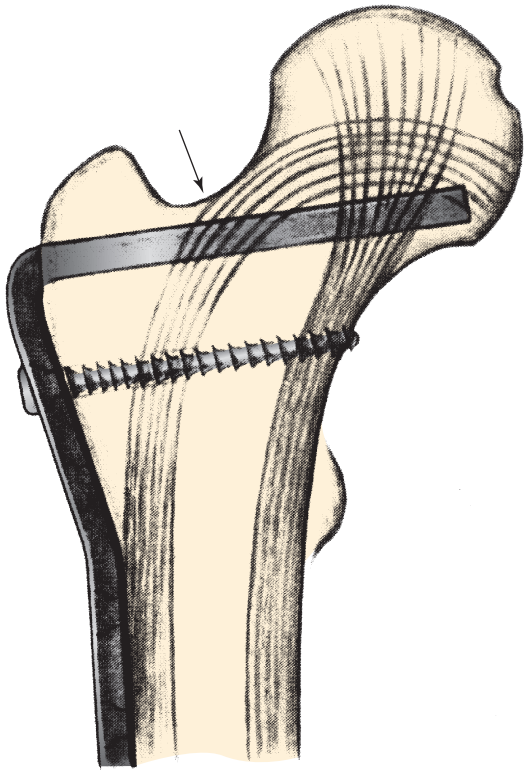


FIG 36-21 The 95-degree condylar blade plate is designed for fixation of the proximal femur. The U-shaped blade is inserted into the center of the neck and the inferior half of the head of the femur. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. *Manual of Internal Fixation,* ed 2, New York: Springer-Verlag; 1979.)

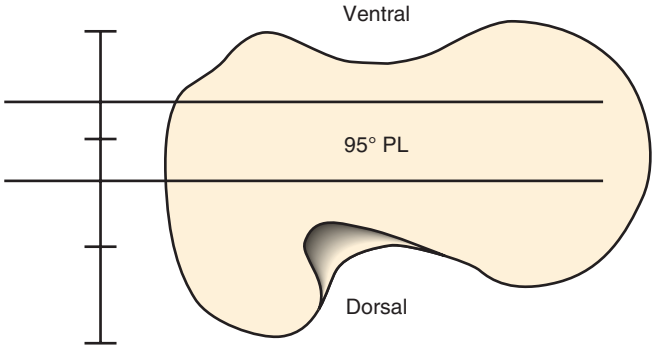


FIG 36-22 The blade is inserted into the center of the femoral neck and head. *PL,* Plate. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. *Manual of Internal Fixation,* ed 2, New York: Springer-Verlag; 1979.)

The standard AO/ASIF (Arbeitsgemainshaft für osteosynthesefragen/Association for the Study of Internal Fixation) technique for hip osteotomy is used. This has been well described and is well known. The ability to solidly compress the two osteotomy fragments insures stability and reduces pain. This compression remains a major advantage of the classical approach. The osteotomy is placed at the level of the proximal third of the lesser trochanter to increase the osteotomy surface contact area and to leave sufficient purchase for the 95-degree condylar blade plate in the proximal fragment. The blade plate is a tool that controls the correction. One needs to ensure only that the seating chisel for the blade plate enters the femoral neck at the proper height and orientation and to attach the side plate to the shaft fragment. The goal is for the blade of the blade plate to be centered in the femoral neck at such an angle that the side plate will sit on the lateral cortex of the femur without altering either flexion-extension or varus-valgus. The standard AO tools aid in this goal (Fig. 36-23).

A standard lateral approach to the hip is altered so the iliotibial track (fascia lata) is entered more anterior than usual to ensure that the trochanter or the shoulder of the plate will not put pressure on the repaired facial incision, causing a dehiscence.

After exposure of the lateral shaft of the femur by elevating the vastus lateralis anteriorly, the condylar plate guide, a mirror image of the 95-degree condylar plate, is placed along the lateral shaft of the femur. It is moved proximally and distally until an extension along its proximal flat surface lines up just below the center of the femoral head, as seen with x-ray image intensification (Fig. 36-24). A 2.5-mm hole is drilled into the femoral neck parallel to the top of the condylar plate guide and centered in the femoral neck. This hole is placed proximal enough to leave room below it to insert a seating chisel on top of the condylar plate guide. It is convenient to slide a 2.0-mm Kirschner wire (K-wire) into the 2.5-mm drill hole and use a frog-leg lateral x-ray to judge its orientation in the femoral neck. With excess femoral anteversion, the femoral neck is often angled quite anteriorly relative to the knee joint and is not exposed; therefore image intensification is used to locate its center. Positioning the limb for a frog-leg lateral x-ray usually results in bending of the K-wire against the iliotibial band, but the position within the femoral neck will indicate if the direction is appropriate. It is common to need to change these bent K-wires after obtaining the frog-leg lateral x-ray, and the ability to slide the 2.0-mm wire in and out of the 2.5-mm hole easily is useful.

Once the proper position of the K-wire is obtained, the seating chisel for the angled blade plate is inserted. A thin chisel may be used to cut into the lateral femoral cortex at the top of the properly positioned condylar plate guide. This cut in the cortex will allow the seating chisel of the blade to be advanced without sliding proximally or distally. A window in the lateral cortex of the greater trochanter for the seating chisel may also be started with drills (Fig. 36-25). The thickness of the 95-degree condylar blade is 4.5 mm, allowing a 4.5-mm drill to be used. A triple drill guide is available to attach to the top of the condylar plate guide to ensure the correct drill direction (Fig. 36-26). This is usually not necessary and predrilling with three parallel 4.5-mm drills leaves a looser fit of the blade within the femoral neck.

As the seating chisel is passed into the femoral neck, it is necessary to hold either the condylar plate guide or the seating chisel guide parallel to the femoral shaft to ensure the side plate will align with the lateral femoral shaft and not create a change in flexion or extension of the femoral shaft (Fig. 36-27). Because of the anterior bow of the femur, the proper position is not parallel to the floor. The condylar plate guide is used repeatedly to check that both the varus-valgus angulation and the flexion-extension angle will not be changed (Fig. 36-28). The seating chisel is advanced slowly until it approaches the center of the femoral head. It is backed out after advancing every 5 mm or so as not to become incarcerated. The slotted hammer is used to prevent twisting of the seating chisel into flexion or extension as it is advanced (Fig. 36-29). The depth of insertion is read off the marks etched on the seating chisel. A chisel is used to remove a small sliver of bone from the inferior edge of the entry site for the blade. This allows the shoulder of the plate to be advanced into the proximal fragment (Fig. 36-30).

When the seating chisel is removed, a 2.0-mm K-wire may be inserted into the chisel track that will slide into the U corner made by the seating chisel (Fig. 36-31 and 36-32). This guarantees that

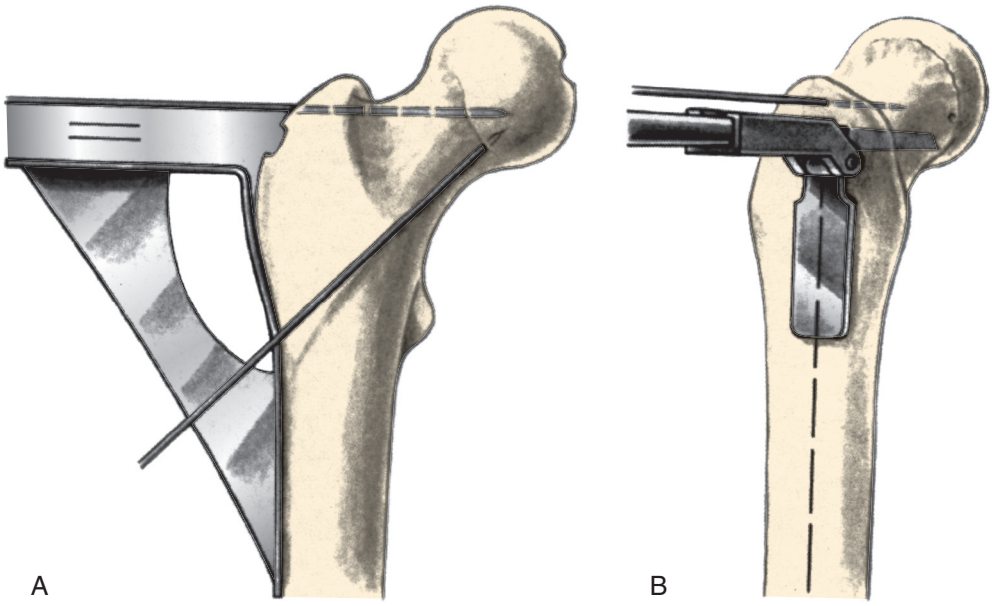


FIG 36-23 **A,** When a 95-degree condylar blade plate is to be used for fixation of a proximal femoral osteotomy, the site of insertion can be located with the aid of the condylar plate guide, which is a mirror image of the condylar blade plate. A K-wire inserted parallel to the top of the condylar plate guide will guide the insertion of the seating chisel. The direction of the femoral neck can be approximated with a K-wire placed along its anterior cortex. The neck must be seen for this to be precise and radiographic control with the image intensifier may be easier than opening the hip capsule. **B,** The seating guide placed in line with the axis of the femur will ensure there is no change in flexion or extension of the hip. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. *Manual of Internal Fixation,* ed 2, New York: Springer-Verlag; 1979.)



FIG 36-24 The condylar plate guide is placed along the lateral femoral shaft. It is moved proximal or distal until a line extending medially parallel to the top of the guide is located just below the center of the femoral head. A K-wire is inserted above and parallel to this line; this K-wire position is checked on the lateral radiograph to ensure it is in the center of the femoral neck. Once proper positioning of the K-wire is obtained, the seating chisel for the blade of the blade plate is inserted into the femoral neck and head parallel to the K-wire and to the top of the condylar plate guide.

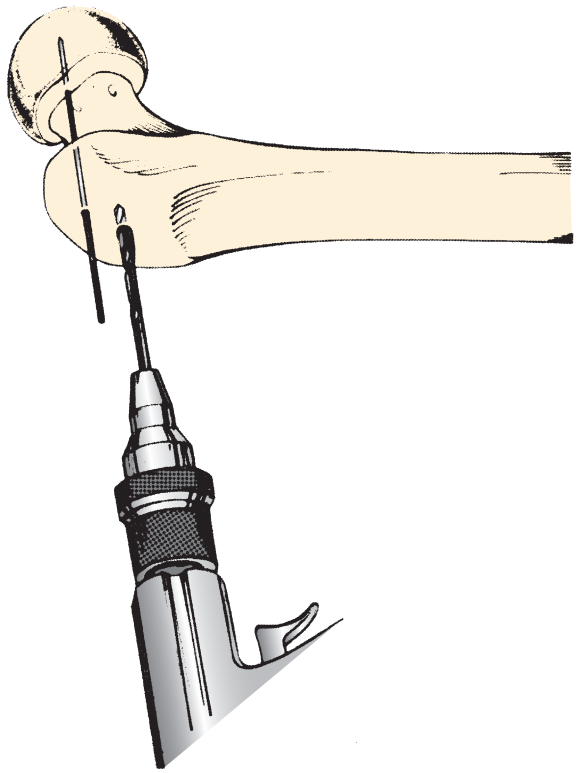


FIG 36-25 The window for the seating chisel may be created in the lateral cortex of the greater trochanter with a 4.5-mm drill. A triple drill guide (4.5 mm) may be attached to the top of the condylar plate guide. (From Schauwecker F. *Practice of Osteosynthesis,* 2nd rev ed., New York: Thieme-Stratton, 1982; p. 187.)

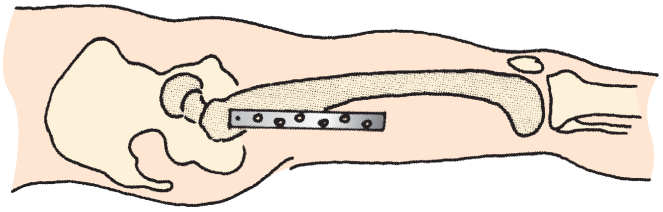


FIG 36-26 A triple drill guide is attached to the top of the condylar plate guide and 2 × 4.5 mm drill bits used to start the window for the seating chisel in the lateral cortex of the greater trochanter. A thin chisel is used to cut the cortex to begin the entry point for the seating chisel.

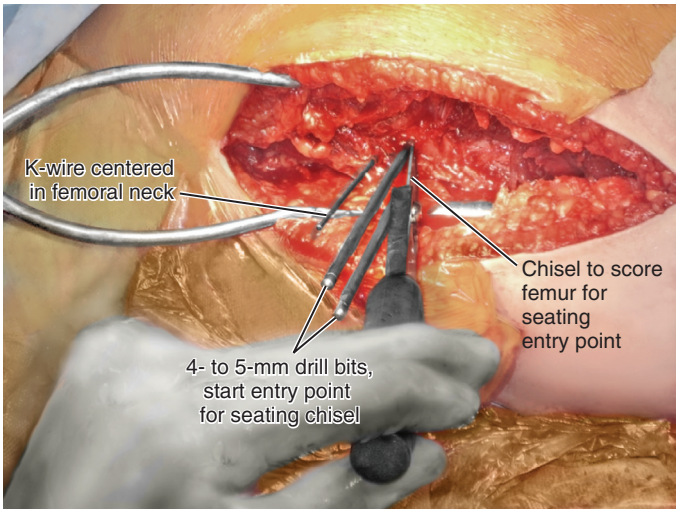


FIG 36-27 The seating chisel guide and condylar plate guide must be placed parallel to the shaft of the femur to avoid causing a flexion or extension change. The tendency is for the plate to be inserted horizontally (shown here), forgetting the anterior curve to the femur, thus causing an increased hip extension. (From Schauwecker F. *Practice of Osteosynthesis,* ed 2, New York: Thieme-Stratton; 1982.)

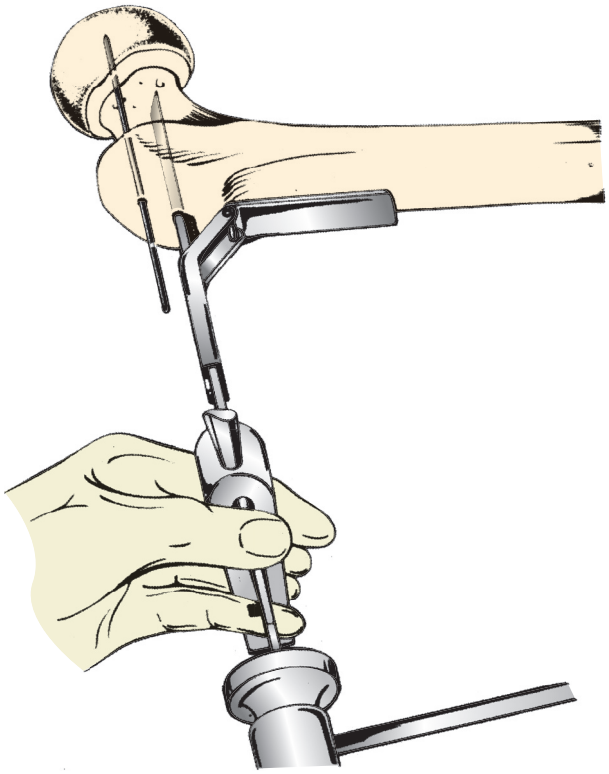


FIG 36-28 The seating chisel is driven into the femoral neck, parallel to the K-wire previously placed. The seating chisel guide is used to ensure the plate will lie centered on the lateral shaft of the femur. This flexion and extension is controlled by the slotted hammer. (From Schauwecker F. *Practice of Osteosynthesis,* ed 2, New York: Thieme-Stratton; 1982.)

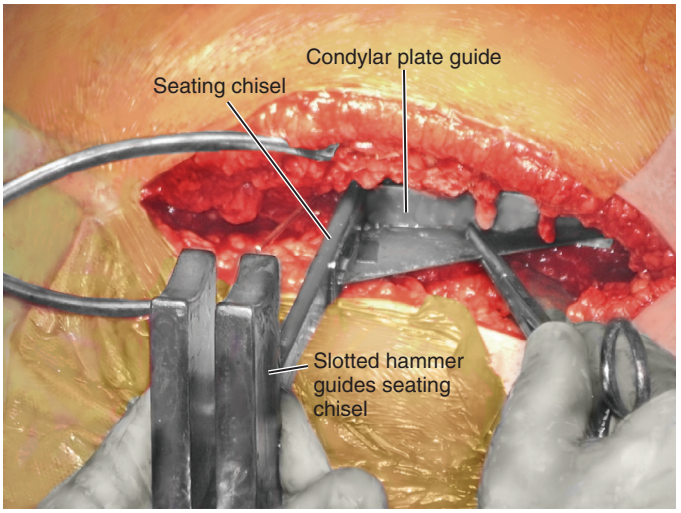


FIG 36-29 The condylar plate guide is placed parallel and touching the lateral femoral cortex, and the seating chisel is kept flush and parallel with the top of the guide. The slotted hammer allows control of the twist of the seating chisel; thus it controls flexion and extension of the osteotomy.

the direction for the blade will not be lost while the osteotomy is completed.

A 2.5-mm drill hole is placed at the location for the osteotomy, usually at the upper third of the lesser trochanter, and drilled from lateral to medial and perpendicular to the femoral shaft coronal plane axis. A 2.5-mm K-wire, which will be used to guide the saw, is inserted into this hole.

Two anterior to posterior K-wires, which are set at the desired angle of correction, are placed in the femur, one proximal and one distal to the selected site for osteotomy (Figs. 36-33 and 36-34). A 2.5-mm drill is used to create the holes for these two K-wires. These are the markers to indicate the torsional correction. For excess femoral anteversion, the need is to externally rotate the distal fragment. The proximal pin is placed first, far enough anterior and medial that it will not come into conflict with the angled blade plate that will be inserted into the proximal fragment. The distal pin is angled from medial to lateral the desired correction amount, usually indicated according to known triangles. Commercially provided triangles of various angles are available to be placed along the proximal K-wire to guide the distal reference 2.5-mm K-wire.

Once these reference pins are in place, the osteotomy is completed with a thin saw (Fig. 36-35). The saw blade is kept perpendicular to the axis of the femur, and the image helps ensure the orientation is proper (Fig. 36-36). Elevators are placed anterior and posterior to the bone to protect the soft tissues, and the image is used to judge the medial depth of the cut. Once the cut is completed, the soft tissues adjacent to the cut are stretched by placing a lamina spreader within

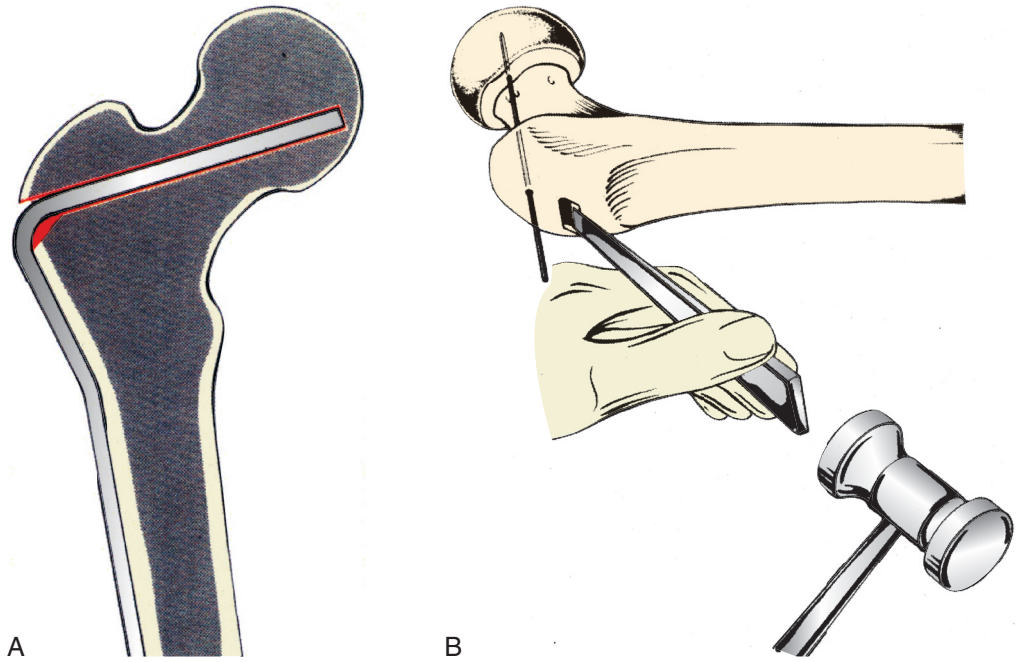


FIG 36-30 A, The shoulder of the condylar blade plate will prevent the plate from seating all the way into the proximal fragment. **B,** A chisel is used to remove the lower edge of the window for the blade plate so it does not block full insertion. (From Schauwecker F. *Practice of Osteosynthesis,* ed 2, New York: Thieme-Stratton; 1982.)

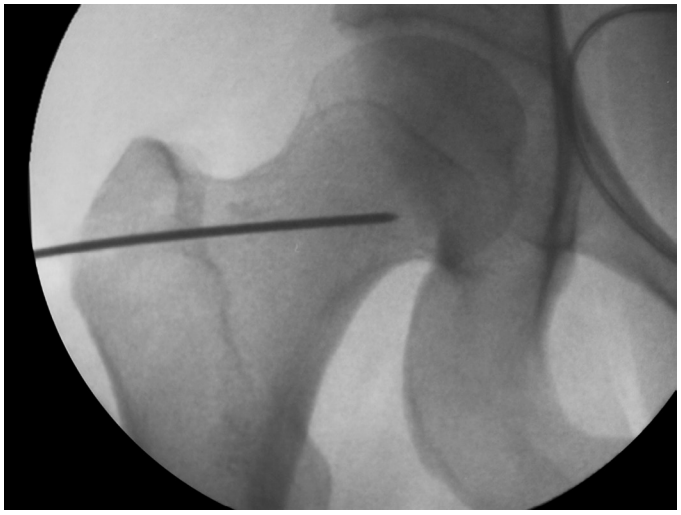


FIG 36-31 A 2-mm-diameter K-wire is inserted in the corner of the U-shaped chisel track so it can be located later when the osteotomy is complete and the blade is ready for insertion.



FIG 36-32 Once the seating chisel has been inserted, it is removed and a 2-mm K-wire is placed into the seating chisel track. A 2.5-mm wire is to be placed in the top half of the lesser trochanter and perpendicular to the femoral shaft.

the osteotomy (Fig. 36-37). This makes it easier to adjust rotation. Next, the blade plate is inserted into the proximal fragment (Fig. 36-38). The previously placed 2.0-mm K-wire in the seating chisel track makes the direction easier to follow. If the blade is properly in line with the track, it can often be pushed in by hand. After it is correctly placed in the femoral neck and head, it is necessary to impact the blade tightly into the proximal fragment (Fig. 36-39). Usually, a five-hole length side plate is sufficient. A longer-length side plate provides greater leverage but requires a longer incision and surgical approach.

The distal fragment is now externally rotated until the two torsional reference K-wires are parallel and the cortices of the osteotomy surface are well aligned circumferentially (Fig. 36-40). If the blade is not driven sufficiently far into the proximal fragment, it may allow the distal fragment to translate more laterally than the proximal fragment such that the surfaces of the osteotomy do not line up. This can be corrected by removing a small amount of bone from beneath the shoulder of the plate and impacting the plate farther into the proximal fragment. Hohmann retractors or clamps may be useful to help align the axis of both proximal and distal shaft fragments while maintaining the desired

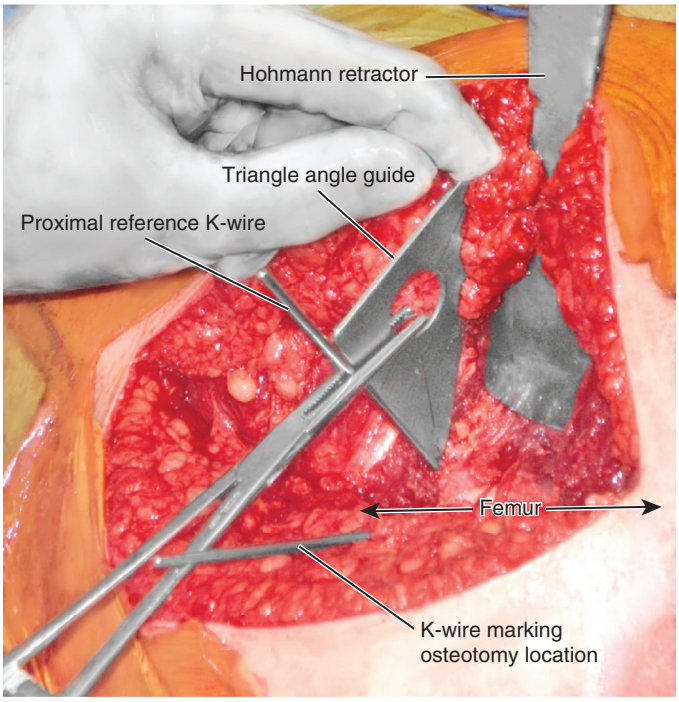


FIGURE 36-33 After the level of osteotomy is selected and marked with a K-wire, K-wires are needed as rotational markers. The first is placed proximal to the level of osteotomy and anterior to the location for the blade plate. For a 50-degree correction, one side of a 50-degree triangle is placed along the vertical K-wire, and a second K-wire will be placed distal to the osteotomy level (bottom K-wire) and parallel to the medial edge of the 50-degree triangle.

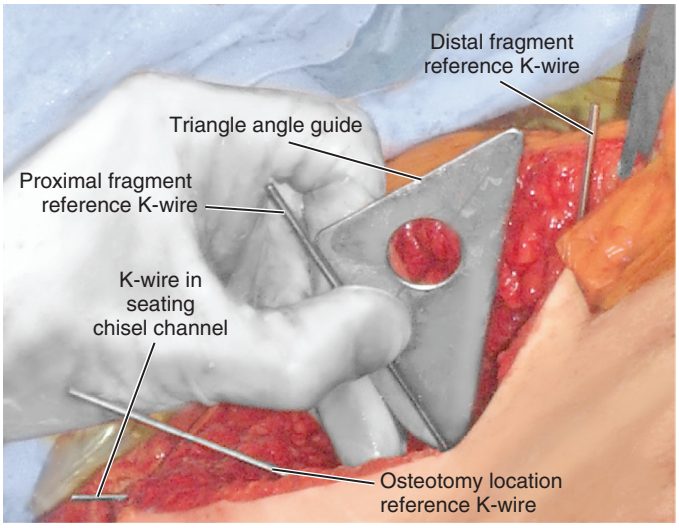


FIG 36-34 The K-wires (*right*) to indicate the angle of correction are seen to subtend an angle of 50 degrees. To the *left* are the K-wires in the osteotomy site and in the seating chisel tract.

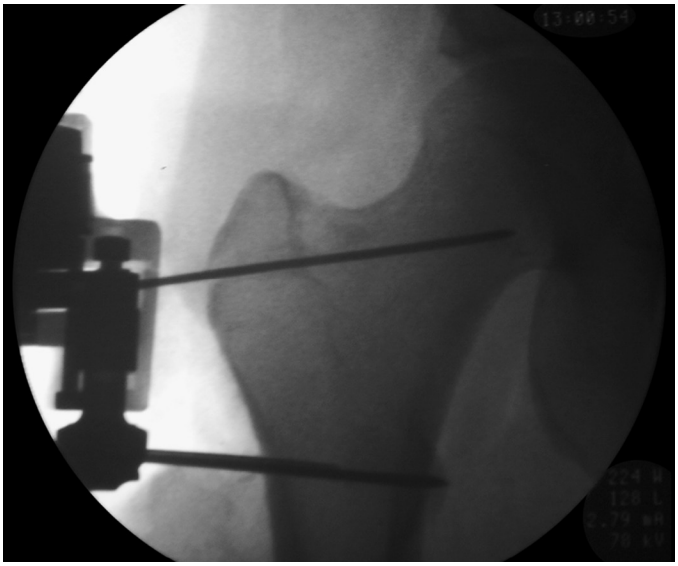


FIG 36-35 The saw cut is started in the lateral cortex, and the saw blade is perpendicular to the shaft in both the anteroposterior and lateral radiographic projections. The K-wires indicate that rotation must be placed before completing the osteotomy and should be placed now.

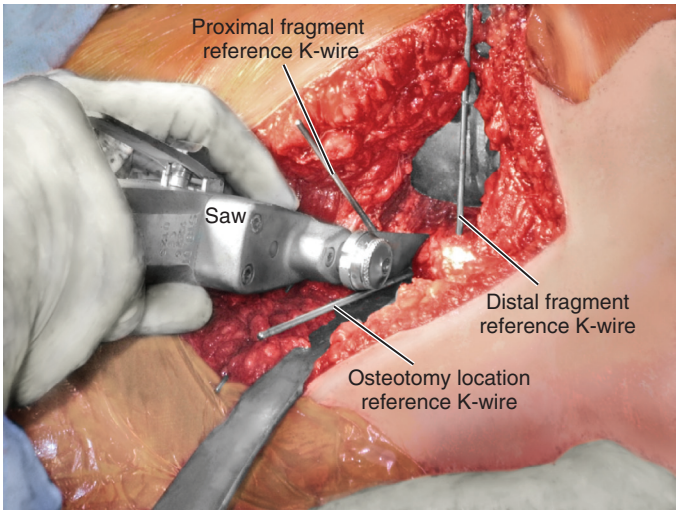


FIG 36-36 An oscillating saw is used to cut the femur transversely. The two rotation wires (*right*) subtend the desired angle of correction, and the lower K-wire is a guide for the saw at the osteotomy level.

rotational correction. Once this position is reached, the articular tension device is attached to the femur distal to the plate (Fig. 36-41). This must be in line with the plate, or the rotation will be changed as tension is applied to the plate.

A tension device placed anterior to the plate will cause external rotation of the distal fragment when tension is applied, and a tension device placed posterior to the plate will cause internal rotation of the distal fragment to be introduced. The articular tension device is color coded, with the red indicating 120 kPa. Using the spanning wrench, an attempt is made to always exceed the 120-kPa indicator (Fig. 36-42). If the screw attaching the tension device to the femoral shaft is bent, I am confident that satisfactory compression of the osteotomy surfaces has been reached. If the blade is not tightly seated in the proximal fragment, it may begin to pull out as tension in placed in the plate. A screw through the proximal plate into the proximal fragment is often necessary to prevent the blade from backing out with subsequent loss of osteotomy compression (Figs. 36-43 and 36-44). I have not found proximal femoral nails or locked plates providing the degree of compression that can be obtained with the angled plates and the articulated tension device.

Rotational osteotomy of the tibia should be performed below the level of the tibial tuberosity. The Q-angle or TT/TG distance is an

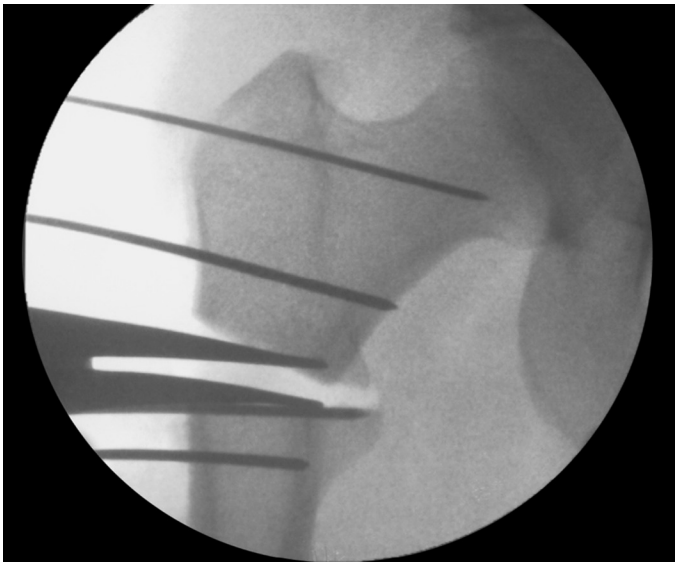


FIG 36-37 When the osteotomy is complete, it is useful to stretch the soft tissue with a lamina spreader. Four K-wires are shown: a 2-mm diameter in the track of the seating chisel, 2 × 2.5 mm diameter rotational wires above and below the osteotomy placed for rotational reference, and the fourth between to serve as a guide for the saw.

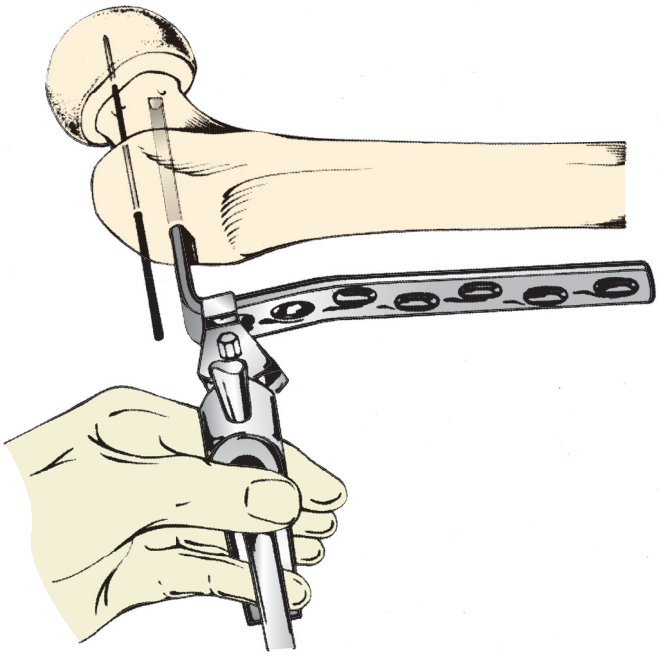


FIG 36-38 The blade can often be inserted by hand. The inserter handle is set so it is parallel to the blade and the insertion is parallel to the orientation K-wire. (From Schauwecker F. *Practice of Osteosynthesis,* ed 2, New York: Thieme-Stratton; 1982.)

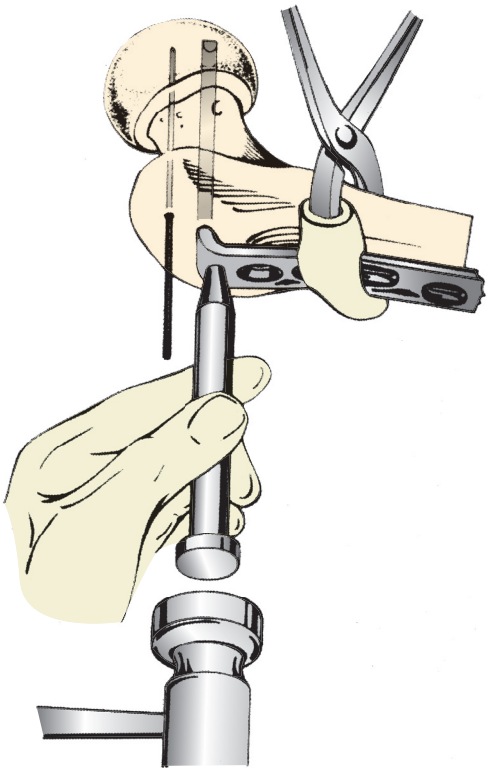


FIG 36-39 The impactor is used to seat the plate fully into the proximal fragment. (From Schauwecker F. *Practice of Osteosynthesis,* ed 2, New York: Thieme-Stratton; 1982.)



FIG 36-40 The desired cortical alignment. The oblique lag screw prevents the plate from backing out and contributes extra compression across the osteotomy. The holes for attachment of the articulated tension device are seen distal to the plate.

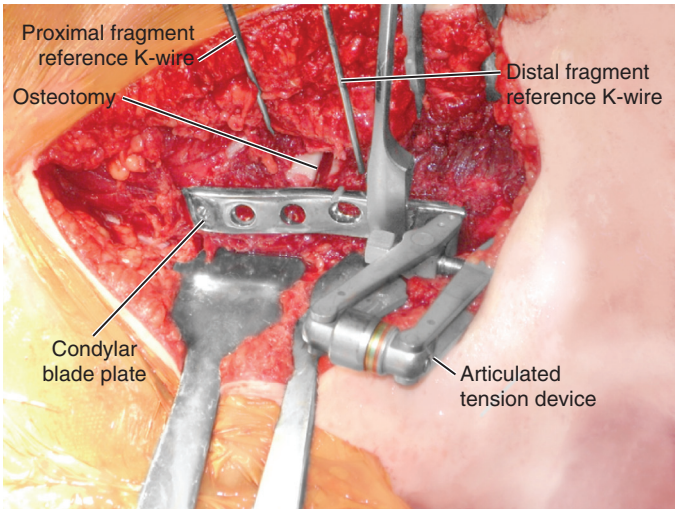


FIG 36-41 The distal fragment has been externally rotated so the rotational wires are parallel, and the gap at the osteotomy is seen between the two K-wires. The articulated tension device has been screwed onto the femur distally. Applying tension to the plate will compress the osteotomy surfaces, providing stability.

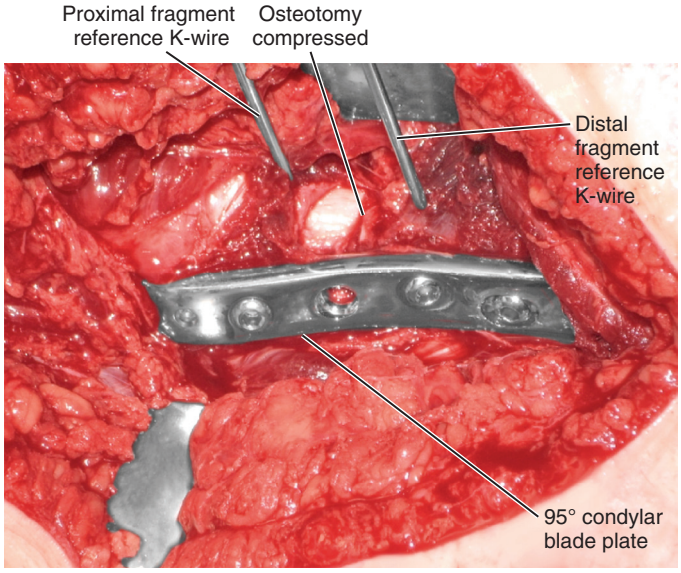


FIG 36-42 The osteotomy is compressed; the two rotational K-wires are parallel.

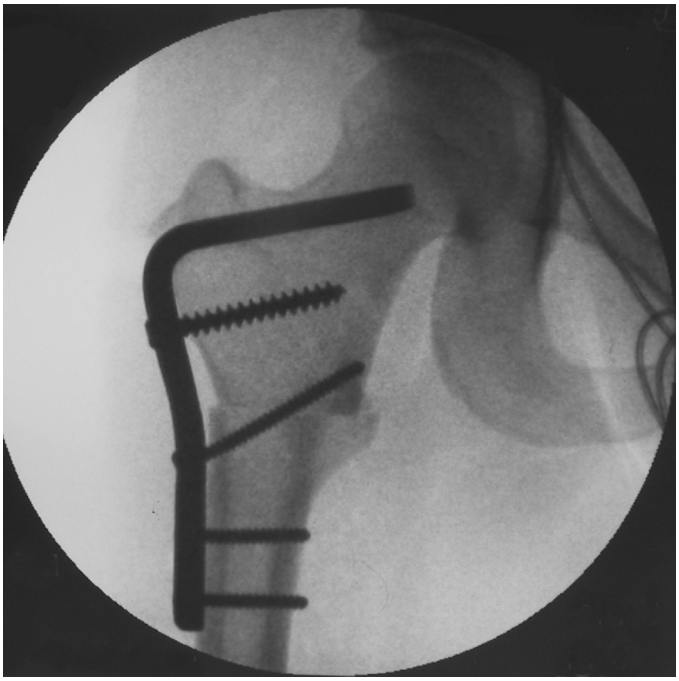


FIG 36-43 The blade has been inserted and the tensioning of the plate complete and screws inserted. The top cancellous screw is used to keep the plate from backing out of the proximal fragment as it is pulled distally with the tensioning device. The distal two screws hold the plate in tension by preventing the plate from proximal migration. The second screw from the top is both an interfragmentary lag screw and adds additional rotational support. For perfect cortical contact without the medial translation of the proximal fragment, bone under the shoulder of the plate could have been removed so it would not prevent the further advancement of the blade into the proximal fragment. The surgeon believed this would have little or no effect on the limb alignment and advised against taking down the fixation at this point.

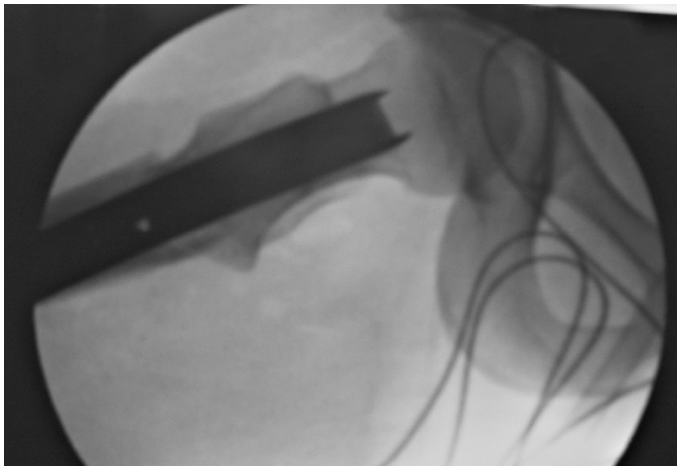


FIG 36-44 The blade is centered in the femoral neck, as seen on the frog-leg lateral view.

important biomechanical arrangement that should not be changed. It makes little difference where the osteotomy is performed because the goal is to realign the knee joint axis with the ankle joint axis in the transverse plane, leaving the trochlear-tubercle relationship normal (Fig. 36-45). I generally place the osteotomy in the proximal tibia below the tubercle and prefer to use the angled blade plate for compression; however, the geometry of the proximal tibia makes the blade insertion site a problem. With a lateral approach, the side plate will come to lie along the two flat surfaces of the proximal lateral tibia so the angle the blade takes into the proximal fragment will determine rotation. The eccentric loading of the plate with the tension device on the lateral tibia may introduce a valgus deformity that must be corrected.

The locking plate allows greater ease of rotational control but still allows a distortion of varus-valgus correction when a compression is applied to the osteotomy. Tensioning of a locked plate that is fixed in the proximal fragment may also result in the distal plate sitting well off the bone, producing an unsatisfactory prominence that can tent the anterior compartment muscle laterally or the sparse subcutaneous tissue medially. Locking plates allow easier adjustment of position, but



FIG 36-45 Excess external tibial torsion is corrected by an internal rotation osteotomy below the level of the tibial tubercle.

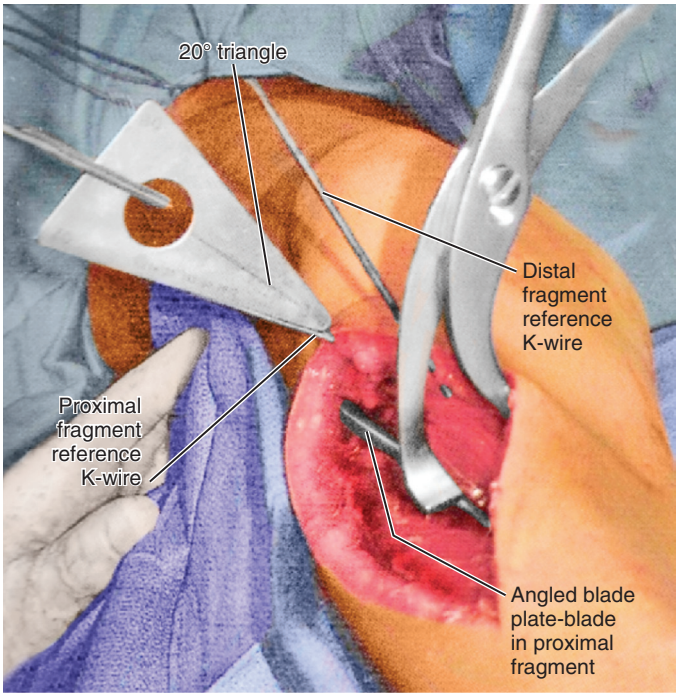


FIG 36-46 A blade of a blade plate has been inserted into the proximal tibial fragment in a direction to prevent changes in varus or valgus, flexion or extension. It is inserted 30 degrees in a posteromedial direction relative to the flat surface on the lateral tibial diaphysis. Two K-wires that were placed parallel before the osteotomy now are changed to an angle of 30 degrees with the distal wire in the distal or shaft fragment having been rotated internally 30 degrees. A clamp is holding the side plate to the lateral tibial cortex while the tension device will be applied.

are often not easily adapted for use of the tension device. This lack of high compression of the osteotomy fragments definitely results in slower union time and more postoperative discomfort than the tight compression that is possible with an angled blade plate. Two 2.5-mm K-wires are placed from anterior to posterior in the tibia, one proximal and one distal to the planned level of osteotomy. These wires may be parallel or subtend the desired angle of correction in the transverse plane. If they are parallel, then the angle between the two after manipulation of the osteotomy fragments indicates the correction angle (Fig. 36-46). If they have been placed at the desired correction angle, then the pins are brought parallel. It is important to have these as reference points before the osteotomy is made. Currently, I use a navigation system (Praxim) that indicates the changed alignment in all three planes (transverse, coronal, and sagittal; Fig. 36-47). It is impressive that small changes in all three planes are usually present, and the manipulation of the fragments to a realignment precise in all three planes is difficult to obtain and difficult to hold while fixation is applied. In my experience, the precision and confidence are greatly improved while using navigation, but the time and effort to obtain the correction is also increased. If a blade plate is used and the blade is inserted at the correct angle, the osteotomy fixation is easier to obtain but more difficult to change if an error is made. Unfortunately, there are no imageless navigation systems for use in the proximal femur.

COMPLICATIONS

As with all major surgery, complications are possible and include malunion with overcorrection, undercorrection or the addition of a varus or valgus deformity, a flexion-extension deformity, nonunion, muscle adhesions, compartment syndrome, vascular or neurological injury, painful trochanter, and painful implants. Implant removal is generally necessary. Generalized complications are the usual expected and are not listed here.

RESULTS OF TORSIONAL REALIGNMENT

Meister and James[30] reviewed seven patients who had undergone tibial rotational osteotomy for anterior knee pain at an average of 10 years previously and rated one patient excellent, five good, and one fair. Bruce and Stevens[3] reviewed 14 patients with anterior knee pain caused by miserable malalignment treated with combined external femoral rotational osteotomy and internal rotational tibial osteotomy at an average of 5 years and reported that all were satisfied. Cooke and colleagues[5] reported on seven patients with anterior knee pain associated with varus and excessive external tibial torsion treated with valgus internal rotation osteotomy in which five were rated as excellent. Delgado and coworkers[7] reported on nine patients with anterior knee pain and 13 osteotomies of the femur or tibia or both, with marked improvement seen at over 2 years. Server and associates[39] reported on 25 patients undergoing internal rotational tibial osteotomy for excessive external tibial torsion and symptoms suggesting patellar subluxation, with 23 of 25 satisfied, including some athletes. Ficat and Hungerford[10] reported one case of recurrent patellar subluxation that responded to osteotomy of both the femur and tibia.

Ruesch in 1995 (unpublished paper) reviewed a series of 35 femoral external rotational osteotomies performed for anterior knee pain and/or instability in 31 patients. Five patients were not located, but 26 (84%) were seen an average of 5.3 years postoperatively. Eighty-eight percent of the group presented with failed PF surgery, with 23 averaging more than two prior surgeries. Only three patients had not had prior surgery. Six osteotomies were diaphysis fixed with intramedullary nails, and 29 were intertrochanteric fixed with 95-degree condylar

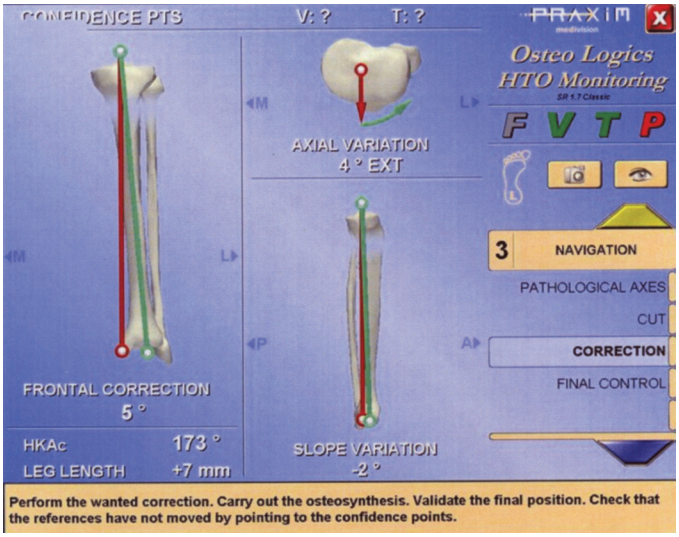


FIG 36-47 Computer screen from a navigation system that allows a direct and accurate reading of the change in position of fragments. This system uses infrared reflectors placed into the femur, the tibia above the osteotomy, and the tibia below the osteotomy. Three planes are represented with the correction in each plane. *Left,* the frontal correction, the sample shows 5 degrees of valgus has been introduced with current hip-knee-ankle line measuring 173 degrees and with an increase in leg length of 7 mm. *Upper central figure,* the horizontal plane correction, an example of 4 degrees of increased external rotation. *Lower central figure,* the sagittal plane change, an example of 2 degrees of recurvatum or extension. The *green V and T* in this program indicate which markers are being visualized by the camera and utilized by the computer. The *red P* is not being seen by the camera. *V* and *T:* are reference points on the metaphyseal and diaphyseal reflectors that are used as a test to ensure there has been no loss of position of these reflectors. (Courtesy OMNI.)

blade plates. Two PF rating scores were used. The average Schwartz and colleagues[37] score was 24.6 points (of 29 points), with 15 patients excellent, 6 good, 5 fair, and 9 poor. The average Shea and Fulkerson[40] score was 82.5 points (of 100 points), with 20 excellent, 6 good, 1 fair, and 8 poor. The poor results mostly reflected significant preexisting arthrosis that was not improved. However, subjectively, 77% indicated a decrease in the amount of pain, 86% less giving way, 80% improved quality of life, and 42% reduced retropatellar crepitation. Of the three patients without prior surgery, the Shea and Fulkerson score was 100 points, and the Schwartz score was 28.7 points.

Latteier (my series; unpublished data) reviewed 72 intertrochanteric external rotational osteotomies in 53 patients presenting with PF dysfunction. The mean follow-up was 9.7 years (range, 2 to 17 years), with a minimum of 2 years. At follow-up, mean Kujala scores had improved from 53 to 86, mean Lysholm scores had improved from 49 to 89, and mean Tegner activity scores had improved from 2.2 to 4.0.

Each patient presents with different combinations of anatomic pathology; thus outcome measures fail to reveal the complete patient profile. Pain in the absence of instability or chondral disease is the most common early presentation. The only objective measurement may be that of abnormal limb torsion. After surgery, patients have reported returning to painless cross-country running after not being able to walk to classes before correction, the loss of bunions, the loss of radiating pain down the lateral side of the limb from pelvis to lateral ankle after 40 years without relief, the loss of retropatellar crepitation on stairs, the first ability to ride a bicycle and ski without pain, and a feeling of increased stability in landing after a jump in basketball. Such observations are not part of any PF scores, and these improvements would therefore be missed. Exercise that constrains the pelvis and feet such as bicycling, classic cross-country skiing, or elliptical machines is a particular problem for these patients because there is no escape for the inward-pointing knee. Strong hip abduction is a benefit for patients with femoral anteversion because it may allow the patient to be active with a knee that points forward, thus relieving knee pain. However, because the hip abductor is working at a mechanical disadvantage, it will often fatigue, and the knee joint must point medially to gain mechanical leverage at the hip. This inward limb rotation forces an increased pronation at the foot such that medial arch strain, posterior tibial tendon strain, and bunions are more common. This chronic foot pronation may allow an increase in equinuus ankle contracture, which then accentuates the increase in internal limb rotation. Excess external tibial torsion with normal femoral torsion presents a different problem. The knee points inward because this is necessary for proper ankle dorsiflexion during gait. The medial knee pain is common because the quadriceps increases the lateral vector on the patella when the foot is pointing forward. The hip abductors, however, are working at near normal mechanical advantage, so pelvic strengthening is less likely to be useful.

CONCLUSIONS

1. Miserable malalignment as described by James[15] exists and must be recognized in the patient with PF pain, instability, or arthrosis.
2. Torsional limb malalignment may present with only pain or may coexist with patellar instability and/or patellar chondrosis, and it may be a biomechanic contributor to the etiology of both instability and arthrosis, but all three conditions must be assessed independently.
3. Restoration of normal limb alignment in all three planes is thought to restore the normal direction of the force vectors that cross the knee joint.
4. The transverse (horizontal) plane is frequently overlooked and is best evaluated with a CT scan or MRI that allows the axis of the hip, knee, and ankle to be measured relative to each other.
5. Realignment of the femur and tibia by rotational osteotomy may not only be appropriate but also necessary. It is the only reasonable surgical treatment for PF symptoms because of skeletal malalignment in the transverse plane.
6. Surgery for instability or for cartilage restoration is more likely to fail in the mechanical environment of persistent lower limb maltorsion.
7. Surgical morbidity must not be underestimated.

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37

Unicompartmental Patellofemoral Replacement

Frank R. Noyes, Sue D. Barber-Westin

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INDICATIONS

Patellofemoral arthroplasty (PFA) is a viable option for symptomatic patients in whom severe joint damage and loss of joint space are present in the patellofemoral (PF) compartment but not the tibiofemoral compartments. Although early reports of this procedure were disappointing, improvements in product materials, design, and robotic technology, as well as a better understanding of patient indications, have improved the expected outcome.

Indications for PFA include symptomatic secondary PF arthritis that is associated with congenital trochlear dysplasia or after joint dislocation or chronic subluxations that are unresponsive to nonoperative and operative measures.[19,22,28,30,31,54] Secondary PF osteoarthritis from trauma or fracture are other frequent indications. Although primary isolated PF osteoarthritis is an indication for PFA, it is important to note that some studies reported that patients with this diagnosis were more likely to have progression of tibiofemoral arthritis than patients with posttraumatic arthritis or dysplasia.[5]

Patient candidates typically have severe anterior knee pain, swelling, and stiffness that limits daily activities. A lengthy course of nonoperative treatment that includes nonsteroidal antiinflammatory medication, steroid injections, physical therapy, and weight control fails to alleviate the anterior patellar pain. In our opinion, the patient should be younger than 60 years, although consideration may be made for those older than 60 years, if no contraindications exist, and the tibiofemoral compartments are not arthritic or symptomatic.

Many patient candidates for PFA will have undergone multiple prior failed surgical procedures such as lateral release, arthroscopic

CRITICAL POINTS Indications

- Symptomatic patients who have severe joint damage and loss of joint space in the PF compartment but not in the tibiofemoral compartments
- Symptomatic secondary PF arthritis associated with congenital trochlear dysplasia or PF arthritis after joint dislocation or chronic subluxations
- Secondary PF osteoarthritis from trauma or fracture
- Failed lengthy course of nonoperative treatment measures

debridement and chondroplasty, extensor mechanism realignment, medial patellofemoral ligament (MPFL) reconstruction, or an articular cartilage procedure such as autologous chondrocyte implantation (ACI) or osteochondral autograft transfer. In our prospective study, 76% of patients who underwent PFA had undergone these types of prior PF procedures that subsequently failed. It is important that the patient has realistic expectations regarding what this operation may and may not accomplish. At our center, most patients are able to walk without support within approximately 2 to 3 weeks postoperatively, and the majority return to daily activities within 4 to 6 weeks. Light, low-impact activities such as walking, swimming, golfing, light hiking, and bicycling can often be performed by 3 months. However, running and high-impact athletics or occupational activities are not advised and, in fact, should be avoided; it is essential that the patient understands and accepts these limitations of the procedure. High flexion-repetitive activities may induce a mild effusion because the patella polyethylene replacement articulates with the tibiofemoral articular cartilage.

CONTRAINDICATIONS

The principal contraindication to PFA is tibiofemoral joint arthritis (articular cartilage deterioration and/or joint space narrowing on standing posteroanterior [PA] radiographs) owing to the evidence that this is the leading cause of failure requiring total knee arthroplasty (TKA). In addition, uncorrected excessive varus or valgus malalignment (greater than 3 degrees), uncorrected PF malalignment, knee ligament instability, inflammatory arthritis, and prior or active infection are contraindications. Patients with patella alta may require distalization of the tibial tubercle. Patients with complex regional pain syndrome, diabetes, knee arthrofibrosis (excessive extension or flexion contracture), chondrocalcinosis, or rheumatoid arthritis are not considered candidates. Patients older than 60 years of age or those who are obese (body mass index [BMI] >31) are also usually not candidates for PFA. Osteopenia (bone mineral density T score between −1.0 and −2.5 standard deviations below normal) and osteoporosis (T score less than −2.5) are contraindications for this operation. Other contraindications include failure to treat the patient with all conservative measures, a history of meniscectomy that is associated with tibiofemoral compartment joint damage or narrowing, noncompliance with rehabilitation, and unrealistic expectations for future activity levels. Magnetic resonance imaging (MRI) is frequently obtained to rule out associated tibiofemoral compartment osteoarthritis that would decrease the success rate. It is realized in younger patients that PFA is a temporary procedure to buy time before TKA, which can later be successfully performed. Younger patients who undergo corrective tibial or femoral osteotomy for varus or valgus malalignment could then be future PFA candidates.

CRITICAL POINTS Contraindications

- Tibiofemoral joint arthritis
- Uncorrected varus or valgus malalignment >3 degrees
- Uncorrected patellofemoral malalignment
- Uncorrected knee ligament deficiency
- Inflammatory arthritis, rheumatoid arthritis
- Complex regional pain syndrome, knee arthrofibrosis, chondrocalcinosis
- Age ≥60 years
- Body mass index >31
- Osteopenia or osteoporosis

IMPLANT DESIGN

There are two main types of PFA implants based on the trochlear preparation method.[30] So-called *first-generation* implants replace worn cartilage without altering the shape of the subchondral bone (Table 37-1). The trochlear implants are placed using an inlay or onlay technique, and their positioning is dependent on the patient's trochlear anatomy. These designs generally have a narrow, excessively deep trochlear component that is too constraining and causes many problems related to patellar catching, poor tracking, and continued anterior knee pain.[7,10,34,46,49,53]

Second-generation PFA implants replace the trochlea based on the femoral trochlear groove of TKA implants.* The shape of the trochlear groove varies greatly between models; from deep, highly constrained models to open, unconstrained models. The patellar component may be shaped as a dome, have facets, or be asymmetrical in design.

The term *third-generation* describes PFA systems that are implanted using 3-dimensional models of the patient's anatomy obtained from computed tomography (CT) scans in which either a custom prosthesis is created (KineMatch PatelloFemoral Replacement[43-45]; Custom Performa Knee Patellofemoral Arthroplast, Biomet Orthopedics[8]) or robotic technology (our preferred technique) is used for implant sizing and orientation and bone resection (MAKOplasty Partial Knee Resurfacing, Stryker Orthopaedics).

CLINICAL EXAMINATION

A thorough history is required including documentation of prior surgical procedures and conservative treatment measures, patellar dislocation or subluxation episodes, and other knee joint injuries. Symptoms typically occur in the anterior or retropatellar regions and are worsened with stair climbing, walking on uneven ground, kneeling, squatting, and prolonged sitting.

The comprehensive physical examination includes a complete PF examination, discussed in detail in Chapter 35, to assess patellar tilt, subluxation, mobility, Q-angle, and lower limb rotational alignment (femoral internal torsion, tibial external torsion). The integrity of the MPFL and medial soft tissue stabilizers is assessed by the amount of lateral patellar displacement (glide), which normally is 1 quadrant of patellar width (at 0 and 20 degrees of flexion). The presence of an active lateral patellar subluxation with knee extension (J sign) indicates deficient medial stabilizers and, often, patella alta. A lack of normal medial translation (<10 mm, 20 degrees of flexion) indicates excessive tightness of the lateral retinacular tissues and often an excessive lateral patellar compression syndrome, requiring Z-plasty lengthening and soft tissue balancing at surgery (to be discussed). The patella and all surrounding tissues are palpated to localize pain. The medial and lateral joint lines are also inspected for any tenderness, indicative of tibiofemoral joint involvement that may contraindicate PFA.

All knee ligament tests are conducted as described in Chapters 7 and 17.

The patient's gait, range of knee motion, lower extremity and hip muscle strength, and neurovascular status are evaluated.

Radiographs taken during the initial examination include standing anteroposterior (AP) at 0 degrees, lateral at 30 degrees of knee flexion, weight-bearing PA at 45 degrees of knee flexion, and PF axial views. A true lateral radiograph in which the distal and posterior

*References 1-3, 6, 8, 11, 12, 18, 20, 23, 29, 34-36, 38, 40-42, 48, 50, 55

TABLE 37-1 Patellofemoral Arthroplasty Prostheses

Product	Clinical Study (References)	Comments
KineMatch PatelloFemoral Replacement (Kinamed, Inc., Camarillo, CA)	36, 43, 44, 45	Third-generation CT-modeled implant
Custom Performa Knee Patellofemoral Arthroplast (Biomet Orthopedics, Warsaw, IN)	8	Third-generation CT-modeled implant
MAKOplasty Partial Knee Resurfacing (MAKI Surgical Corp., Ft. Lauderdale, FL)		Third-generation, robotic technology, CT-modeled implant; no clinical studies at time of writing
Avon (Stryker, Kalamazoo, MI)	1, 2, 11, 18, 20, 23, 29, 34, 35, 38, 40, 42, 48, 50	Second-generation off-the-shelf implant; most widely studied PFA
Vanguard Patellofemoral Replacement System (Biomet Orthopedics)	36	Second-generation off-the-shelf implant; only 1 study that mixed results of 3 prostheses together
Gender Solutions PatelloFemoral Joint (Zimmer, Warsaw, IN)	36	Second-generation; only 1 study that mixed results of 3 prostheses together
Journey Patellofemoral Joint System (Smith & Nephew, London, UK)	6	Second-generation off-the-shelf implant
Hermes (Ceraver, France)	41	Second-generation off-the-shelf implant
iBalance Patellofemoral Joint System (Arthrex, Naples, FL)		Second-generation off-the-shelf implant; no clinical studies at time of writing
SIGMA High Performance Partial Knee (DePuy Synthes Joint Reconstruction, Warsaw, IN)		Second-generation off-the-shelf implant; no clinical studies at time of writing
Femoro Patella Vialli (FPV) (Wright Medical Technology, Arlington, TN)	3, 12, 34, 55	Second-generation off-the-shelf implant; design of prosthesis "questionable"[12]
Richards Model I, II, III (Smith & Nephew)	9, 14, 21, 52	First generation; replaced with Journey
Lubinus Total Patella Glide Replacement (Waldamer Link, Hamburg, Germany)	7, 34, 49	First generation; all investigators discontinued prosthesis
Low Contact Stress PatelloFemoral Joint (DePuy Orthopedics)	10, 33, 56	First generation; company discontinued
Autocentric (DePuy Orthopedics)	5, 13, 17, 53	First generation; discontinued[53]

CT, Computed tomography; *PFA*, patellofemoral arthroplasty.

aspects of the femoral condyles are perfectly superimposed should be obtained to evaluate trochlear depth. Measurements of patellar height and patellar trochlear contact are made on lateral radiographs (Fig. 37-1). Double-stance full-standing radiographs of both lower extremities, from the femoral heads to the ankle joints, are obtained in knees in which varus or valgus lower extremity alignment is detected on clinical examination. MRI is required to determine the cartilage status of the entire knee joint, along with all other soft tissue structures.

PREOPERATIVE PLANNING

The PFA operative technique described in this chapter that the senior author (F.R.N.) has used since 2008 uses a cemented implant (RESTORIS MCK [Multicompartmental Knee] PF implant system, Stryker Orthopaedics) that is positioned using 3-dimensional modeling and computer-assisted robotic surgical navigation (Robotic Arm Interactive Orthopedic System [RIO], Stryker Orthopaedics). Before surgery, customized CT scans (CT Scanning Protocol Knee Arthroplasty PN 200004) are obtained with the patient lying supine with a motion rod attached to the operative leg. The CT scans are saved in DICOM 3 format and transferred to software that processes the hip, knee, and ankle data to create 3-dimensional bone models of the femur and tibia. Calculations made for implant sizing, orientation, and alignment are based on the patient's bone anatomy. Fine tuning of the component position and orientation based on patient-specific anatomy and cartilage thickness is completed intraoperatively. The primary preoperative planning steps for the trochlear implant are summarized in Figure 37-2 (see MAKOplasty Partial Knee Application User Guide 206388 Rev 01 and Surgical Technique and Planning Guide #201844, Stryker). The recommended positioning limits are:

1. Trochlear internal/external rotation: 4 degrees internal to 0 degree (ideal, 0 degree rotation), which is considered acceptable for the implant to be recessed into an abnormal prominent lateral trochlea to avoid internal rotation of the implant. Every degree of internal rotation medializes the trochlear groove approximately 0.5 mm and raises the patellar jump height approximately 0.3 mm. External rotation of the trochlear component is not recommended because it will decrease the lateral patellar jump height and increase the risk of lateral patellar subluxation.
2. The largest size trochlear implant is selected that will not overhang. There should be 0 to 2 mm of inset from the medial and lateral ridges and there should be no interference with the anterior cruciate ligament (ACL).
3. Alignment is set between 3 degrees varus and 2 degrees valgus (ideal, 0 to 2 degrees varus). Every degree of varus/valgus rotation translates the trochlear groove entrance by approximately 0.6 mm. The trochlear component should not be placed in more than 2 degrees of valgus because this will align the trochlear groove away from the anatomic axis of the femur and increase the risk of lateral patellar subluxation. The PF component trochlear groove pathway is curved proximally 6 degrees to align with the anatomic axis when the implant is planned at 0 degrees of varus-valgus.

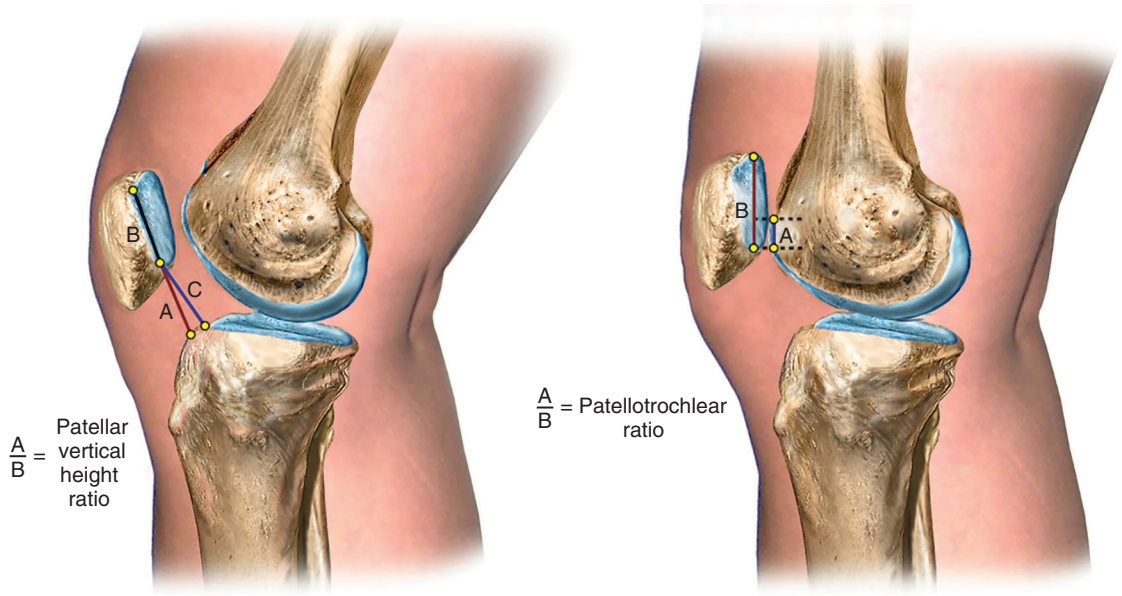


FIG 37-1 **Left,** Method used to determine patellar vertical height ratio on lateral radiograph with a quadriceps contraction to show the maximum elevated position of the patella. The numerator, *line segment A*, is the distance between the most ventral (anterosuperior) rim of the tibial plateau and the lowest end of the patellar articular surface. The denominator, *line segment B*, is the maximum length of the patellar articular surface. An alternative numerator, *line segment C*, locates the tibial reference point on the middle of the tibial plateau. The patellar vertical-height ratio equals A/B or C/B. **Right,** Alternative patellotrochlear ratio measurement. The mean ratio is 32 ± 12%; >50% indicates patella infera; <12% indicates patella alta.

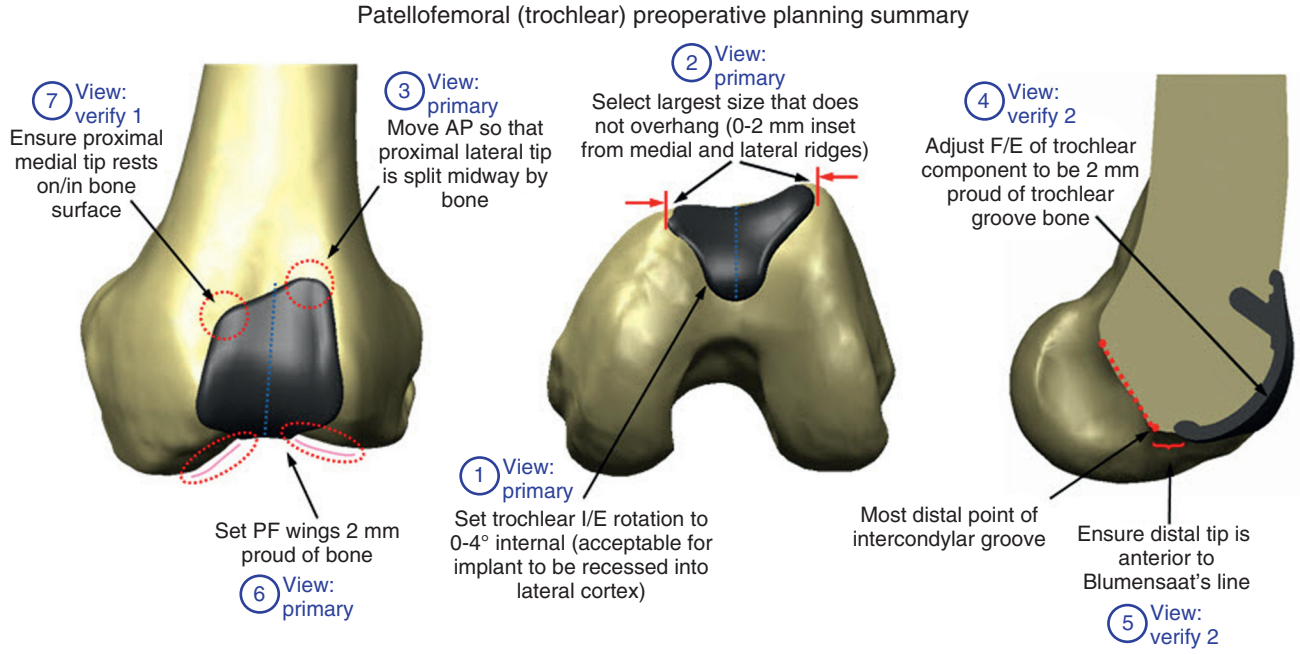


FIG 37-2 The preoperative planning steps for the precise location of the trochlear implant. *AP*, Anteroposterior; *F/E*, finite-element; *I/E*, internal/external; *PF*, patellofemoral.

4. The flexion-extension of the trochlear component is adjusted to be approximately 2 mm proud of the trochlear groove bone. This should be set between 5 degrees of flexion and 5 degrees of extension. Verification should be made that the distal tongue does not violate the intercondylar notch and cause ACL impingement. The PF distal tip should be anterior to Blumensaat's line.

SURGICAL TECHNIQUE

The reader is referred to the MAKOplasty Partial Knee Application User Guide 206388 Rev 01 and Surgical Technique and Planning Guide #201844, Stryker Orthopaedics, for the Robotic RIO PFA, which are summarized in this chapter.

The surgical positioning of the lower limb, along with the robotic arm instrumentation, is shown in Figure 37-3. A femoral array has been placed 8 cm above the patella. The surgeon views the operative resection of the trochlea on the screen (not shown). The leg is positioned in a leg holder that allows easy adjustment of knee flexion and controls rotation. There are multiple steps required in the registration of the lower limb and trochlear anatomy of the patient that are summarized in the user and planning guides.

Incision

With the knee flexed to 30 degrees, an anteromedial skin incision is made adjacent to the medial border of the patella, extending from the superior border of the patella to the top of the tibial plateau. The incision is extended proximally or distally as required for adequate visualization. The subcutaneous tissues are undermined and retractors placed to expose the medial retinaculum. An incision in the quadriceps tendon 3 cm above the patella (senior author's choice) or a medial subvastus or midvastus arthrotomy is created through the medial retinaculum, capsule, and synovium. The length of the incision and arthrotomy must be sufficient enough to enable patellar retraction for insertion of the trochlear implant and femoral registration. All compartments and cruciate ligaments are inspected to confirm the indications for PFA. The fat pad is partially removed as required and any synovium above the trochlea for exposure. The patella is reflected laterally to expose the PF joint space.



FIG 37-3 The operative positioning of the lower limb, along with the Robotic Arm Interactive Orthopedic System (Stryker Orthopaedics).

Registration

The techniques for registration are followed as specified in the surgical technical guide. Patient landmarks are collected and registered to verify femoral and tibial checkpoints. Bone registration is performed, but osteophytes are not removed. The cartilage in the trochlear groove and distal femur is mapped to ensure smooth transition from the implant to the femoral condyles and femoral component. The RIO is placed in the operative field and registration and verification performed of the position of the robotic arm and cutting tool tip.

Implantation of Trochlear Component

The intraoperative real-time fine tuning steps of the component position and orientation are summarized in Figure 37-4. Before bone resection, an assessment of ligament tension and visualization of implant articulation throughout the range of knee motion are performed. RIO provides tactile feedback and 3-dimensional visualization to facilitate the planned bone resection. Real-time virtual visualization is used during bone resection to confirm proper implant alignment and positioning. The surgeon controls the robotic arm, removing a precise amount of trochlea cartilage and bone based on the preoperative planning.

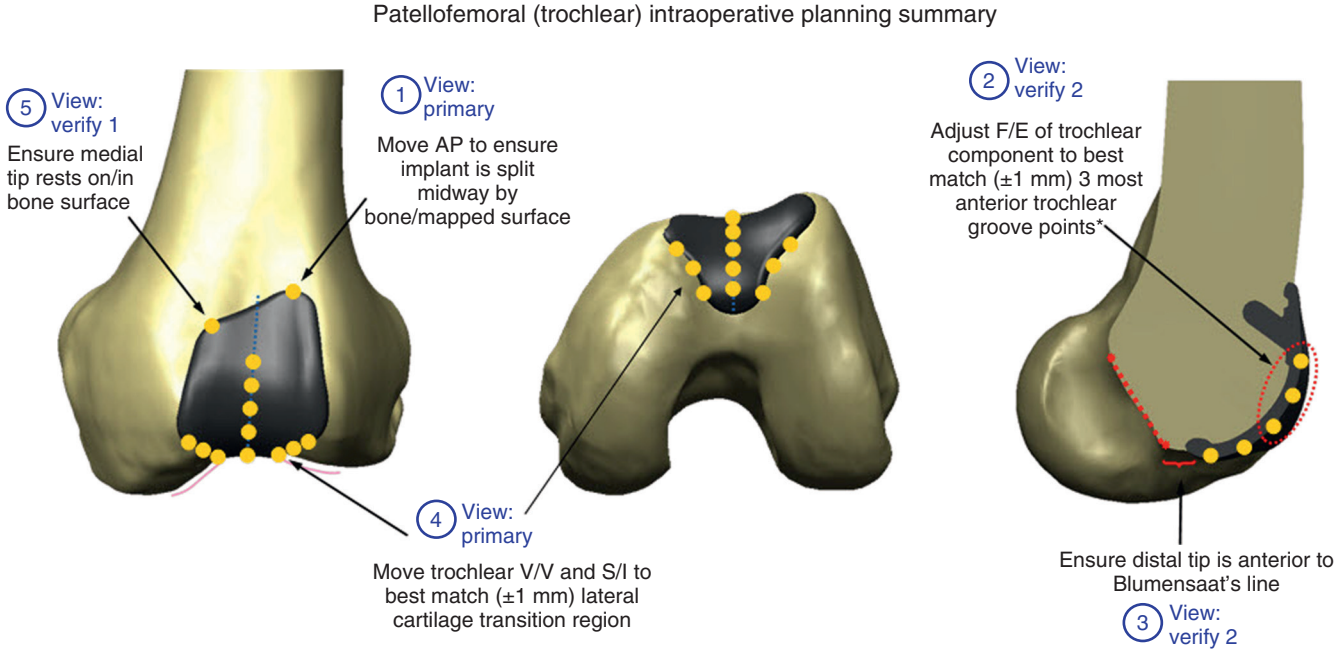


FIG 37-4 The intraoperative planning steps for the precise placement of the trochlear implant. *If the mapped points like on arthritic bone and not cartilage, adjust finite-element to be approximately 2 mm proud of bone surface.

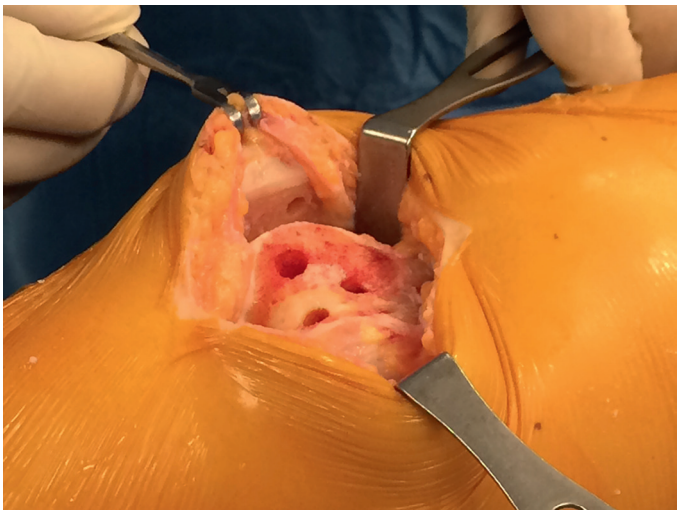


FIG 37-5 The resected bone for the trochlear and patellar components.

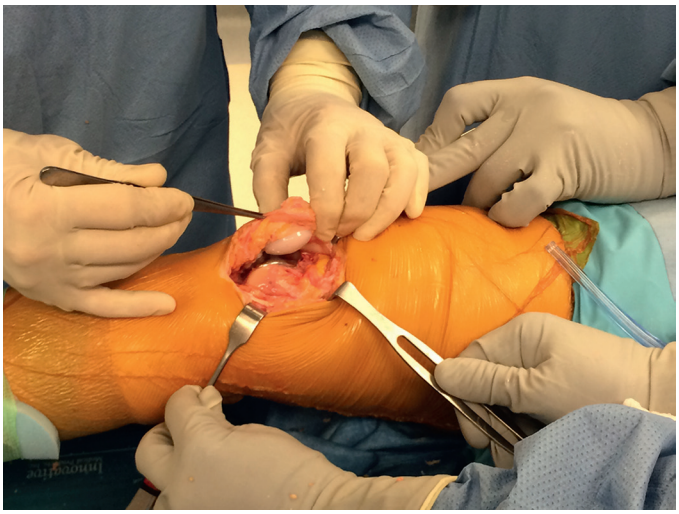


FIG 37-6 The final position and alignment of the patellofemoral implants, just before soft tissue balancing of the medial retinacular tissues and medial patellofemoral ligament.

As previously described, ensure that the trochlear implant is not in external rotation or valgus to decrease the risk of lateral patellar subluxation. The MAKO recommendations for the trochlear implant is 0 degree external rotation, 0 to 2 degrees varus, and 0 to 5 degrees of flexion. The proximal edge of the trochlear component is flush with the bone. It is important to map the articular cartilage-trochlear outline to verify the computer selected placement of the prosthesis. With the initial use of the burr, the depth is carefully observed again as a check on the selected trochlear positioning. The intraoperative placement of the patella and trochlear components are shown in Figure 37-5.

The implantation of the trochlear component begins with the insertion of the selected trochlear implant trial, which is impacted. Any proud cartilage and bone is resected with a rongeur and smooth patellar transitioning is confirmed. The trial implant is removed and fatty deposits from cancellous porous structures are removed.

Patellar Resection and Component Placement

The patella is measured with the leg in full extension with calipers that have a ±0.5 mm degree of accuracy. The patellar size is estimated by measuring the superior-inferior height of the patellar articular surface. The proper resection thickness is calculated based on patellar size and facet arthrosis. A saw guide is used to resect the articular surface of the patella, maintaining a residual patellar height of 14 to 15 mm.

With the knee in full extension, the patella sizing/drill guides are used to select the appropriate size patellar implant of 26, 29, 32, 35, 38, or 41 mm in diameter. There should be no overhang of the bone superiorly or inferiorly. The patella sizing drill guide should be aligned with the former patellar ridge (i.e., medialized on the patellar bone) to lateralize the remaining patellar bone. Caution is warranted in that centering the patella sizing drill guide will medialize the remaining patellar bone, which can overtighten the lateral soft tissue restraints. Three peg holes are drilled. A trial patellar implant is placed onto the resected patella and calipers are used to measure the patellar thickness. If the overall thickness is greater than the original patellar bone, additional bone may be shaved to avoid overstuffing the PF joint. The knee should be taken through a range of motion to ensure proper patellar tracking and transitioning.

Final Cement Technique

Cement is applied to the trochlear implant, ensuring that cement fully covers the back side of the implant, including the distal "tongue." Cement is applied to the resected cavity and firmly packed into the bone. The trochlear implant is placed onto the femur and impacted. The surgeon confirms that the implant is fully seated and carefully removes any excess extruded cement.

Cement is applied to the resected patellar surface, drilled peg holes, and implant and the patellar component is placed onto the resurfaced patella. Adequate clamping force is used to ensure the patellar implant is fully seated onto the patellar bone. Excess cement is removed as required. Once the cement has dried, patellar central tracking and range of motion are again checked before wound closure (Fig. 37-6). Checkpoints, bone pins, and arrays are removed and the extensor mechanism is closed as described later.

SURGICAL DECISION MAKING FOR SPECIAL PROBLEMS

Correction of Trochlear Dysplasia

Dejour and colleagues[15] described a qualitative classification system of four types of trochlear dysplasia: type A, trochlear morphology preserved with a fairly shallow trochlea; type B, flat or convex trochlea; type C, asymmetry of trochlear facets with convex lateral facet and hypoplastic medial facet; and type D, asymmetry of trochlear facets and cliff pattern. Many years later, Nelitz and coworkers[37] evaluated MRI criteria of 80 knees with symptomatic PF instability to determine whether specific measurements of the femoral trochlea could be assigned to Dejour's classification system. Given the marked variation in trochlear morphology, none of the quantitative MRI measurements could be assigned to this system. A similar conclusion was reached in a study by Lippacher and associates[26] who also noted that lateral radiographs underestimated the severity of trochlear dysplasia compared with axial MRI.

Nelitz and coworkers[37] reported median values of eight trochlear indices that distinguished Dejour type A (low-grade dysplasia) from the higher-grade dysplasia categories (B-D) and, based on their findings, recommended that a two-grade system be used instead of a four-grade system. The cut-off values between low- and high-grade dysplasia

CRITICAL POINTS Surgical Decision Making for Special Problems

- There is a high frequently of trochlear dysplasia that is corrected to a normal anatomic profile involving depth, sulcus angle, and proximal-distal and rotational alignment of the implant. Abnormal trochlear morphology frequently involves excessive lateral trochlear height, absent central groove, and medial trochlear hypoplasia. The potential problem of an onlay prosthetic design involves elevation of the trochlea and excessive soft tissue tensions that require added releases.
- Abnormal lateral position of the tibial tubercle, with increased TT-TG values, should be diagnosed preoperatively. In most cases, the TT-TG alignment is corrected by reestablishing a normal trochlear groove with prosthesis placement. Marked increased TT-TG values require correction with tibial tubercle medialization.
- Prior lateral dislocations resulting in attenuated and insufficient medial soft tissue restraints requires concurrent MPFL reconstruction to provide medial stability. A partial quadriceps tendon graft turndown that avoids patellar tunnels is recommended. For primary and secondary osteoarthritis, correcting trochlear morphology along with soft tissue balancing of existing medial structures provides stability.
- Avoid overtightening MPFL and medial retinacular tissues in soft tissue balancing by always allowing for a normal 1 quadrant lateral glide at 20 and 0 degrees of knee flexion.
- Lateral retinacular release indications are absence of a normal passive medial glide, patellar tilting, and failure to track centrally with knee flexion. Lateral soft tissue balancing is performed using Z-plasty lengthening and closure to restore normal lateral tension. Normal patellar tracking is always tested and restored at surgery.
- Infrapatellar contracture with abnormal scarred tissues and fat pad scar is frequent and should be removed at surgery.
- Patella alta is measured and, in most cases, distal transfer of the tibial tubercle is not required because the patella articulates with the lengthened proximal extent of the trochlear prosthesis. Distal tibial tubercle displacement is reserved for markedly abnormal patella alta conditions, with complete lack of patellar dome and trochlear contact at the beginning of knee flexion.

were 2 mm for depth of the trochlear groove, 48% for trochlear facet asymmetry, and 11 degrees for lateral trochlear inclination.

In the senior author's experience, there is a high frequency of abnormal trochlear morphology at the time of PFA that is corrected by the trochlear implant. The most common abnormality is excessive height of the lateral trochlea that is corrected at surgery. The mistake is to not correct this abnormal height because it would allow excessive internal rotation of the trochlear implant. In these cases, there is frequently hypoplasia of the medial trochlea. A complete reshaping of the dysplastic trochlea is performed to restore the normal trochlear depth and position that is based on the selected design of the trochlear prosthesis. It is necessary to cut into the abnormal lateral trochlear groove, maintain the center of the trochlear groove, and avoid medialization of the groove. The MAKO robotic technique has the distinct advantage in that the trochlear reshaping is performed using 3-dimensional computer adjustments, which is then transferred to the patient. The trochlea is shaped to afford a retained lateral buttress for patellar stability as previously described. The prosthesis has only a moderate trochlear depth, thereby avoiding other patellar implant designs that have an accentuated trochlea containment. There are specific recommendations for implant planning and intraoperative placement that the reader is referred to in the operative guide. Some custom onlay trochlea designs do not correct abnormal trochlear morphology and potentially produce overstuffing of the PF joint. Note is made that lateral release procedures and other soft tissue balancing procedures are commonly necessary as previously described.

Correction of Increased Tibial Tubercle-Trochlear Groove Distance

The preoperative examination already discussed involves measurement of PF-tibial tubercle alignment by Q-angle, CT, and, when abnormal, rotational MRI (see Chapter 35). In instances of trochlear dysplasia, an abnormal tibial TT-TG offset is frequently correctable at surgery by reestablishing a more normal lateral trochlear position in the placement of the trochlear prosthesis. Any excessive medial placement of the trochlear prosthesis will increase the TT-TG distance. There are select cases in which a highly abnormal TT-TG ratio requires a concurrent tibial tubercle medialization owing to persistent lateral tracking demonstrated at surgery. No specific rules have been established regarding TT-TG limits that require correction, and judgment at surgery is therefore required. For tibial tubercle medialization, the findings are usually a TT-TG ratio of 20 mm or greater and an obvious Q-angle of 20 degrees or greater that can be increased to 35 to 40 degrees with external tibial rotation (physiologic posterolateral laxity allows excessive tibial rotation). The goal of surgery in cases of extensor mechanism malalignment is to correct abnormal alignment and instability with added soft tissue balancing to ensure a successful long-term result.

Valgus-Aligned Lower Extremity with Excessive Body Mass Index

Of concern is the patient with an abnormal valgus malalignment of the lower extremity and an abnormal TT-TG ratio. There exists in these cases high lateral PF pressures of the patella dome and trochlear prosthesis. The problem is further compounded by the occurrence, in most of these patients, of excessive BMI. This represents a contraindication to PFA, and the patient is advised to obtain nutritional counseling and demonstrate weight loss to normal indices before PFA is considered. The patient is expected to do his or her part to decrease PF loading. These patients also have the potential for early lateral tibiofemoral compartment arthrosis and future necessity to perform a TKA. It is recognized that lack of patient compliance with weight loss may frequently occur, and therefore this patient profile usually represents a contraindication to PFA.

In select younger patients in whom a corrective femoral osteotomy has been performed, the goal of the PFA is to buy time before TKA. There should still exist greater than 50% lateral joint space on 45 degrees weight-bearing radiographs to warrant the PFA. A similar recommendation applies to varus-aligned knees already discussed. A prior meniscectomy to the affected compartment further amplifies the contraindication to PFA in these knees.

Prior Lateral Dislocations, Insufficient Medial Patellofemoral Ligament

The diagnosis of an insufficient MPFL and medial retinaculum structures, with preoperative symptomatic PF instability, should be established by both the history and physical examination of increased lateral patellar translation of 75% or greater patellar width at 0 and 20 degrees of knee flexion. At surgery, it is important to determine the integrity of the remaining MPFL and medial retinacular restraints. Although many MPFL reconstructions have been published, it is important to avoid any MPFL fixation tunnels into the patella. The senior author has described a quadriceps tendon turndown procedure to reconstruct the MPFL and adjust the tension in the remaining

medial retinaculum structures (see Chapter 35).[39] This procedure involves suture fixation without patellar or femoral tunnels. It should be noted that in most cases of prior PF dislocation, there are adequate medial soft tissues and a simpler pants-over-vest plication procedure of the MPFL and medial retinaculum restores medial stability. In addition, correction of trochlear dysplasia adds to extensor mechanism stability.

Excessive Medial Soft Tissue Tightening (Medial Patellofemoral Ligament and Medial Retinaculum)

The condition of excessive tightness of the MPFL and medial retinaculum suture closure at surgery must be closely monitored because this represents one of the most common factors that produces medial pain and limitation of knee flexion postoperatively. With the limited medial parapatellar incision that extends 2 cm above the patella, it is not necessary in most knees to excessively tighten or reef at the time of suture closure. Three nonabsorbable sutures are placed in the VMO, MPFL, and MPML structures and tensioned to restore normal medial stability that allows for a 1 quadrant or normal 10-mm lateral glide at 0 and 20 degrees of knee flexion. With the knee flexed to 120 degrees, there should be no disruption of the sutures. This technique ensures that a medial overpressure syndrome is not produced that will limit knee flexion and produce medial pain. Specific details of the MPFL and medial retinaculum tensioning are discussed in Chapter 35. The importance of performing patellar mobilization postoperatively to maintain normal patellar glide is discussed later.

Lateral Retinacular Release

The tension in the lateral retinacular structures is determined at the time of the PFA, with verification that there is normal tracking without tilting of the patellar prosthesis throughout knee flexion. The amount of medial patellar translation on the glide test performed at 20 degrees of knee flexion determines the amount of resting tension, and it should be possible to translate the patella at least 10 mm in the medial direction. When present, contracted lateral retinacular tissues resist medial patellar translation, and obvious tilting of the patella is observed with knee flexion. When necessary, the senior author prefers to perform a Z-plasty lengthening of the lateral retinaculum, termed a mini-release. In more contracted lateral soft tissue conditions, the vastus lateralis tendon requires a Z-plasty lengthening. These conditions represent an excessive lateral patellar compression syndrome, with complete absence of a normal medial patellar glide. The diagnosis should be made by performing these tests before surgery. All of the lengthened structures are closed under normal tension with sutures and soft tissue balancing to affect joint closure and prevent a medial patellar subluxation syndrome that has been recognized after excessive lateral release procedures.

Infrapatellar Contracture

The presence of an infrapatellar contracture should always be identified at surgery (Fig. 37-7). This represents a plate of scar tissue often 5 mm thick that extends from the inferior patellar pole to the anterior aspect of the tibia, just posterior to the patellar tendon. This band will limit normal patellar mobility and requires resection. The finding of a prominent fat pad with excessive lobule formation that may impinge postoperatively requires subtotal fat pad resection. A thickened medial plica is also resected when present. Recurrent PF disease of any type (frequently along with prior surgical procedures) usually results in abnormal and scarred infrapatellar tissues requiring attention at surgery. Care is taken at tourniquet deflation to be meticulous in electrocoagulation of fat pad bleeding and other soft tissue bleeding points.



FIG 37-7 Coronal T1 magnetic resonance imaging of infrapatellar scar contracture, which extends from the inferior pole of the patella, posterior to the fat pad, onto the anterior ventral tibial surface. These contractures, commonly found in multiple-operated knees, limit patellar mobility and require surgical excision at the time of patellofemoral arthroplasty.

Patella Alta

The presence of a patella alta requires diagnosis preoperatively and measurement of the patella height indices illustrated and discussed in detail along with the operative technique in Chapter 35. It is rare to have to perform a distal displacement of the tibial tubercle because the trochlear groove of the implant extends farther proximal than the native trochlea. This allows the patella to be guided into the trochlea and corrects the lateral extension subluxation (J-sign) that is present preoperatively, along with medial soft tissue balancing. There are rare instances in which the patella alta is so highly abnormal (>1.6 Linclau ratio) that the patellar dome does not engage into the prosthetic trochlea at 0 to 20 degrees of knee flexion. This will be obvious at surgery and requires distal displacement of the tibial tubercle. In these cases, it is necessary to restore a normal tension to the MPFL and medial retinaculum, and in some instances, determine that excessive tightness is not present in the lateral retinaculum. The test is to place the knee at 20 degrees of flexion and perform medial and lateral patellar displacement (glide) to determine the resting tension of these structures. The test is also repeated at 0 degrees of knee extension to ensure the medial structures have a normal resting tension that allows the patella to guide into the trochlear groove.

POSTOPERATIVE MANAGEMENT

The postoperative rehabilitation protocol is shown in Table 37-2. Patients begin immediate range of knee motion (ROM), patellar

Text continued on p. 1048

TABLE 37-2 Noyes Knee Institute Rehabilitation for Patellofemoral Arthroplasty

	1-2	3-4	5-6	7-8	9-12*
ROM minimum goals:					
0-110 degrees	X				
0-135 degrees		X			
Weight bearing:					
100% body weight with assistive devices	X				
100% body weight, wean from assistive devices		X			
Patellar mobilization	X	X	X	X	
Modalities:					
EMS	X	X	X		
Pain/edema management (cryotherapy)	X	X	X	X	
Stretching: hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X
Strengthening:					
Quadriceps isometrics, straight-leg raises	X	X	X	X	X
Closed-chain: gait retraining, toe raises, wall-sits, minisquats	X	X	X	X	X
Knee flexion hamstring curls (90 degrees)		X	X	X	X
Knee extension quadriceps (90-30 degrees)		X	X	X	X
Hip abduction-adduction, multihip		X	X	X	X
Leg press (70-10 degrees)		X	X	X	X
Balance/proprioceptive training: weight shifting, minitrampoline, BAPS, BBS	X	X	X	X	X
Conditioning:					
UBC	X	X	X	X	X
Bike (stationary)		X	X	X	X
Aquatic program			X	X	X
Swimming (kicking)				X	X
Walking				X	X
Stair-climbing machine				X	X
Ski machine				X	X
Elliptical machine				X	X
Upper body weight training			X	X	X
Core training			X	X	X

PHASE 1: WEEKS 1-2

General Observation

Full weight bearing with crutches/walker when:
- Pain controlled
- Hemarthrosis controlled
- Voluntary quadriceps contraction achieved

Factors Evaluated (Goal)

Pain (controlled)
Hemarthrosis (mild)
Patellar mobility (good)
ROM (0-110 degrees)
Quadriceps contraction and patellar migration (good)
Soft tissue contracture (none)

Activity	Frequency	Duration
ROM		
ROM (0-110 degrees), hang 10-20 lb of weight if <0 degrees	6 ×/day, 10 min	
Patellar mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	3 ×/day, 15 min	
Straight-leg raises (flexion, extension, abduction, adduction)		3 sets × 10 reps
Active quadriceps isometrics		10 reps
Knee extension quadriceps, active/active-assisted (range as tolerated)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps

TABLE 37-2 Noyes Knee Institute Rehabilitation for Patellofemoral Arthroplasty—cont'd

PHASE 1: WEEKS 1-2

Activity	Frequency	Duration
Balance Training	3 ×/day, 5 min	
Weight shift side-side and forward-backward		5 sets × 10 reps
Balance board/two legged		
Cup walking		
Single-leg stance		
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
Goals	• ROM 0-110 degrees • Adequate quadriceps contraction • Control inflammation and effusion	

PHASE 2: WEEKS 3-4

General Observation	Full weight bearing without assistive devices when gait pattern normal and: • Pain controlled • Hemarthrosis controlled • Voluntary quadriceps contraction, full extension achieved
Factors Evaluated (Goal)	Pain (controlled) Effusion (mild) Patellar mobility (good) ROM, minimum (0-135 degrees) Quadriceps contraction and patellar migration (good) Soft tissue contracture (none)

Activity	Frequency	Duration
ROM	3 ×/day, 15 min	
Passive, 0-135 degrees, hang 10-20 lb weight if <0 degrees; flexion overpressure: stool rolls, wall-slides if <90 degrees		
Patellar mobilization		
Ankle pumps (plantar flexion with resistance band)		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2-3 ×/day, 20 min	
Straight-leg raises (flexion, extension, abduction, adduction)		3 sets × 10 reps
Isometric training: multiangle (0, 60 degrees)		1 sets × 10 reps
Knee extension quadriceps (resistance, 90-30 degrees)		3 sets × 10 reps
Closed-chain: wall-sits (0-45 degrees)		30-60 sec ×5
Knee flexion hamstring curls (0-90 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Balance Training	3 ×/day, 5 min	
Weight shift side-side and forward-backward		5 sets × 10 reps
Balance board/two legged		5 reps
Cup walking		
Single-leg stance		

Continued

TABLE 37-2 Noyes Knee Institute Rehabilitation for Patellofemoral Arthroplasty—cont'd

PHASE 2: WEEKS 3-4

Activity	Frequency	Duration
Aerobic Conditioning	2 ×/day, 10 min	
UBC		
Stationary bicycling (high seat, low resistance)		
Modalities	As required	
EMS		20 min
Cryotherapy		20 min
Goals	• Muscle control • ROM 0-135 degrees • Control inflammation and effusion	

PHASE 3: WEEKS 5-6

General Observation	• Independent ambulation • Pain controlled without narcotics • Hemarthrosis controlled • ROM 0-135 degrees • Muscle control throughout ROM
Factors Evaluated (Goal)	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-135 degrees) Muscle control (3+/5) Inflammatory response (none)

Activity	Frequency	Duration
ROM	3 ×/day, 10 min	
Passive, 0-135 degrees; continue overpressure program if <0-100 degrees		6 ×/day
Patellar mobilization		
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (ankle weight 2.5-10 lb)		3 sets × 10 reps
Heel raise/toe raise		3 sets × 20 reps
Knee extension (resistance, 90-30 degrees)		3 sets × 10 reps
Knee flexion (active, 0-90 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Closed-chain: wall-sits (0-45 degrees)		5 reps
Balance Training	2 ×/day, 5 min	
Balance board/two legged		
Cup walking		
Single-leg stance		
Aerobic Conditioning	1-2 ×/day, 10 min	
UBC		
Stationary bicycling (high seat, low resistance)		
Water walking (water thigh to waist high)		

TABLE 37-2 Noyes Knee Institute Rehabilitation for Patellofemoral Arthroplasty—cont'd

PHASE 3: WEEKS 5-6

Activity	Frequency	Duration
Modalities	As required	
Electrical muscle stimulation		20 min
Cryotherapy		20 min
Goals	• ROM 0-135 degrees • Control inflammation and effusion • Muscle control • Early recognition of complications (motion, RSD, patellofemoral) • Full weight bearing	

PHASE 4: WEEKS 7-8

General Observation	• ROM 0-135 degrees • Can stand/walk for 30 min
Factors Evaluated (Goal)	Pain (mild/no CRPS) Effusion (minimal) Patellar mobility (good) ROM (0-135 degrees) Muscle control (4/5) Inflammatory response (none)

Activity	Frequency	Duration
ROM	2 ×/day, 10 min	
Hamstring, gastrocnemius-soleus stretches		5 reps × 30 sec
Strengthening	2 ×/day, 20 min	
Straight-leg raises (flexion, extension, abduction, adduction) with weights or rubber tubing		3 sets × 10 reps
Closed-chain:		
Wall-sits		5 reps
Mini-squats (rubber tubing, 0-30 degrees)		3 sets × 20 reps
Forward step-ups (2- to 4-inch block)		3 sets × 10 reps
Hamstring curls (resistance, 0-90 degrees)		3 sets × 10 reps
Knee extension (resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Balance Training	2 ×/day, 5 min	
Balance board, single legged (stable vs. unstable surface)		
Single-leg stance		
Aerobic Conditioning	1-2 ×/day, 10-15 min	
UBC		
Water walking		
Swimming (straight-leg kicking)		
Stationary bicycling		
Stair-climbing machine (low resistance, low stroke)		
Ski machine (short stride and level, low resistance)		
Modalities	As required	
Cryotherapy		20 min
Goals	• Full weight bearing • Muscle control • Control inflammation, effusion • ROM 0-135 degrees	

Continued

TABLE 37-2 Noyes Knee Institute Rehabilitation for Patellofemoral Arthroplasty—cont'd

PHASE 5: WEEKS 9-12

General Observation	ROM 0-135 degrees	
Factors Evaluated (Goal)	Pain (minimal/no CRPS) Manual muscle test (hamstrings, quadriceps, hip abductors/adductors/flexors/extensors) (4+/5) Swelling (minimal) Patellar mobility (good) Gait (symmetric)	
Activity	**Frequency**	**Duration**
ROM	2-3 ×/day, 10 min	
Hamstring, gastrocnemius-soleus, quadriceps, ITB stretches		5 reps × 30 sec
Strengthening	1-2 ×/day, 20 min	
Straight-leg raises		3 sets × 10 reps
Straight-leg raises with weights or rubber tubing		3 sets × 30 reps
Hamstring curls (resistance, 0-90 degrees)		3 sets × 10 reps
Knee extension (resistance, 90-30 degrees)		3 sets × 10 reps
Leg press (70-10 degrees)		3 sets × 10 reps
Closed-chain:		
Wall-sits		To fatigue ×3
Mini-squats (rubber tubing, 0-40 degrees)		3 sets × 20 reps
Lateral step-ups (2- to 4-inch block)		3 sets × 10 reps
Multihip machine (flexion, extension, abduction, adduction)		3 sets × 10 reps
Balance Training	2 ×/day, 5 min	
Balance board, single legged (stable vs. unstable surface)		
Single-leg stance		
Aerobic Conditioning	1-2 ×/day, 15 min	
Water walking		
Swimming (straight-leg kicking)		
Stationary bicycling		
Walking		
Stair-climbing machine (low resistance and stroke)		
Ski machine (short stride and level, low resistance)		
Modalities	As required	
Cryotherapy		20 min
Goals	• Increase strength and endurance • Increase balance and coordination • ROM 0-135 degrees	

*After postoperative week 12, patient continues strengthening and conditioning program as desired.
BAPS, Biomechanical Ankle Platform System (Patterson Medical); *BBS*, Biodex Balance System; *CRPS*, complex regional pain syndrome; *EMS*, electrical muscle stimulation; *ITB*, iliotibial band; *ROM*, range of motion; *RSD*, reflex sympathetic dystrophy; *UBC*, upper body cycle.

mobilization, quadriceps strengthening, and balance training with partial weight bearing allowed. A continuous passive motion machine is not required or routinely used by us. Patients perform passive and active ROM exercises in a seated position for 10 minutes a session, approximately six times per day. Full passive knee extension must be obtained immediately to avoid excessive scarring. If the patient has difficulty regaining at least 0 degree by the seventh postoperative day, he or she begins an overpressure program. The foot and ankle are propped on a towel or other device to elevate the hamstrings and gastrocnemius that allows the knee to drop into full extension. This position is maintained for 10 minutes and repeated four to six times per day. A 10- to 20-lb weight may be added to the distal thigh and knee to provide overpressure to stretch the posterior capsule. Knee flexion is gradually increased to 110 degrees by the second postoperative week and 135 degrees by the third to fourth postoperative week. Passive knee flexion exercises are performed initially in the traditional seated position, using the opposite lower extremity to provide overpressure. Other methods to assist in achieving flexion greater than 90 degrees include chair rolling, wall slides, knee flexion devices, and passive quadriceps stretching exercises (see Chapter 11).

Patients use a walker or crutches with full weight bearing allowed as tolerated. Full weight bearing without crutches is permitted when the patient demonstrates a normal gait pattern, which is usually by the third to fourth postoperative week. Balance, proprioception, and strengthening exercises are gradually increased as supervised by the therapist and shown in Table 37-2 through approximately the 12th postoperative week. At that time, the patient is encouraged to continue the strengthening and aerobic conditioning program as desired.

COMPLICATIONS AND FACTORS LEADING TO FAILURE

First-generation PFA studies reported frequent problems related to patellar maltracking or subluxation, anterior knee pain, and improper positioning of the implant.[4,7,27,31,34,46,49] Fortunately, these problems have been markedly reduced with second- and third-generation implant design, improved operative techniques, and selection of patient candidates. Currently, the progression of tibiofemoral arthritis is one of the most common causes of failure or unsatisfactory results.[2,5,9,13,21,24,27,31,38,40,52,53,55] Therefore it is essential that the preoperative evaluation rules out patients with existing articular cartilage damage or joint space narrowing in either tibiofemoral compartment.

Problems with regaining normal knee motion have been reported that required arthroscopic lysis of adhesions in 9% in two series[8,35] and manipulation under anesthesia in 1% to 18% in other studies.[2,12,14,21,23,41,52] The majority of studies have not reported the final amount of knee motion achieved[2,3,8,23,35,38,48] or only provided means and standard deviations of the operative and contralateral knees.[11,40,42]

The need for additional operations (except revisions) after PFA varies among studies. van Jonbergen and colleagues[52] performed "arthrotomy, arthroscopy, or other" operative procedures in 51 of 181 knees (28%) after PFA with the Richards II implant. Lateral retinacular release was done in 2% to 11% in five studies.[5,9,10,12,42] Other complications such as infection and deep venous thrombosis appear to be extremely rare after PFA.

Prosthesis-related bone loss (postoperative decrease in bone mineral density) reported after TKA[25,47] has been believed to be related to strain shielding. Strain shielding may promote reduction of bone density and bone resorption, although overload promotes excessive formation of bone that causes an increase in bone density and may induce fatigue damage.[16] Loss of bone may lead to periprosthetic fracture or weakening of the implant fixation, resulting in loosening and implant failure.[32,47] In a study involving five synthetic femur models, Meireles and colleagues[32] experimentally determined the strain shielding effect of PFA (Journey, Smith & Nephew) during level walking, stair climbing, and deep squatting. The study found that, during deep squatting to 90 degrees, PFA reduced strains in the medial and distal regions of the femur compared with the preoperative condition (−72% and −67.5%, respectively) and increased strain in the anterior region (182%). There were no major strain reductions during level walking or stair-climbing conditions. No clinical studies have assessed bone mineral density after PFA.

CLINICAL STUDIES

The survivorship rates reported after first-generation PFA are shown in Table 37-3 and the clinical outcomes are shown in Table 37-4. High revision rates because of problems previously discussed lead to the discontinuation of most of these implants. Outcomes for second-generation implants are shown in Tables 37-5 and 37-6. The Avon PFA

TABLE 37-3 Survival/Success Rates of First-Generation Patellofemoral Arthroplasty

Study	Prosthesis	Knees: Patients	Mean Follow-up (Range) (yr)	Survival End Points	SURVIVAL/SUCCESS RATES (%) 2-3 yr	5 yr	7 yr	10 yr	15 yr	20 yr
van Jonbergen et al[51] (2010)	Richards II	181:157	13.3 (2-30.6)	Revision TKA or PFA, prosthesis removal	—	—	—	84	—	69
Cartier et al[9] (2005)	Richards II, III	79:70	10 (6-16)	Repeat surgery mechanical problem, wear, loosening, sepsis, deterioration TF joint	—	96	91	84 at 10 yr, 75 at 11 yr	—	—
Kooijman et al[21] (2003)	Richards II	45:45	17 (15-21)	Revision TKA or PFA	—	95*	95*	90*	80*	55*
de Winter et al[14] (2001)	Richards II	26:24	11 (1-20)	Implant removal, revision TKA, or no improvement	—	—	77	—	—	—
Yadav et al[56] (2012)	Low Contact Stress	49:49	4.2	Revision	—	48	—	—	—	—
Charalambous et al[10] (2011)	Low Contact Stress	51:35	2.1 (0.4-5)	Revision or moderate to severe pain	46	14	—	—	—	—
Board et al[7] (2004)	Lubinus	17:17	1.6 (0.2-4.7)	Unsatisfactory according to patient	53	—	—	—	—	—
Smith et al[46] (2002)	Lubinus	29:29	4.1 (0.5-7.5)	Revision or rated fair/poor	—	64	—	—	—	—
Tauro et al[49] (2001)	Lubinus	62:48	7.5 (5-10)	Revision or moderate pain	—	—	48	—	—	—
van Wagenberg et al[53] (2009)	Autocentric II	24:20	4.8 (2-11)	Revision TKA or PFA	—	71	—	—	—	—
Gadeyne et al[17] (2008)	Autocentric	43:43	6.2 (6.5-15)	Revision	—	76	—	—	—	—
Argenson et al[5] (2005)	Autocentric	57:57	16.2 (12-20)	Revision	—	—	—	58	—	—
De Cloedt et al[13] (1999)	Autocentric	45:45	6 (3-12)	Revision	—	82	—	—	—	—

Reported as either Kaplan-Meier survival rates or derived from failures as described in the report.
*Percentages estimated from Kaplan-Meier survival graphs.
PFA, Patellofemoral arthroplasty; *TF*, tibiofemoral; *TKA*, total knee arthroplasty.

TABLE 37-4 Clinical Outcomes of First-Generation Patellofemoral Arthroplasty

Study	Prosthesis	Knees (*n*)	Mean Age (Range) (yr)	Mean Follow-up (Range) (yr)	Knees With Outcome Data (*n*)	Knee Rating Scores (Mean)	Other Outcomes
Cartier et al[9] (2005)	Richards II, III	117	60 (36-81)	10 (6-16)	79	AKS Knee, 77% excellent, 14% fair, 9% failed; Function score, 72% excellent, 19% fair, 9% failed	47 (80%) no pain, 12 (20%) moderate or worse pain; 7% revised
Kooijman et al[21] (2005)	Richards II	56	50 (30-77)	17 (15-21)	35	AKS Knee score range, 30-200	22 no further symptoms, 8 occasional pain, 5 no improvement or worse; 18% revised
de Winter et al[14] (2001)	Richards II	26	59 (22-90)	11 (1-20)	21	AKS Knee score, 90 (range, 65-100); Function score 78 (range, 0-100)	Patient perception: 9 excellent, 7 good, 4 improved, 1 not improved; 19% revised
Yadav et al[56] (2012)	Low Contact Stress	49	53 (23-79)	4.2	49	Oxford: significant improvement at 3 and 12 mo only	20% knees revised
Charalambous et al[10] (2011)	Low Contact Stress	51	63.8 (47-84)	2.1 (0.4-5)	28	AKS Knee score, 87 (range, 63-88); Function score, 80 (range, 62-100)	Patient perception: 15 excellent/good, 7 satisfactory, 6 unsatisfactory; 23 no/mild pain, 11 moderate/severe pain; 33% revised
Board et al[7] (2004)	Lubinus	17	66 (37-82)	1.6 (0.2-4.7)	17	Tegner range, 1-3; Lysholm range, 16-84; VAS pain 5.2 preoperative, 7.3 F/U	Patient perception: 59% satisfactory, 41% unsatisfactory; 24% revised
Smith et al[46] (2002)	Lubinus	45	72 (42-86)	4.1 (0.5-7.5)	29	Hungerford & Kenna system: 13 excellent, 10 good, 2 fair, 4 poor	Patient perception: 21 better, 6 same, 2 worse; 72% felt surgery worthwhile; 19% revised
Tauro et al[49] (2001)	Lubinus	76	65 (50-87)	7.5 (5-10)	41	Bristol 81 (range, 42-100); outcome score satisfactory 45%, unsatisfactory 55%	53% no pain, 26% mild pain, 21% moderate pain; 28% knees revised
van Wagenberg et al[53] (2009)	Autocentric II	24	63 (38-81)	4.8 (2-11)	10	KOOS: symptoms 60, pain 47.5, ADL 42.5, sports 21.5, quality of life 42; Oxford: 36; VAS: 4.3	30% patients satisfied; 29% revised
Gadeyne et al[17] (2008)	Autocentric	43	67	6.2 (6.5-15)	43	ADL scale: 58% good	24% revised
Argenson et al[5] (2005)	Autocentric	66	57 (21-82)	16.2 (12-20)	29	AKS Pain score, 78.5 (range, 60-100); Function score, 81 (range, 40-100)	21 no pain, 11 moderate pain; 43% revised

ADL, Activities of daily living; *AKS*, American Knee Society; *F/U*, follow up; *KOOS*, Knee Osteoarthritis Outcome Survey; *NA*, not available; *VAS*, visual analogue scale.

TABLE 37-5 Survival or Success Rates of Second-Generation Patellofemoral Arthroplasty

Citation	Prosthesis	Knees: Patients	Mean Follow-up (Range) (yr)	Survival End Points	SURVIVAL/SUCCESS RATES (%)					
					2-3 yr	5 yr	7 yr	10 yr	15 yr	20 yr
Mont et al[35] (2012)	Avon	43:37	7 (4-8)	Revision of any components	—	95	82	—	—	—
Sarda et al[42] (2011)	Avon	44:40	4.5 (3-8)	Revision TKA	—	95	—	—	—	—
Odumenya et al[40] (2010)	Avon	50:32	5.3 (2-10)	Revision	—	100	—	—	—	—
Dahm et al[11] (2010)	Avon	23:23	2.4 (2-4.1)	Knee condition worse	96	—	—	—	—	—
Starks et al[48] (2009)	Avon	37:29	2	NA	100	—	—	—	—	—
Leadbetter et al[23] (2009)	Avon	79:70	3 (2-5.5)	Knee Society Score <80 points, revision	84	—	—	—	—	—
Ackroyd et al[2] (2007)	Avon	83:63	5.2 (5-8)	Moderate to severe pain or revision	—	88	—	—	—	—
Nicol et al[38] (2006)	Avon	103:79	7.1 (5.5-8.5)	Revision	—	—	86	—	—	—
Beitzel et al[6] (2013)	Journey PFJ	23:23	2	Revision	96	—	—	—	—	—
Phillippe & Caton[41] (2014)	Hermes	85:70	12 (10-16)	No improvement or revision	—	—	—	93	—	—
Al-Hadithy et al[3] (2014)	Femoro Patella Vialli	53:41	3.1 (1-5.8)	Revision	97	—	—	—	—	—
Davies[12] (2013)	Femoro Patella Vialli	52:44	2	Revision or no improvement	65	—	—	—	—	—
Williams et al[55] (2013)	Femoro Patella Vialli	48:48	2.1 (0.5-4.1)	Revision or no improvement	79	—	—	—	—	—

Reported as either Kaplan-Meier survival rates or derived from failures as described in the report.
NA, Not available; *PFJ*, patellofemoral joint; *TKA*, total knee arthroplasty.

TABLE 37-6 Clinical Outcomes of Second-Generation Patellofemoral Arthroplasty

Study	Prosthesis	Knees (*n*)	Mean Age (Range) (yr)	Mean Follow-up (Range) (yr)	Knees With Outcome Data (*n*)	Knee Rating Scores (Mean)	Other Outcomes
Mont et al[35] (2012)	Avon	43	49 (27-67)	7 (4-8)	38	AKS Knee score, 87 (range, 50-100); Function score, 82 (range, 20-100)	12% revised
Sarda et al[42] (2011)	Avon	44	62 (43-88)	4.5 (3-8)	39	AKS Knee score, 85 (range, 28-100)	Patient rating: 87% good/excellent, 8% fair, 5% poor; 4% revised
Odumenya et al[40] (2010)	Avon	50	66 (42-88)	5.3 (2-10)	50	Oxford 30.5; EuroQol General Health 75 unilateral PFA, 50 bilateral PFA	2% revised
Dahm et al[11] (2010)	Avon	23	60 (39-81)	2.4 (2-4.1)	23	AKS Knee score, 89 (range, 69-100); Function score, 84 (range, 51-100); Tegner 4.3 (range, 3-6)	Pain: none 35%, mild 43%, moderate 22%; Patient rating: 74% much better, 22% somewhat better, 4% worse; no revisions
Starks et al[48] (2009)	Avon	37	66 (30-82)	2	37	AKS Knee score, 95; Function score, 85	97% satisfied with results at 2 years; 1 patient revised patellar button
Leadbetter et al[23] (2009)	Avon	79	58 (34-77)	3 (2-5.5)	79	AKS Knee score, 83 (range, 60-100); 84% AKS >80, 16% <80 (clinical failures)	90% no problems daily activities; 9% revised; 28% returned to sports/fitness activities

Continued

TABLE 37-6 Clinical Outcomes of Second-Generation Patellofemoral Arthroplasty—cont'd

Study	Prosthesis	Knees (*n*)	Mean Age (Range) (yr)	Mean Follow-up (Range) (yr)	Knees With Outcome Data (*n*)	Knee Rating Scores (Mean)	Other Outcomes
Ackroyd et al[2] (2007)	Avon	83	68 (46-86)	5.2 (5-8)	83	Oxford 39	18% revised
Beitzel et al[6] (2013)	Journey PFJ	25	46 (28-67)	2	22	Significant improvements VAS pain, Lysholm, WOMAC (mean values not given)	1 revised
Phillippe & Caton[41] (2014)	Hermes	85	71	12 (10-16)	80	Oxford 40	Patient perception: 88% very satisfied, 6% mildly satisfied, 6% no improvement; 4% revised
Al-Hadithy et al[3] (2014)	Femoro Patella Vialli	53	62 (39-86)	3.1 (1-5.8)	51	Oxford 38, significant improvement	1 revised
Davies[12] (2013)	Femoro Patella Vialli	52	61 (38-84)	2	51	Oxford 19 (range, 3-41); AKS Knee score, 81 (range, 45-100); Function score 70 (range, 25-100)	13.5% revised

AKS, American Knee Society; *PFA*, patellofemoral arthroplasty; *VAS*, visual analogue scale; *WOMAC*, Western Ontario and MacMaster Universities Osteoarthritis Index.

TABLE 37-7 Survival/Success Rates of Third-Generation Patellofemoral Arthroplasty

Study	Prosthesis	Knees: Patients	Mean Follow-up (Range) (yr)	Survival End Points	SURVIVAL/SUCCESS RATES (%)					
					2-3 yr	5 yr	7 yr	10 yr	15 yr	20 yr
Sisto & Sarin[45] (2010)	KineMatch	25:22	11.3 (7.8-14.9)	NA	—	—	—	100	—	—
Sisto & Sarin[43] (2006)	KineMatch	25:22	6.1 (2.7-9.9)	NA	—	100	—	—	—	—
Butler & Shannon[8] (2009)	Custom Performa Knee	22:21	5	Revision, worn or broken patellar component	—	77	—	—	—	—

Reported as either Kaplan-Meier survival rates or derived from failures as described in the report.
NA, Not available.

is the most widely studied of these implants to date, with midterm survival rates (5 to 7 years) of 323 knees ranging from 82% to 100%. Inconsistent results have been reported 2 to 3 years after the Femoro Patella Vialli (Wright Medical Technology); survivor rates range from 65% to 97%.

Only two small series have been reported regarding mid- to long-term outcomes of third-generation PFA implants (Tables 37-7 and 37-8).[8,43,45] No revisions were required in 25 patients who received a KineMatch implant (Kinamed Inc.) followed a mean of 11 years postoperatively.[45] In 22 patients who received a Custom Performa Knee (Biomet Orthopedics), five had problems with the patellar button; one was revised because of poor sizing, three had worn, and one broke.[8] There were no problems with the trochlear components.

Lonner[27] retrospectively compared his early outcomes of the first-generation Lubinus with those of the Avon and reported incidence rates of fair and poor results (from PF dysfunction, subluxation, catching, substantial pain) of 17% and 4%, respectively. This investigator and coworkers[20] revised 14 Lubinus failures in 11 patients to the Avon implant for component malalignment and patellar subluxation, wear and synovitis, and component malposition. The PFA revisions were performed a mean of 5.6 years (range, 0.6-10.7 years) postoperatively. Only three patients were younger than 60 years at the time of the revision. At a mean of 5 years postrevision, two knees had undergone TKA, and three had poorer function compared with the preoperative condition. The remaining six knees had improved pain and knee function. The authors commented that PFA revision should only be considered in cases where the bone stock in the trochlear region is adequate to allow implantation of a new implant and if the tibiofemoral compartments are normal and do not produce symptoms. If these conditions do not exist, then conversion to TKA is the appropriate procedure.

TABLE 37-8 Clinical Outcomes of Third-Generation Patellofemoral Arthroplasty

Study	Prosthesis	Knees (*n*)	Mean Age (Range) (yr)	Mean Follow-up (Range) (yr)	Knees With Outcome Data (*n*)	Knee Rating Scores (Mean)	Other Outcomes
Sisto & Sarin[45] (2010)	KineMatch	25	45 (23-51)	11.3 (7.8-14.9)	25	None	All patients very satisfied with results, would have procedure again; no revisions
Sisto & Sarin[43] (2006)	KineMatch	25	45 (23-51)	6.1 (2.7-9.9)	25	AKS Knee score, 91 (range, 82-96); Function score, 89 (range, 81-94); significant improvement	No problems normal walking; no revisions
Butler & Shannon[8] (2009)	Custom Performa Knee Patellofemoral Arthroplast	22	48 (35-63)	5	22	WOMAC overall 28; pain 5.5, stiffness 2.4, function 20.6 (all significantly better scores compared with preoperative)	5% revised patellar button

AKS, American Knee Society; *WOMAC*, Western Ontario and McMaster Universities Osteoarthritis Index.

ILLUSTRATIVE CASES

Case 1. A 35-year-old woman sustained a patellar fracture and underwent an open reduction and internal fixation and subsequently developed a patella infera (Fig. 37-8, *A*). Because of severe PF symptoms that were unresponsive to conservative treatment, she underwent a PF arthroplasty 3 years later. The preoperative sagittal CT segment is shown in Figure 37-8, *B*, and the preoperative axial CT segment is shown in Figure 37-8, *C*. The demonstration of the required anatomic landmarks for the trochlear implant is shown in Figures 37-8, *D* and *E*. The intraoperative verification of the trochlear implant placement is shown in Figure 37-8, *F*. The postoperative anteroposterior (Fig. 37-8, *G*) and lateral (Fig. 37-8, *H*) radiographs show the residual patella infera, which is expected to cause increased

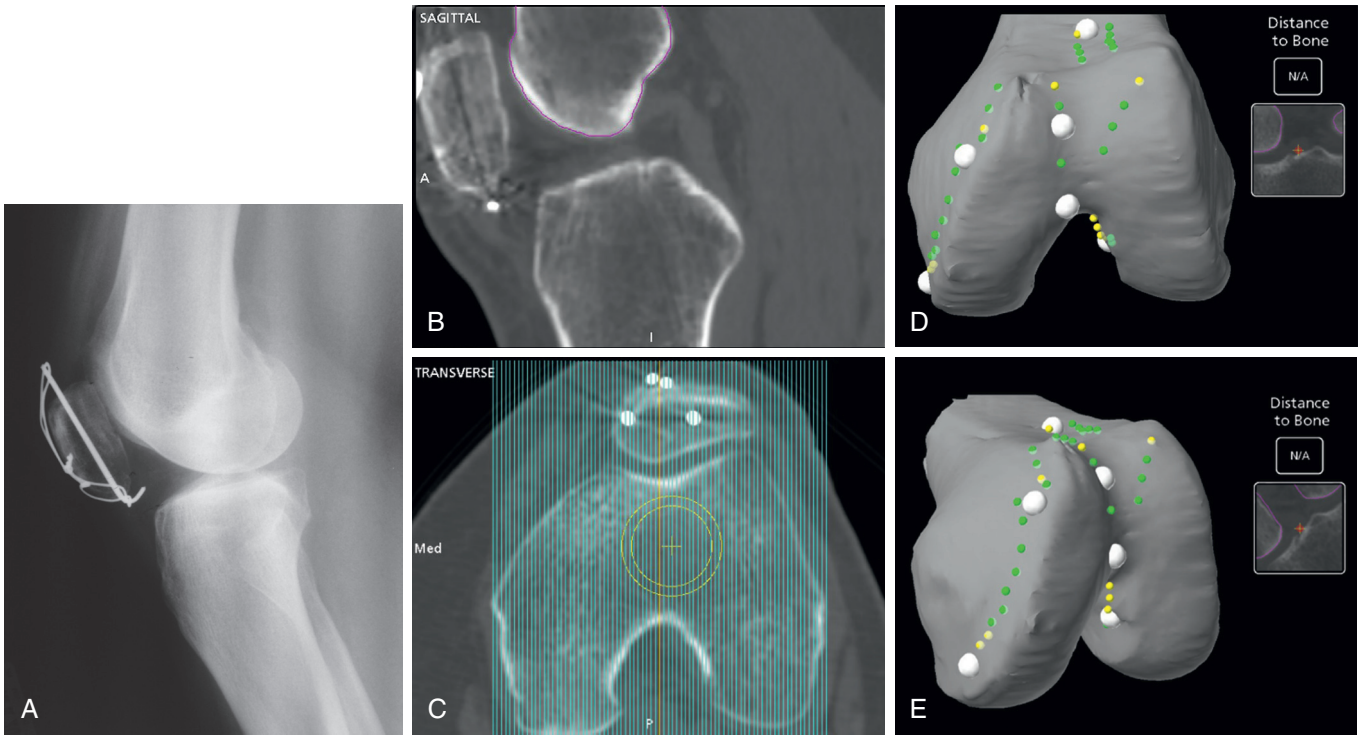
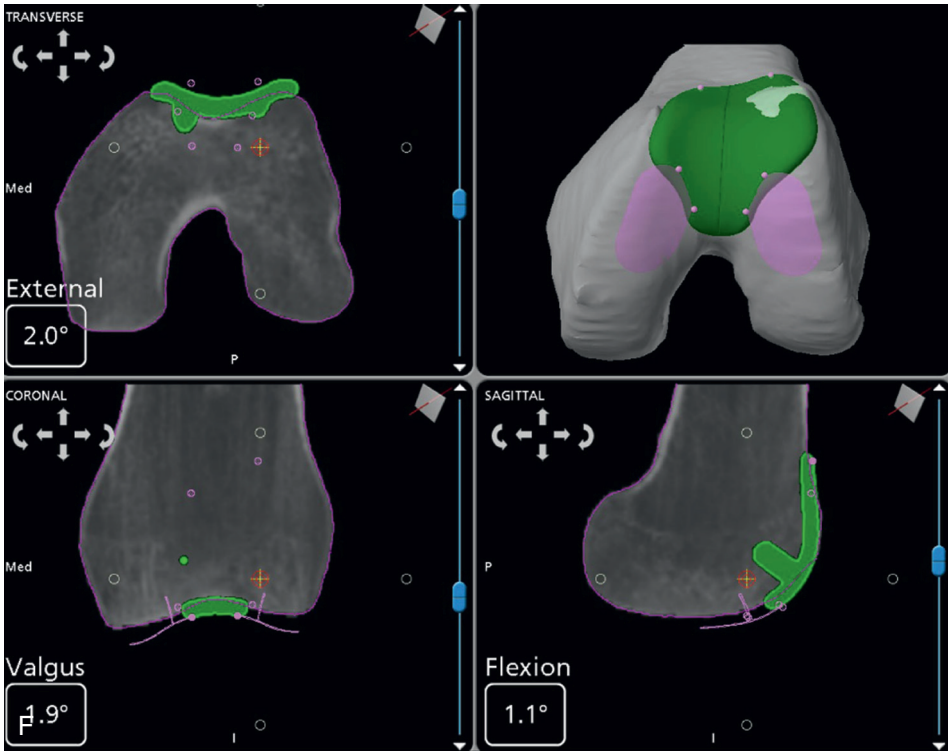


FIG 37-8 Case 1.

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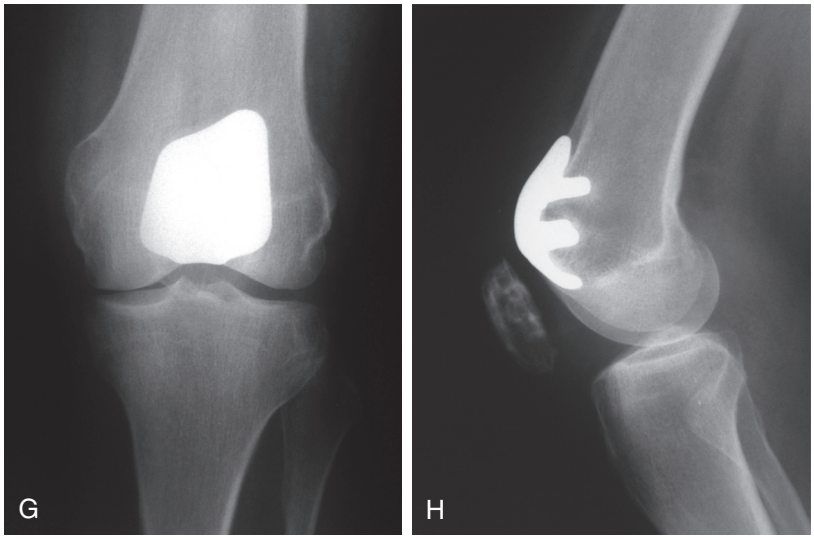


FIG 37-8, cont'd

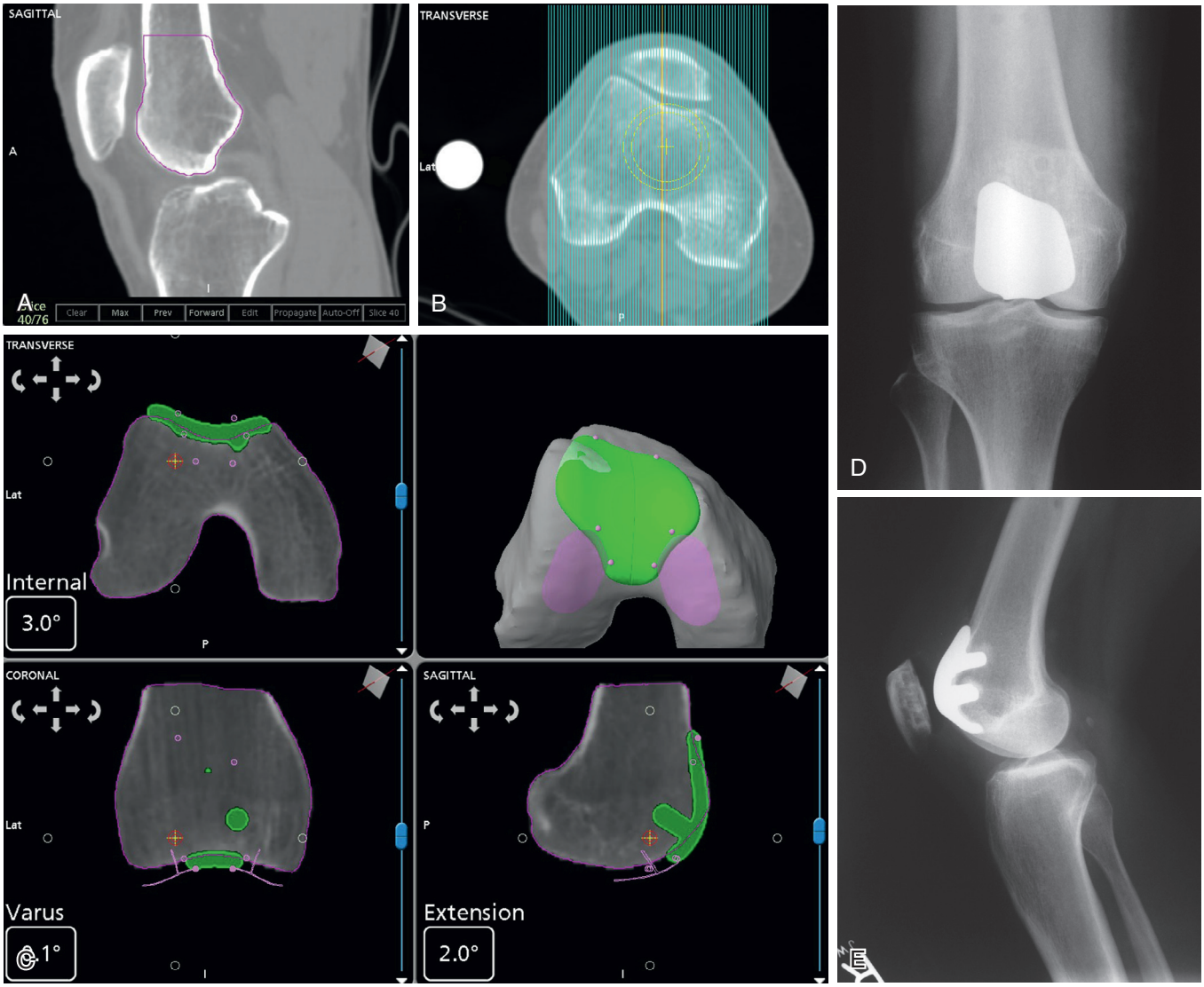


FIG 37-9 Case 2.

proximal patellar component pressures. Even so, the patient is asymptomatic with daily activities and markedly improved from her preoperative state.

Case 2. A 50-year-old woman with advanced PF arthritis and underlying trochlear dysplasia presented after failure of nonoperative treatment with marked disability with daily activities. The preoperative coronal CT segment (Fig. 37-9, *A*) and axial CT segment (Fig. 37-9, *B*) images show trochlear dysplasia and hypoplasia of the medial aspect of the trochlea. Figure 37-9, *C* shows the intraoperative placement of the trochlear implant and the resection required of the lateral trochlea for proper placement of the implant. Postoperative anterior (Fig. 37-9, *D*) and lateral (Fig. 37-9, *E*) radiographs demonstrate correct positioning of the PF arthroplasty. At 2 years postoperative, the patient is asymptomatic with daily activities.

Case 3. A 55-year-old woman underwent PF arthroplasty for advanced PF arthritis. Figure 37-10, *A* shows an obvious patella alta (Linclau ratio 1.30). The preoperative axial CT segment (Fig. 37-10, *B*) shows a prominent lateral trochlea. Figure 37-10, *C* shows the intraoperative placement of the trochlear component with verification of the proximal trochlear component that provided suitable contact with the patellar component in view of the patella alta condition. A distal advancement of the tibial tubercle was not required. Appropriate soft tissue balancing was required. The intraoperative photographs of this patient are shown in Figures 37-5 and 37-6.

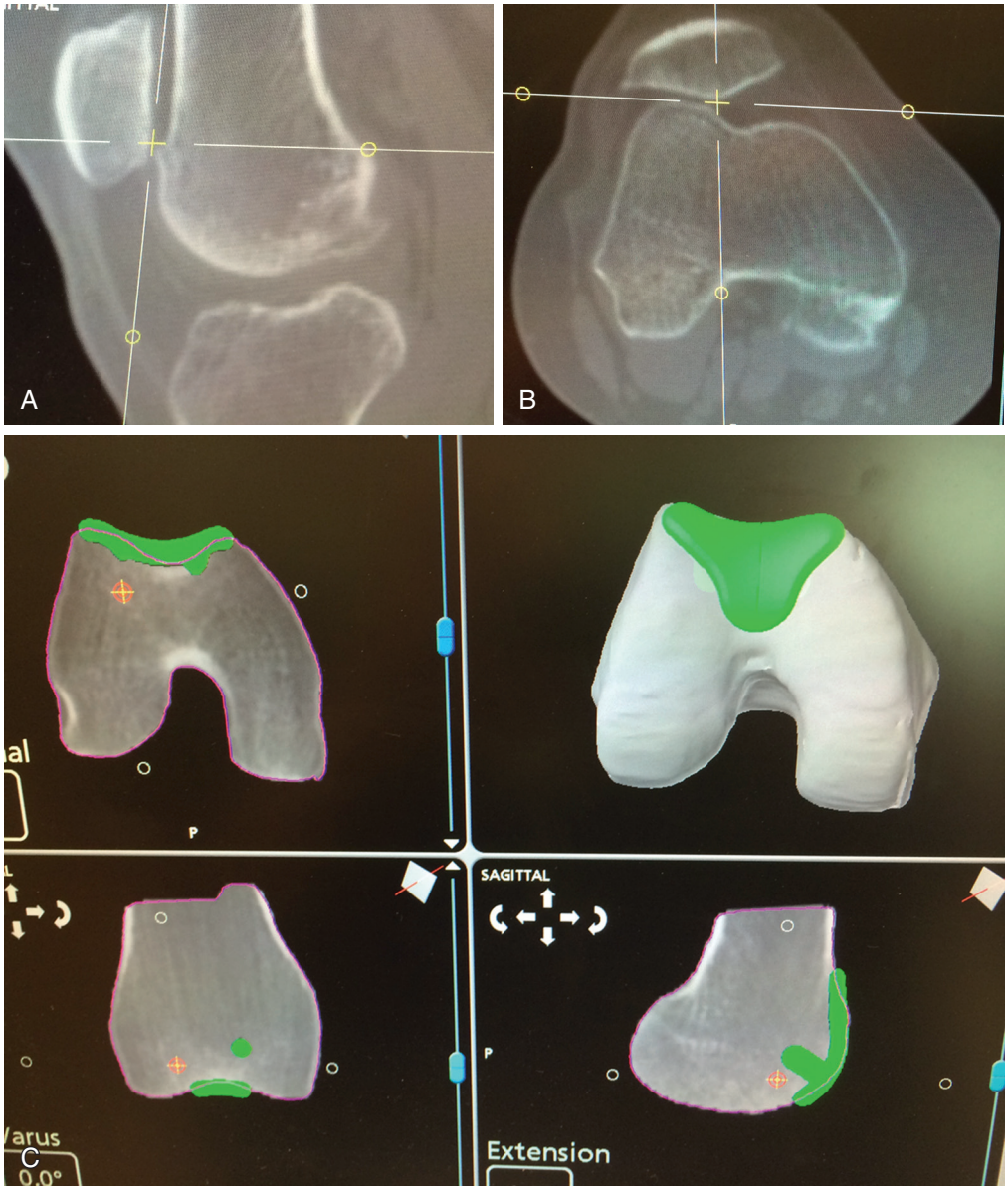


FIG 37-10 Case 3.

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Video Content

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Video 30-2

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38

Prevention and Treatment of Knee Arthrofibrosis

Frank R. Noyes, Sue D. Barber-Westin

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Video 11-1 Arthroscopic Treatment of Arthrofibrosis Following Major Knee Ligament Reconstruction

Video 11-2 Patient 2: Demonstration of Extension Cast to Resolve Knee Flexion Contracture

Video 11-3 Cincinnati SportsMedicine Experience: Treatment of Knee Arthrofibrosis

Video 24-3 Patient 1: 2 Weeks Postoperative Medial Meniscus Allograft; Prior Opening Wedge HTO for Varus Malalignment; Motion Complication Requiring Aggressive Treatment

Video 24-4 Patient 2: 3 Weeks Postoperative Meniscus Allograft and Treatment for Motion Complications, Beneficial Effect of Early Range of Motion Under Anesthesia

Video 30-1 Patient 3: 8 Days Postoperative TKR Requiring Overpressure Program for Lack of Full Knee Extension

INTRODUCTION

Loss of a normal range of knee motion following an injury or ligament reconstruction is a potentially devastating complication. Many investigations and publications have appeared since the early 1990s regarding this problem, and it continues to be one of the most frequently reported complications after surgical procedures such as autologous chondrocyte implantation (ACI), knee ligament reconstructions, and total knee arthroplasty (TKA).[37,52,66,93,98,154,176] Although the definition and use of the term *arthrofibrosis* varies among authors, it implies a loss of knee flexion, extension, or both compared with the contralateral normal knee. Stephenson and associates[176] estimated that the number of patients who undergo major knee surgery in the United States that are subsequently affected by arthrofibrosis is at least 85,000 a year. Of these, 21,000 are at risk of requiring additional surgery, and 54,000 may have an unsuccessful outcome of treatment for this complication.

Primary arthrofibrosis is caused by an exaggerated inflammatory response to an injury or surgical procedure, followed by the production of fibroblastic cells and an increase in the deposition of extracellular matrix proteins.[182] Proliferative scar tissue or fibrous adhesions form within the joint, which can result in either localized or diffuse involvement of all of the compartments of the knee and the extra-articular soft tissues (Fig. 38-1). In the most severe cases, dense scar tissue obliterates the normal peripatellar recesses, suprapatellar pouch, intercondylar notch, and articular surfaces. Formation of dense scar tissue in the infrapatellar region may result in a patella infera and permanent limitation of normal knee flexion and extension. The consequent pain and restricted knee motion resulting from arthrofibrosis may lead to disabling events, including severe quadriceps atrophy, loss of patellar mobility, patellar tendon adaptive shortening, patella infera, and articular cartilage deterioration.[129,130]

The incidence of arthrofibrosis after knee ligament reconstructive surgery varies according to several factors. In our experience, two of the most commonly noted factors are knee dislocations and major

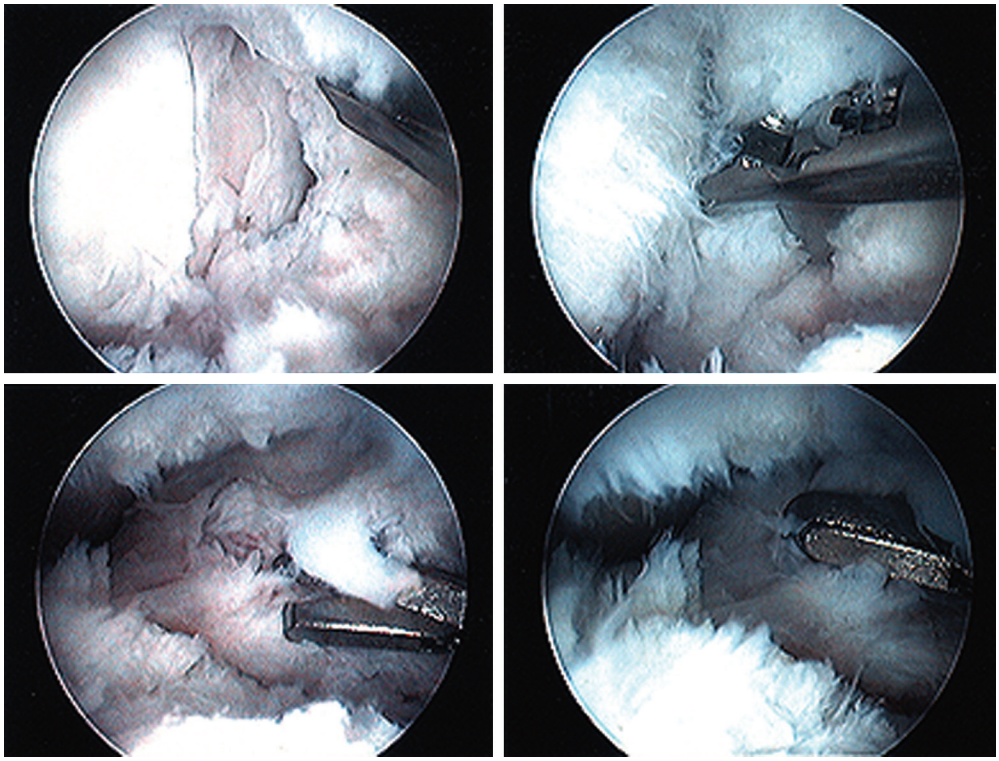


FIG 38-1 Proliferative formation of scar tissue requiring arthroscopic debridement and lysis of adhesions. A contracture of medial and lateral parapatellar soft tissues is shown, along with patella and trochlear cartilage deterioration.

CRITICAL POINTS Introduction

- Arthrofibrosis implies a loss of knee flexion, extension, or both compared with the contralateral normal knee.
- Primary arthrofibrosis is caused by an exaggerated inflammatory response to an injury or surgical procedure followed by the production of fibroblastic cells and an increase in the deposition of extracellular matrix proteins. Proliferative scar tissue or fibrous adhesions form within the joint, which can be either localized or diffuse.
- Incidence of arthrofibrosis following ligament reconstructive surgery varies.
- Wide disparity exists among authors regarding the treatment of this problem.
- Limitations in knee motion may occur owing to reasons other than arthrofibrosis:
  - Mechanical block from a displaced bucket-handle meniscus tear.
  - Impinged or improperly placed ACL graft.
  - Cyclops lesion.
  - Improper ACL graft tensioning.
  - Contracture of posterior capsular structures.
- If not resolved, these problems may result in the development of secondary arthrofibrosis.
- Most individuals have some amount of hyperextension to allow the normal "screw-home" mechanism to occur: knee stabilized in extension during the stance phase, with the quadriceps muscle relaxed.
- Normal knee flexion averages 140 degrees in men and 143 degrees in women.
- Patients not involved in athletics tolerate small flexion deficits. Significant flexion deficits <90 degrees cause problems with squatting, stair-climbing, and sitting.
- Loss of just 5 degrees of extension may produce a flexed-knee gait, fatigue the quadriceps muscle, and cause patellofemoral pain.
- Prevention of knee arthrofibrosis is paramount and preferred over the current treatment options for this complication.

concurrent operative procedures (Table 38-1).[12,113-127] Studies show wide disparity among authors regarding the treatment of this problem, especially the postoperative time that intervention is warranted and what type of treatment should be implemented for losses of knee extension and flexion and patella mobility.

Note that limitations in knee flexion and extension may occur because of reasons other than arthrofibrosis. Any acute injury causing pain and swelling may cause a short-term loss of knee motion, which usually resolves as symptoms subside. Other factors influencing the restoration of knee motion include a mechanical block from a displaced bucket-handle meniscus tear, an impinged or improperly placed anterior cruciate ligament (ACL) graft, a cyclops lesion,[80] improper graft tensioning that constrains normal knee joint motion,[30] and graft fixation at 30 degrees or more of extension.[7] In addition, contracture of the posterior capsular structures may limit knee extension. If not resolved, these problems may result in the development of what is termed *secondary arthrofibrosis*, complicating the course of treatment.

Normal knee motion varies, but most individuals have some amount of hyperextension, which averages 5 degrees in men and 6 degrees in women.[41,42,93] This degree of hyperextension is required so that the normal "screw-home" mechanism that allows the knee to be

TABLE 38-1 Incidence of Knee Motion Problems After Knee Operations: Our Clinical Studies

Study	Operation	Patients (*n*)	Type of Ligament Graft, Concomitant Procedures	Motion Problems Requiring Therapeutic Intervention (%)
JBJSA, 1990[115]	ACL reconstruction	40	Allograft, acute	17
JBJSA, 1991[113]	ACL reconstruction	64	Allograft only, chronic	8
		40	Allograft + EA, chronic	18
JBJSA, 1992[114]	ACL reconstruction	66	Allograft only, chronic	8
		49	Allograft + LAD, chronic	2
CORR, 1992[126]	ACL reconstruction	90	Allograft only	4
		52	Allograft + EA	10
		52	Allograft + meniscus repair	12
		13	Allograft + MCL repair	23
AJSM, 1995[117]	ACL reconstruction	34	Allograft + MCL repair	26
		12	Allograft + MCL conservative treatment	17
AJSM, 1997[118]	ACL reconstruction	30	PT autograft, acute	10
		57	PT autograft, chronic	2
AJSM, 1997[12]	ACL reconstruction	47	PT autograft, men	4
		47	PT autograft, women	6
AJSM, 1997[119]	Multiple ligament reconstruction for knee dislocation	11	Allograft + autograft; all ACL + PCL	45
		6	Also + MCL	
		6	Also + PL	
KSSTA, 2000[125]	ACL reconstruction	219	PT autograft only	6
		37	PT autograft + PL procedure	5
		194	PT autograft + meniscus repair	8
		17	PT autograft + patellar realignment	18
		9	PT autograft + MCL repair	22
AJSM, 2000[123]	HTO, closing wedge	38	PT allograft or PT autograft	0
		3	HTO + ACL	0
JBJSA, 2004[124]	Meniscus transplantation	18	Transplant only	0
		16	Transplant + OAT	12
		4	Transplant + knee ligament procedure	50
JBJSA, 2005[116]	PCL reconstruction	11	Isolated	18
		8	PCL + other knee ligament	25
AJSM, 2006[127]	HTO, opening wedge	49	HTO only	0
		4	HTO + ACL	0
		2	HTO + OAT	0
AJSM, 2007[122]	PL anatomic reconstruction	2	PL only	0
		12	PL + knee ligament procedure	17

ACL, Anterior cruciate ligament; *EA*, iliotibial band extraarticular procedure; *HTO*, high tibial osteotomy; *LAD*, ligament augmentation device; *MCL*, medial collateral ligament; *OAT*, osteochondral autograft transfer; *PCL*, posterior cruciate ligament; *PL*, posterolateral; *PT*, patellar tendon.

stabilized in extension during the stance phase may occur, with the quadriceps muscle relaxed. Soucie and colleagues[172] provided the following ranges of knee motion, according to gender and age from a sample of 674 healthy subjects: (1) ages 9 to 19 years: 2.4 to 142.3 degrees for girls and 1.8 to 142.2 degrees for boys, (2) ages 20 to 44 years: 1.6 to 141.9 degrees for women and 1.0 to 137.7 degrees for men, and (3) ages 45 to 69 years: 1.2 to 137.8 degrees for women and 0.5 to 132.9 degrees for men.

It is generally assumed that at least 125 degrees of knee flexion is required for activities of daily living.[42,93] Rowe and coworkers[146] measured knee kinematics during functional activities in a group of 20 subjects aged 49 to 80 years and reported that 90 degrees of flexion is required for gait and slopes, 90 to 120 degrees for stairs and sitting, and 135 degrees for bathing. Patients not involved in athletics tolerate small flexion deficits. Significant flexion deficits of less than 90 degrees cause problems with squatting, stair climbing, and sitting. Athletes have a poorer tolerance for even minor losses of flexion, which affect running and jumping. Cosgarea and associates[34] reported that deficits of 10 degrees or more of flexion were associated with decreased running speed.

All patients, regardless of their activity level, have greater problems with loss of knee extension. A loss of just 5 degrees of extension may produce a flexed-knee gait, fatigue the quadriceps muscles, and cause patellofemoral pain.[78,81,108,111,149] Limitation of more than 20 degrees may cause a functional limb-length discrepancy.[34] Many years ago, Perry and colleagues[141] demonstrated the effect of a loss of extension on joint contact pressures, quadriceps muscle activity, and fatigue. These investigators measured the extensor forces required to stabilize the flexed knee during simulated weight bearing in cadaver specimens. The quadriceps force required to stabilize the knee was 75% of the load on the head of the femur at 15 degrees of flexion, which increased to 210% at 30 degrees of flexion and to 410% at 60 degrees of flexion. The quadriceps force was equal to 20% of average maximum quadriceps strength at 15 degrees of flexion but increased to 50% at 30

degrees of flexion. Surface pressure in the tibiofemoral and patellofemoral joints also increased with greater amounts of knee flexion.

It has become evident that the prevention of knee arthrofibrosis is paramount and preferred over using the currently available treatment options for this complication. This chapter discusses the risk factors and preventive measures for loss of knee motion after knee injury and surgery. In addition, conservative medical and therapeutic treatment intervention strategies are discussed that are usually successful in resolving a transient limitation of knee motion if initiated early postoperatively. Surgical procedures for severe cases of restriction of knee motion are presented. Our clinical studies involving 650 ACL-reconstructed knees are included to provide support for treatment recommendations.

TERMINOLOGY AND CLASSIFICATION SYSTEMS

A variety of terms have been used to describe, define, or classify a limitation of knee flexion and extension, including arthrofibrosis, flexion contracture, ankylosis, infrapatellar contracture syndrome, and motion loss. Some of the terms indicate a specific process, but others simply imply a limitation of motion compared with the contralateral normal knee. *Ankylosis* is one such generic term that indicates stiffness of joints that occurs for any reason and may represent loss of knee flexion, extension, or both. The term *motion loss* is another general phrase used to describe deviations from the amount of flexion and extension compared with the contralateral normal knee. Conversely, *arthrofibrosis* describes a specific cause for a limitation of knee motion, which is the formation of diffuse scar tissue or fibrous adhesions within a joint.[78,137,142] *Flexion contracture* indicates a loss of extension attributable to any cause and is accompanied by a relative shortening of the posterior soft tissues (in either the capsule or muscles). Petsche and Hutchinson[142] state that *arthrofibrosis* and *flexion contracture* are general terms, and it is necessary to indicate a specific cause for loss of motion.

Classification systems have been proposed by various authors to describe limitations in knee motion, based either on the anatomic location of scar tissue and adhesions or on the amount of knee motion in the affected joint (Table 38-2).[18,44,137,163,174] Sprague and coworkers[174] first introduced a system based on the arthroscopically observed location of scar tissues and adhesions in 24 patients who had a severe limitation of knee motion. Paulos and associates[137] described three stages of knee motion restrictions caused by infrapatellar contracture syndrome. Del Pizzo and colleagues[44] and Shelbourne and coworkers[163] developed classification systems based on the deviation of knee motion compared with the opposite knee. Blauth and Jaeger[18] described a system based on the total arc of motion in the affected knee.

CRITICAL POINTS Terminology and Classification Systems

- Terms used to describe limitation knee motion: *arthrofibrosis, flexion contracture, ankylosis, infrapatellar contracture syndrome, motion loss.*
- The term *arthrofibrosis* describes a specific cause for a limitation of knee motion, which is the formation of diffuse scar tissue or fibrous adhesions within a joint.
- Classification systems describe limitations in knee motion, based either on the anatomic location of scar tissue and adhesions, or on the amount of knee motion in the affected joint.
- Our classification system is based on the anatomic sites where scar tissue, adhesions, and adaptive shortening of soft tissues occur.

We have developed a classification system based on the anatomic sites at which scar tissue, adhesions, and adaptive shortening of soft tissues occur (Fig. 38-2 and Table 38-3). This system is advantageous because it highlights the areas that must be addressed surgically, as is discussed.

RISK FACTORS AFTER KNEE LIGAMENT RECONSTRUCTION

A variety of factors appear to influence the requirement for treatment intervention for knee motion limitations (Table 38-4) and the final amount of knee flexion and extension gained after ligament reconstruction. These factors are related to the severity of the injury, the timing of surgery, preoperative treatment, technical aspects of the ligament reconstruction, and the postoperative course and rehabilitation.

TABLE 38-2 Classification Systems of Arthrofibrosis

Study	Classification System
Sprague et al[174] (1982)	I: Discreet bands or a single sheet of adhesions traversing the suprapatellar pouch II: Near-complete obliteration of suprapatellar pouch and peripatellar gutters with masses of adhesions III: Multiple bands of adhesions or complete obliteration of suprapatellar pouch with extracapsular involvement
Del Pizzo et al[44] (1985)	Based on deviation from full extension and amount of flexion present: Mild: <5 extension, >110 flexion Moderate: 5-10 extension, 90-100 flexion Severe: >10 extension, <90 flexion
Paulos et al[137] (1987)	Three stages of infrapatellar contracture syndrome: I: Prodromal stage (2-8 wk postoperative) hardened synovium, fat pad, retinaculum marked by painful motion, restricted patellar mobility, quadriceps muscle lag II: Active stage (6-20 wk postoperative) peripatellar swelling, severely restricted patellar motion, hardening anterior tissues, step-off between patellar tendon and tibial tuberosity III: Residual stage (>8 mo postoperative) fat pad atrophy, patellofemoral crepitus and arthrosis, patella infera, quadriceps atrophy
Blauth & Jaeger[18] (1990)	Based on total arc of motion: I (mild): >120 II (moderate): 80-120 III (severe): 40-80 IV (extreme): <40
Shelbourne et al[163] (1996)	Based on deviation from full flexion and extension of opposite, normal knee: I: <10 extension, normal flexion II: >10 extension, normal flexion III: >10 extension, >25 loss of flexion IV: >10 extension, >30 loss of flexion, patella infera

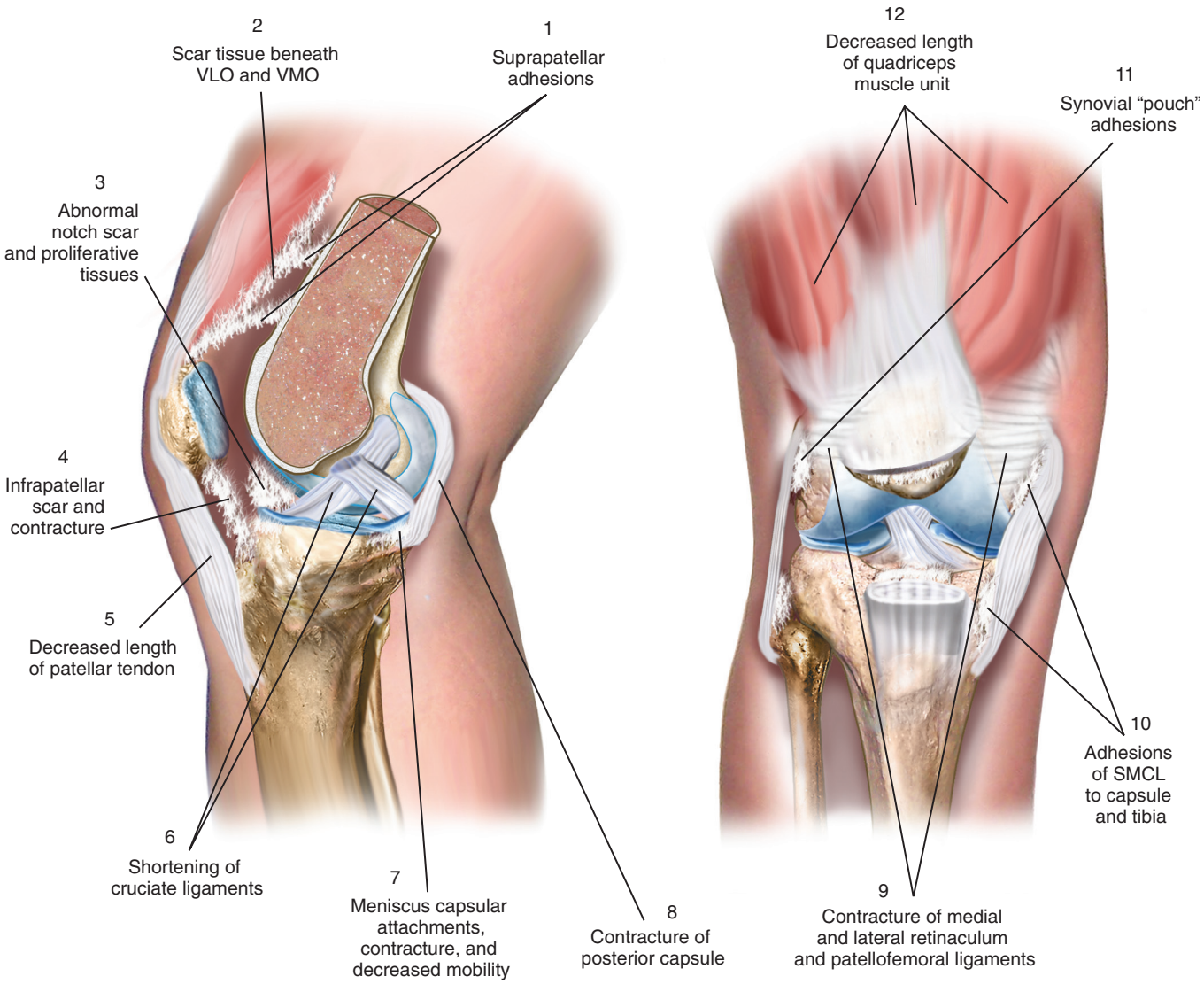


FIG 38-2 Multiple areas of soft tissue contracture, adhesions, and scar tissue formation with knee arthrofibrosis. *SMCL*, Superficial medial collateral ligament; *VLO*, vastus lateralis oblique; *VMO*, vastus medialis obliquus.

Although it remains uncertain why some knees are more likely to form an abnormal scar response to trauma and surgery than others, knowledge of these factors may help reduce this problem.

Severity of the Injury

Patients who sustain knee dislocations are at increased risk for developing motion complications (Fig. 38-3).[33,46,105,119,158,167] These injuries frequently occur from high-energy accidents that produce extreme soft tissue swelling and edema, hematomas, muscle damage, and other multiple trauma that must be resolved before consideration of knee soft tissue reconstructions. Early operative intervention when possible is advised for multiple ligament injuries that involve the lateral and posterolateral structures where acute repair and augmentation procedures are performed (see Chapter 17). For all other dislocations, surgery is delayed with the limb immobilized in a posterior plaster splint or bivalved cast with a posterior pad to prevent posterior tibial subluxation. Even in these severe knee injuries, it is possible to start immediate range of motion and prevent scar tissue formation that may compromise the outcome of a subsequent ligament reconstruction. Too often, these serious knee joint injuries are not treated with an early motion and function program. When surgical treatment is elected, the reconstructive and repair procedures of torn ligaments, capsular structures, and menisci are performed in a manner that allows immediate knee motion to be instituted postoperatively.[119]

Preoperative Issues

Performing anterior cruciate ligament (ACL) and other knee ligament reconstruction within a few weeks of the injury or before the resolution of swelling, pain, quadriceps muscle atrophy, abnormal gait mechanics, and motion limitations has been noted by many authors to correlate with postoperative knee motion problems.[35,100,108,160,161,165,178,189] Shelbourne and associates[165] noted an increased rate of arthrofibrosis in patients who underwent acute ACL reconstruction (within 1 week of the injury) compared with those in whom the reconstruction was delayed for at least 21 days. Similar findings were reported by Wasilewski and colleagues,[189] who noted that arthrofibrosis was found in 22% of

TABLE 38-3 Our Anatomic Classification System of Arthrofibrosis

Loss of Flexion

Quadriceps Muscle

- Shortens because of scar tissue and intramuscular changes, limiting normal muscle lengthening

Suprapatellar Pouch

- Scar tissue may form underneath quadriceps VMO, VLO, limiting muscle extensibility.
- Scar tissue from the superior pole of the patella produces patellar clunk, may extend as a band just above the femoral trochlea.
- Scar tissue and adhesions obliterate the suprapatellar pouch. Medial and lateral capsular pouches.

Medial and Lateral Capsular Pouches

- Scar down and become adhesive to the medial and lateral side of the femur

Patellar Retinaculum and Associated Ligaments

- Scar tissue forms with thickening, shortening, limiting patellar mobility

Patellar Tendon

- Tendon shortens or may adhere to the tibia.
- Infrapatellar scar tissue inferior pole to tibia just anterior to fat pad.

Medial and Lateral Extraarticular Ligament Structures

- Scar tissue, adhesions, adaptive shortening.

Loss of Extension

Posterior Capsule

- Scar tissue, adhesions, shortening of structures

Femoral Notch

- In-growth scar tissue, cyclops lesion

Hamstrings Muscle

- Shortening of musculotendinous unit

Cruciate Ligaments

- ACL, PCL adaptive shortening

ACL, Anterior cruciate ligament; *PCL*, posterior cruciate ligament; *VLO*, vastus lateralis oblique; *VMO*, vastus medialis obliquus.

TABLE 38-4 Risk Factors for the Development of Knee Arthrofibrosis

Magnitude of the injury: dislocation, multiple ligament injury
Normal or nearly normal knee motion not restored before surgery
Acute ligament reconstruction in swollen, painful knee
Technical errors in ACL graft placement, fixation, tensioning
Concurrent MCL repair or reconstruction
Infection
Immobilization
Chronic joint effusion
Quadriceps atrophy, shutdown
Poor rehabilitation, noncompliant patient
Cyclops lesion
Complex regional pain syndrome, reflex sympathetic dystrophy

ACL, Anterior cruciate ligament; *MCL*, medial collateral ligament.



FIG 38-3 Acute knee dislocation leads to severe disruption of soft tissues, swelling, hemorrhage, and muscle damage always resulting in motion problems and risk of arthrofibrosis.

CRITICAL POINTS Risk Factors after Knee Ligament Reconstruction

- Severity of injury: knee dislocations increase risk for developing motion complications. Surgery is delayed in all cases except those with ruptures to the posterolateral structures.
- Preoperative issues: performing knee ligament reconstruction within a few weeks of the injury or before the resolution of swelling, pain, quadriceps muscle atrophy, abnormal gait mechanics, and motion limitations correlates with postoperative knee motion problems.
- Technical factors at surgery: improper ACL graft placement, overtensioning graft at surgery, performing concurrent MCL repair with ACL reconstruction.
- Postoperative course and rehabilitation: immobilization is detrimental to all of the knee joint structures and may result in a permanent limitation of knee motion, prolonged muscle atrophy, patella infera, and articular cartilage deterioration. Begin knee motion, patellar mobilization, muscle-strengthening exercises the day after surgery. Treat joint effusion immediately.
- Postoperative infection, complex regional pain syndromes, and reflex sympathetic dystrophy may cause knee motion problems.

acutely reconstructed knees versus 12.5% of knees reconstructed with chronic ACL deficiency. Mohtadi and coworkers[108] found that ACL reconstructions performed less than 6 weeks postinjury had a higher rate of knee stiffness than those done more than 6 weeks post-injury (11% and 4%, respectively).

Mauro and associates[100] followed 229 patients who underwent ACL reconstruction to determine the incidence of loss of knee extension at 4 weeks after surgery. Fifty-eight patients (25%) had not regained full extension equal to the contralateral knee. When compared with the group of patients who had regained full extension, the group that had

a limitation were noted to have had a shorter mean time from injury to surgery (60 days and 93 days, respectively; $P < .05$), a greater preoperative loss of extension (4 and 1 degrees, respectively; $P < .05$), and a greater percentage that underwent autograft reconstruction than allograft reconstruction (28.5% and 14%, respectively; $P < .05$).

Although Bach and colleagues[8] did not observe a significant difference in knee motion complications between acute and chronic ACL-reconstructed knees, these authors stressed the need to delay surgery until patients achieved 120 degrees of knee motion and swelling had resolved. The authors found "no advantage to performing urgent acute ACL reconstruction."[8] Sterett and coworkers[177] found no association between surgical timing and postoperative motion problems. However, in their series, all patients had achieved at least 0 to 120 degrees, had good quadriceps control, and could perform a straight-leg raise without an extensor lag before undergoing surgery. Eight percent of the patients in this investigation's acute subgroup required arthroscopic debridement of scar tissue. Meighan and associates[103] also found no advantage in performing early ACL reconstruction and noted an increased rate of complications in patients who underwent surgery within 2 weeks of the injury compared with those who had surgery between 8 and 12 weeks postinjury. The delayed group had a faster return of knee motion and quadriceps strength.

Other authors have not found a higher rate of postoperative motion problems after acute ACL reconstruction.[4,25,86,171] However, it appears that delaying surgery until knee motion is regained, swelling is resolved, and a good quadriceps contraction is demonstrated is advantageous for decreasing the risk of postoperative arthrofibrosis. The inflammatory response to the initial injury varies among patients. Although some have little effusion and swelling, others have an exaggerated inflammatory response characterized by pain, soft tissue edema, and redness and increased warmth to tissues surrounding the knee. These knees are placed into an initial conservative treatment program to resolve these problems first and are also carefully monitored after ACL reconstruction for a similar exaggerated inflammatory reaction postoperatively. Knees with isolated ACL ruptures that have little swelling and demonstrate normal motion early after injury may be considered for earlier reconstruction. In addition, knees with multiple ligament ruptures that include the posterolateral structures are also candidates for early surgical repair, as discussed in Chapter 17.

Technical Factors at Surgery

Improper ACL graft placement has been frequently noted to cause loss of knee motion.[14,54,76,78,81,91,97,107,145,162,166,193] On the tibia, grafts placed anterior to the native ACL insertion result in impingement on the roof of the intercondylar notch when the knee is extended.[74,75,99] Yaru and colleagues[193] recommended that, with passive extension, there should be a 3-mm clearance between the anterior portion of the intercondylar notch and the graft to prevent impingement. Grafts placed lateral to the insertion site impinge on the lateral wall of the notch. In addition, Romano and coworkers[145] found that ACL grafts placed too far anteriorly in the tibial tunnel can cause knee extension deficits, and grafts placed too far medially in the tibial tunnel can cause knee flexion deficits. On the femur, an excessive anterior graft placement causes deleterious forces on the graft, leading to limitations in flexion and potential graft failure (Fig. 38-4).

Overtensioning ACL grafts may lead to abnormal knee kinematics.[106,142] In addition, the degree of knee extension during graft tensioning and fixation may affect postoperative motion.[7,30,59,104,111] Austin and associates[7] noted in a cadaver study that the amount of graft tension (44 N or 89 N) did not effect knee extension; however, tensioning the graft in knee flexion was associated with extension deficits. The authors reported that grafts tensioned and fixed at 30 degrees of flexion had more than a 12 degree increase in knee flexion after ACL reconstruction compared with those tensioned and fixed at 0 degrees of flexion. From a two-part biomechanic and clinical study, Nabors and colleagues[111] suggested that grafts tensioned in full extension result in a low incidence of knee motion loss. In their series of 57 patients who underwent patellar tendon autograft ACL reconstruction, only one patient had a mild (5 degrees) loss of extension.



FIG 38-4 Lateral radiographs show excessive anterior placement of the femoral tunnel limiting knee flexion and the anterior tibial tunnel limiting knee extension. The graft failed as motion was regained postoperatively.

Concurrent medial collateral ligament (MCL) repair with ACL reconstruction has been associated with an increased risk of knee arthrofibrosis.[65,117,159] Harner and associates[65] postulated that concurrent MCL primary repair may cause a limitation of knee motion attributable to the disruption of the medial capsule because the procedure does not restore the normal tissue planes, resulting in scar formation and a heightened pain response. Our studies[117] and the studies of Shelbourne and coworkers[159,164] led to the recommendation many years ago to treat the majority of combined ACL/MCL ruptures conservatively. This allows healing of the medial-side injury followed by ACL reconstruction in appropriately indicated patients (see Chapter 19). There are exceptions to this rule, and any surgical procedure on the medial side of the knee joint should be carefully observed postoperatively for a limitation of motion or, in acute knee injuries, the development of heterotopic soft tissue ossification requiring treatment.[157,186]

Postoperative Course and Rehabilitation

There is consensus in the literature that immobilization is detrimental to all of the knee joint structures and may result in a permanent limitation of knee motion, prolonged muscle atrophy, patella infera, and articular cartilage deterioration.[35,128-130,138,151] Early knee joint motion decreases pain and postoperative joint effusions, aids in the prevention of scar tissue formation and capsular contractions that can limit

normal knee flexion and extension, decreases muscle disuse effects, maintains articular cartilage nutrition, and benefits the healing ACL graft.[3,35,36,43,49,62,71,133,140,152,170] Modern rehabilitation programs incorporate immediate knee motion and muscle-strengthening exercises the day after surgery, both of which have been shown to be safe and not deleterious to healing grafts (see Chapters 10, 11, and 12). Importantly, the immediate motion program must include patellar mobilization (inferior, superior, medial, and lateral directions) to avoid an infrapatellar contracture.

Patient compliance with postoperative rehabilitation is essential in recovering full knee motion. In our experience, the small percentage of patients who have permanent restrictions in extension or flexion have often been unwilling to perform the required motion, strengthening, and patellar mobilization exercises postoperatively. In addition, in instances in which an early postoperative limitation of motion has been recognized, these patients are also unwilling to undergo treatment recommendations such as overpressure exercises, extension casts, and other modalities that are usually effective in resolving these problems.[125,126] Thus in a majority of cases, the inflammatory and fibrotic response that follows surgery and initially limits knee motion is treatable if no delay occurs in instituting a gentle motion and overpressure program along with appropriate antiinflammatory medications. There is a distinct group of patients, in the range of 1% to 2%, who demonstrate a pathologic exaggerated fibrous tissue proliferative response most likely from a genetic basis, in which the treatment is prolonged and may not be successful. This unique group of patients is discussed in a later section of this chapter.

Significant lower extremity muscle atrophy represents an unresolved problem after ACL reconstruction because the magnitude of quadriceps atrophy and strength loss may exceed 20% to 30% in the first few months postoperatively.[40,67,77,83,136,155,179] Prolonged quadriceps atrophy may affect the ability to regain normal knee motion and maintain knee extension. Chronic swelling may also cause a limitation of knee motion by inhibiting the function of the quadriceps muscle.[135,173,180,181] It is important that a knee joint effusion be treated to lessen its deleterious effect on quadriceps function.

Other Risk Factors

Infection may result in loss of knee motion after ACL reconstruction. The rule followed in our clinical practice is to always consider first that an exaggerated inflammatory response with joint swelling, synovitis, and early limitation of joint motion is caused by a joint infection until proved otherwise. Even when an infectious process appears to have been excluded, a knee joint that does not respond to the gentle modalities to regain knee motion or that has continued pain or lack of patellar mobility should undergo repeat aspiration, cell count, culture, and diagnostic studies. In our experience, the most severe cases of arthrofibrosis that initially were presumed to be caused by a genetic abnormality were subsequently proven to have an occult unrecognized infectious etiology. In patients with an established infectious process, the principles of treatment have been discussed (see Chapter 7), and it is important that gentle motion and overpressure programs continue to maintain the joint motion. Even in knees with swelling of soft tissues and the initial host response to an infection, it is possible within days after arthroscopic lavage, debridement, and appropriate antibiotics to initiate motion exercises and prevent a flexion contracture or patella infera. Although aggressive management of this complication usually leads to resolution of the infection, studies report permanent loss of extension and flexion in the majority of patients treated which may be avoidable.[102,156,183,191]

Recent reports by Csintalan and associates[38] and Nwachukwu and coworkers[131] identified female gender as a significant risk factor for the development of arthrofibrosis after ACL reconstruction. Csintalan and associates[38] studied a cohort of 14,522 primary ACL reconstructions and reported a hazard ratio (HR) for reoperations related to arthrofibrosis of 2.48 for women compared with men (P <.001). In addition, these authors reported any prior surgery was also a significant risk factor (HR, 3.02; P = .005). Nwachukwu and coworkers[131] studied 933 consecutive ACL reconstructions performed in patients aged 7 to 17 years and reported an overall arthrofibrosis rate of 8.3%. Statistically significant risk factors were female gender (P = .0001), patient aged 16 to 18 years (P = .007), patellar tendon autograft (P = .03), and concomitant meniscal repair (P = .007).

Complex regional pain syndromes and reflex sympathetic dystrophy may cause knee motion problems as a result of quadriceps atrophy, chronic swelling, and an increased sensitivity to pain.[61,132] These issues are discussed in detail in Chapter 40. Appropriate management using a variety of medical specialists is essential to diagnose and treat these problems.

PATHOPHYSIOLOGY AND EXPERIMENTAL PREVENTION STUDIES

In 1972, Enneking and Horowitz[48] published one of the first studies on the pathophysiology of a joint contracture after immobilization in humans. The investigators described in a series of case reports the presence of fibrofatty connective tissue in the infrapatellar fat pad, suprapatellar pouch, and posterior recesses of the knee joint with eventual obliteration of the joint cavity. Over time, this tissue was replaced with mature fibrous connective tissue.

Tissue homeostasis is maintained by the normal level of cell growth and proliferation along with the production and turnover of the extracellular matrix.[20,22] Polypeptides known as cytokines or growth factors are responsible for the constant signaling that occurs both between local cells (paracrine) and within cells (autocrine). Cytokines exist as

CRITICAL POINTS Pathophysiology and Experimental Prevention Studies

- Cytokines or growth factors responsible for constant signaling occurring both between local cells and within cells.
- TGF-β is a key cytokine that initiates and ends process of tissue repair. Its actions enhance the deposition of extracellular matrix and regulate the actions of other cytokines.
- Overexpression of TGF-β1 results in progressive accumulation of matrix in tissues and an elevated number of myofibroblasts, leading to fibrosis.
- Specific ASMA-expressing myofibroblasts generate tissue contraction, are responsible for collagen overproduction during fibrotic diseases. TGF-β is capable of upregulating ASMA and collagen in fibroblasts.
- ASMA is involved in scar formation and scar tissue contraction during the course of primary arthrofibrosis.
- Collagen type VI could play a contributory role in the deposition of extracellular matrix that leads to arthrofibrosis.
- Primary arthrofibrosis may be the result of an immune response.
- The effectiveness of various agents such as decorin, hyaluronic acid, chitosan, mitomycin C, and various IL-1 receptor antagonists (anakinra), as well as low-dose irradiation, in high-level human studies for early or later-stage arthrofibrosis has not been investigated to date.
- It is hopeful that chemical agents will become available to treat fibrotic response to injury by controlling elevated levels of myofibroblast up regulators and fibrogenic growth factors.

small proteins that signal cells in response to injury and infection. One cytokine, interleukin-1 (IL-1), has been found to stimulate platelets and macrophages to release a variety of growth factors, including transforming growth factor-β (TGF-β). TGF-β is thought to be one of the factors (among others[26,82,153]) mediating Dupuytren's contracture.[2] Cytokines regulate all aspects of tissue remodeling and may act positively or negatively on tissue damage. This variability results in a wide range of potential responses to injury among patients.

TGF-β, released by platelets, tendon fibroblasts,[168,169] and the joint capsule,[63,64] has been identified as a key cytokine that both initiates and ends the process of tissue repair. Although other growth factors are involved in tissue remodeling, TGF-β is unique in its actions that enhance the deposition of extracellular matrix and regulate the actions of other cytokines.[144,169] An overexpression of TGF-β_1 results in progressive accumulation of matrix in tissues and an elevated number of myofibroblasts, leading to fibrosis.[20,22,63,64,72,73,84,109,190] Border and Noble[20] believe that repeated injury or trauma may also cause autoinduction of TGF-β beyond normal levels, creating a "chronic, vicious circle of TGF-β overproduction" resulting in tissue fibrosis that may also occur in organ systems such as the kidney, liver, and lung. Investigators have documented that elevated levels of myofibroblasts and TGF-β occur rapidly, within 2 weeks following injury in experimental models, and that these changes are similar to those observed in humans with chronic elbow joint contractures.[63,72,73]

Zeichen and coworkers[194] compared tissue samples of 13 patients with arthrofibrosis obtained a mean of 16 months after the inciting knee ligament surgery with those of 8 patients undergoing primary ACL surgery. Histologic examination from the patients with arthrofibrosis showed marked synovial hyperplasia, infiltration of inflammatory cells, and vascular proliferation with an increased level of collagen types VI and III. None of the control subjects demonstrated these findings. These authors noted that this confirmed the observations of Murakami and associates[110] regarding the association between an inflammatory process and proliferation of fibroblasts. The suggestion was made that collagen type VI could play a contributory role in the deposition of extracellular matrix that leads to arthrofibrosis.

There is evidence that during the exaggerated fibrotic response that occurs in knee arthrofibrosis, a certain amount of tissue contraction or shrinkage occurs.[23,137,162] Specific α-smooth muscle actin (ASMA)-expressing myofibroblasts generate tissue contraction during wound healing and are responsible for collagen overproduction during fibrotic diseases.[39,45,50,58] TGF-β is capable of up regulating ASMA and collagen in fibroblasts.

Unterhauser and associates[182] measured the amount of ASMA-containing fibroblastic cells in arthrofibrotic tissue to determine whether the number of these cells was increased over that found in normal tissue. Tissue biopsies were obtained from 9 patients who underwent surgery for arthrofibrosis that had developed after ACL reconstruction. The patients all had primary arthrofibrosis and underwent the debridement procedure between 4 and 12 months after the ACL reconstruction. Tissue samples were also taken from 5 patients who underwent ACL reconstruction for chronic ligament deficiency and from 8 patients who had follow-up arthroscopy after ACL reconstruction for meniscus pathology; all 13 of these control patients showed no signs of arthrofibrosis. Significantly higher expressions of ASMA-positive fibroblastic cells were found in the collagen bundles and remaining fatty tissue in the study group compared with both control groups (23.4% of the total cell count vs 2.3% and 10.8%, respectively; $P < .001$). These authors concluded that this cell type is involved in scar formation and scar tissue contraction during the course of primary arthrofibrosis. They speculated that the expression of ASMA is most likely variable according to the time from the onset of the disease to tissue biopsy and probably decreases as the disease progresses.

Unterhauser and associates[182] also reported that the fatty tissues in the arthrofibrotic knees were replaced by a dense collageneous network with parallel fiber orientation. A significantly higher total cell count and lower vessel density were measured in the arthrofibrotic knees compared with the control group that underwent ACL reconstruction. Similar findings were noted by Mariani and colleagues[96] who biopsied 17 knees with arthrofibrosis that occurred after a variety of surgical procedures. The tissue samples were obtained less than 6 months from the onset of stiffness in 9 patients, from 6 to 12 months in 5 patients, and more than 12 months in 4 patients. The histological evaluations demonstrated collagen-producing fibroblastic tissue with differing amounts of cellularity and vascularization. This study supports the hypothesis that arthrofibrotic tissue undergoes progressive remodeling and acquires the characteristics of mature collagen, all within the first 6 months after the onset of joint stiffness. There was no association between the amount of knee motion and time from surgery or the degree of tissue maturation. The severity of loss of motion was associated only with the location and amount of adhesive tissue in the knee joint.

Many investigations have suggested that antifibrotic agents may be of potential use in preventing or combating arthrofibrosis because they inhibit the TGF-β signaling pathway.[1,13,28,56,57,85,89,182,195] However, the effectiveness of various agents such as decorin, hyaluronic acid, chitosan, mitomycin C, and various IL-1 receptor antagonists in high-level human studies for early or later-stage arthrofibrosis has not been investigated to date.

The use of powerful antiinflammatory medications, typically used for rheumatoid arthritis, may be useful in the future in patients who do not respond to high doses of oral corticosteroids. Magnussen and coworkers[94] reported a series of four patients who were treated with an intraarticular injection of Kineret (anakinra), an IL-1 receptor antagonist, to treat persistent postoperative inflammation and scarring after ACL reconstruction. The injections were performed on postoperative days 36, 38, 41, and 97. The patients regained normal or nearly normal knee motion; three did not undergo other procedures but one did require debridement of scar tissue from the anterior compartment. Brown and associates[27] also used intraarticular anakinra injections in eight patients, four of whom had chronic refractory arthrofibrosis and four of whom had "limited" arthrofibrosis with varying results. There was no control group or validated rating system used, and range of motion and joint effusion were based on "clinician estimate." With so few data published to date, no recommendation can be made regarding the use of Kineret for knee arthrofibrosis at present.

Decorin is a human proteoglycan that has been shown in many experimental models to inactivate the effects of TGF-β and have a beneficial effect in arthrofibrotic tissues. Several years ago, Fukushima and coworkers[57] reported that injection of decorin improved both the muscle structure and function of lacerated muscle to near-complete recovery in mice. More recently, Zhang and associates[195] found that decorin reduced the effect of TGF-β in regard to intrinsic cell expansion in cultured synovial fluid explants from osteoarthritic knees. Abdel and colleagues[1] assessed the effects of four intraarticular injections of decorin that were performed 8 weeks after an operation that was done to induce a knee joint contracture in rabbits. There was no significant effect on improving the flexion contractures. However, genetic analysis showed a significant alteration in several fibrotic genes that were likely associated in the arthrofibrosis process. These authors suggested that earlier injection might produce better results in terms of preventing joint contractures. Several other experimental models have demonstrated the effectiveness of decorin in inhibiting adhesion

formation in intraarticular adhesions,[55] skeletal muscle injury,[87,196] kidneys,[21,79] and lungs.[60] There are no current human trials on the use of decorin for the prevention or treatment of knee arthrofibrosis.

Emami and coworkers[47] investigated the effects of bevacizumab (Avastin), an agent that inhibits vascular endothelial growth factor, on preventing arthrofibrosis after surgery in a rabbit model. Given in either one or two injections, these authors reported reduced joint fibrosis, with better clinical and histological findings in the two-injection group. This was especially evident in the statistically significant reduced number of fibroblasts ($P = .002$), inflammatory cells ($P = .01$), vascularity ($P < .05$), and collagenous matrix deposition ($P < .05$).

Liang and colleagues[89] applied topical hydroxycamptothecin, a chemotherapeutic drug, to rabbit knees in an attempt to prevent intraarticular adhesions after surgery in which cortical bone was removed from the femoral condyles. After 4 weeks, there was a significant reduction of adhesions in knees that received 1.0 mg/mL or 2.0 mg/mL compared with lower doses and controls ($P<.05$). Another well-known chemotherapeutic agent, mitomycin C, was investigated by Yan and coworkers[192] in the rabbit model. The agent was applied following removal of cortical bone from the femoral condyle and the effects evaluated 4 weeks later. There was a dose-dependent significant effect on suppression of the formation of adhesions, with 0.1 mg/mL required to reduce the adhesion score, the hydroxyproline content, and the fibroblast number compared with controls.

Wang and associates[188] studied the effects of weekly intraarticular injections of 0.3 mL hyaluronic acid in immobilized rabbit knees performed for 8 weeks. Compared with the control group, the experimental group had significantly greater range of motion ($P = .002$), a lower mean adhesion score ($P = .01$), and lower mean collagen content ($P = .001$).

In a small animal model, Bedair and associates[13] showed that an angiotensin II systemic receptor blocker decreased fibrosis and enhanced muscle regeneration in acutely injured skeletal muscle and hypothesized that the blocker modulated TGF-β_1. Hagiwara and colleagues[64] reported that the joint capsule has the potential to produce TGF-β_1 and connective tissue growth factor, both of which play a role in causing fibrosis.

Two small case series used a single dose of low-level irradiation (700 to 800 rads) before repeat revision TKA in patients with long-standing arthrofibrosis.[9,51] The idea was derived from the established use of low-dose irradiation for the prevention of heterotopic ossification before total hip arthroplasty in high-risk patients,[10,139,185] and the potential effects of irradiation in preventing the differentiation of mesenchymal stem cells into osteoblastic precursors.[11] Farid and associates[51] employed this treatment method in 14 patients with severe idiopathic arthrofibrosis in an effort to suppress fibroblastic and fibroosseous proliferation postoperatively. Major improvements in knee motion and function were experienced in all but one patient, and there were no complications related to the irradiation therapy. Baier and colleagues[9] described three patients who had similar treatment and marked improvements in knee flexion. However, these authors cautioned that the influence of radioactivity on soft tissues has not been investigated, and bony nonunion may occur. Both series were retrospective, and no control group or randomization procedures were performed.

Bosch and colleagues[24] advanced the hypothesis that primary arthrofibrosis is the result of an immune response. Tissue samples obtained from 18 patients between 4 and 48 months from the triggering event to surgical debridement demonstrated synovial hyperplasia with fibrotic enlargement of the subintima and infiltration of inflammatory cells. These authors believed their findings supported an immune response as the cause of capsulitis leading to formation of diffuse scar tissue. The clinical implication was to avoid further surgery or aggressive manipulation while patients have acute capsulitis and to wait 3 to 6 months for the inflammatory response to resolve before debridement is considered. As is discussed, too often, there is a delay in treatment that results in a permanent limitation of knee motion. Unfortunately, even though a delay in treatment may allow tissues to "quiet down," the resulting fibrotic tissue that forms becomes well organized and dense and treatment is thus more difficult. It is anticipated that in the future, chemical agents will become available to treat fibrotic response to injury by controlling elevated levels of myofibroblast upregulators and fibrogenic growth factors.[1,13,32,47,53,57,63,72,73,88,112,195]

PREVENTION

Preoperative

Following an acute ACL tear and before reconstruction, the surgeon-therapist team must manage pain, effusion, quadriceps weakness, knee motion limitations, and gait abnormalities. Knee joint effusion and hemarthrosis are treated with appropriate nonsteroidal antiinflammatory medications (NSAIDs), cryotherapy, compression, and limb elevation. Patients are taught safe and effective muscle strengthening exercises (such as straight-leg raises, bicycling, minisquats, wall sits, calf raises, and knee extensions from 90 to 30 degrees) and must demonstrate good quadriceps control without an extensor lag before consideration is made for surgery. Regaining normal or nearly normal knee motion is essential and may take several weeks after an ACL rupture. The exceptions are knees with a mechanical block to motion, such as a displaced meniscus tear, in which early surgical intervention is warranted to preserve and repair the meniscus. A decision regarding future ACL reconstruction is based on the patient's activity goals and other factors (see Chapter 7). Other exceptions are knees with concomitant posterolateral ligament ruptures who are candidates for surgical intervention within 7 to 10 days of the injury (see Chapter 17). Knees with concomitant MCL tears are treated conservatively for at

CRITICAL POINTS Prevention

Preoperative

- After ACL injury, surgeon-therapist team manages pain, effusion, quadriceps weakness, knee motion limitations, gait abnormalities, other knee ligament injuries before ACL reconstruction.

Intraoperative

- Principles of correct graft placement, tensioning, and fixation are paramount to avoid a limitation of knee motion postoperatively.
- ACL graft placed within the femoral and tibial footprint, occupying the central two thirds or more, Limited notchplasty usually required.
- Femoral tunnel: anteromedial portal or a two-incision procedure favored.
- ACL graft conditioning: approximately 44-N tension placed on the distal graft sutures, knee flexed from 0 to 120 degrees for 30 flexion-extension cycles. Arthroscope verifies ideal graft position, no impingement against the lateral femoral condyle or notch with full hyperextension.

Postoperative

- First weeks: control knee joint pain and swelling, regain adequate quadriceps muscle contraction, initiate immediate knee motion exercises, and maintain adequate limb elevation.
- Goal: achieve 0 to 90 degrees of knee motion by the seventh postoperative day. Begin overpressure program immediately if goal not obtained.

least 4 to 8 weeks to allow the medial-side structures to heal and regain motion and muscle strength before proceeding to ACL reconstruction (see Chapter 19).

Intraoperative

The principles of correct graft placement, tensioning, and fixation are paramount to avoid a limitation of knee motion postoperatively (see Chapter 7). The ACL graft is placed within the femoral and tibial footprint, occupying the central two thirds or more of the footprint, to achieve an anatomic position that allows the graft to control the pivot shift and anterior tibial translation. To achieve an anatomic graft placement in the center of the tibial attachment frequently requires a limited notchplasty to avoid a limitation of knee extension. For the femoral tunnel, an anteromedial portal drilling technique or a two-incision procedure is favored to obtain a central anatomic femoral footprint placement. An endoscopic transtibial drilling technique is not recommended.[70,95] In nearly all chronic ACL-deficient knees, there is an overgrowth of cartilage and spur formation in the femoral notch, which necessitates a notchplasty to prevent ACL graft impingement.

The ACL graft is conditioned after femoral fixation by placing approximately 44-N tension on the distal graft sutures and flexing the knee from 0 to 120 degrees for 30 flexion-extension cycles. The arthroscope is used to verify that the graft position is ideal and there is no impingement against the lateral femoral condyle or notch with full hyperextension. The knee is placed at 20-degree flexion, and the tension on the graft is reduced to approximately 10 to 15 N to avoid overconstraining anteroposterior (AP) tibial translation. Alternatively, the graft can be tensioned to a higher load with knee extension. After graft fixation, a Lachman test is performed and anterior tibial translation of 2 to 3 mm should be elicited, indicating that the graft has not been over-tightened. If the graft has a "bow-string," tight appearance with no anterior tibial translation on testing, the distal tensioning and fixation procedure is repeated with less tension placed on the graft.

In knees that undergo concomitant meniscus repair, the sutures are tied with the knee at 30 degrees of flexion to prevent capsular shortening or increased pain with postoperative extension exercises. If an associated medial or lateral ligament reconstruction is required, care is taken to avoid overtensioning the tissues and grafts and to place a graft in the correct position on the femur (with the isometric point determined at surgery) to allow restoration of normal knee flexion (see Chapter 7). Posteromedial and posterolateral capsular plication procedures are performed in a manner that will not result in a limitation of knee extension, which is tested at the operative table.

Postoperative

The first week following ACL or other knee ligament reconstruction represents a critical time period for patients to control knee joint pain and swelling, regain adequate quadriceps muscle contraction, initiate immediate knee motion exercises, and maintain adequate limb elevation (see Chapter 11). A bulky compression dressing (cotton-Ace elastic bandage) is used for 48 hours followed by antiembolic compression stockings and a supplemental Ace bandage. Cryotherapy is begun in the recovery room after surgery. NSAIDs are used for 5 days along with pain medication to allow the immediate exercise protocol to be successfully implemented. Electrogalvanic stimulation or high-volt electrical muscle stimulation may be used along with ice, compression, and elevation to control swelling.[134]

Beginning on the first postoperative day, patients perform passive and active range of motion exercises in a seated position for 10 minutes a session, approximately four to six times per day. This is accompanied by patellar glides (mobilization), which are performed in all four planes (superior, inferior, medial, and lateral) with sustained pressure applied to the appropriate patellar border for at least 10 seconds (Fig. 38-5). The goal is to achieve 0 to 90 degrees of knee motion by the seventh postoperative day. Patients who are unable to achieve this amount of extension and flexion are immediately placed into an overpressure motion program, described in detail later in this chapter. In our experience, the exercises and modalities in the overpressure program resolve the majority of knee motion limitations when initiated early postoperatively. In 650 knees that underwent ACL reconstruction described elsewhere in this chapter, only 18 (3%) required a gentle manipulation under anesthesia, and 6 (<1%) underwent surgical debridement and lysis of adhesions after the overpressure program failed to resolve knee motion limitations.



FIG 38-5 Patellar mobilization is performed by the therapist during physical therapy visits and at home by the patient or family member several times daily.

Hamstring and gastrocnemius-soleus flexibility exercises are begun immediately, as are straight-leg raises in all four planes of hip movement. With a semitendinosus-gracilis tendon harvest, hamstring strengthening is delayed for 4 weeks. Partial weight bearing is permitted as long as pain and swelling are controlled and a voluntary quadriceps contraction demonstrated. Isometric quadriceps contractions are also begun the first postoperative day and are performed on an hourly basis following the repetition rules of 10-second holds, 10 repetitions, 10 times per day. The remainder of the rehabilitation program is detailed in Chapter 11.

DIAGNOSIS AND CLINICAL PRESENTATION

The early detection of a limitation of knee motion after ACL reconstruction is paramount for resolving the problem and preventing permanent arthrofibrosis. The establishment of specific knee flexion and extension goals according to the amount of time that has elapsed postoperatively and concurrent major operative procedures performed is required. In all knees, full passive knee extension must be obtained immediately to avoid excessive fibrous tissue proliferation in the intercondylar notch and posterior capsular contracture. In patients with physiologic bilateral knee hyperextension, we recommend the gradual return of 3 to 5 degrees of hyperextension in the reconstructed knee and not more than 5 degrees of hyperextension owing to potentially deleterious forces on the healing graft. Specific range of knee motion goals after ACL reconstruction (Table 38-5) are communicated to the patient before surgery and during postoperative assessments. Knee motion is carefully documented by the therapist in a closely supervised

TABLE 38-5 Our Goals for Restoration of Knee Motion After Anterior Cruciate Ligament Reconstruction

Operative Procedure Details	Weeks Postoperative	Range of Knee Motion Goal (Degrees)*
ACL B-PT-B autograft reconstruction, isolated or with meniscus repair, patient desires to return to strenuous athletics as soon as possible	1-2	0-110
	3-4	0-120
	5-6	0-135
ACL revision reconstruction (any graft source) or ACL primary reconstruction (with allograft or semitendinosus autograft) or complex reconstructions with concomitant operative procedures, or knees with noteworthy articular cartilage lesions	1-4	0-90
	5-6	0-120
	7-8	0-135
ACL reconstruction with posterior cruciate ligament reconstruction (see Chapter 16)	1-2	0-90
	3-4	0-110
	5-6	0-120
	7-8	0-135
ACL reconstruction with posterolateral procedure (see Chapter 17)	1-4	0-90
	5-6	0-110
	7-8	0-120
	9-12	0-135

*In patients with physiologic bilateral knee hyperextension, we recommend the gradual return of 3-5 degrees of hyperextension in the reconstructed knee. Greater than 5 degrees of hyperextension is not recommended owing to potentially deleterious forces placed on the healing graft.

ACL, Anterior cruciate ligament; *B-PT-B*, bone-patellar tendon-bone.

CRITICAL POINTS Diagnosis and Clinical Presentation

- Early detection limitation of knee motion after ACL reconstruction is paramount for resolving the problem.
- Full passive knee extension is obtained immediately to avoid excessive fibrous tissue proliferation in the intercondylar notch, posterior capsular contracture.
- Joint aspiration with cell analysis and culture for any indication of joint redness, warmth, limitation of knee motion.
- Initial phase primary arthrofibrosis (transient) occurs within first few weeks after surgery. Limitations in knee motion usually resolve with conservative measures with compliant patient.
- If not treated, condition becomes more established, requires operative management. Findings:
  - Shortening of the posteromedial and posterolateral capsule, ACL graft, quadriceps muscles
  - Significant ingrowth fibroproliferative tissue into intercondylar notch
- Comprehensive debridement and lysis of adhesions, inpatient epidural and physical therapy program, and weeks of outpatient therapy may be successful in achieving significant gains in knee motion.
- Final phase of arthrofibrosis (established) involves patellar infera and articular cartilage damage. Requires comprehensive evaluation, appropriate radiographs, bone scans, and MRI. Determine patellar vertical height, location grafts, and presence cyclops lesion.

postoperative rehabilitation program so that detection of a knee motion problem occurs in a timely manner. Failure to meet these goals prompts entering the patient in an overpressure program using appropriate medical and therapeutic measures to be described.

Joint aspiration with cell analysis and culture is important with any indication of joint redness, warmth, and limitation of knee motion. A serum sedimentation rate is usually not reliable after surgery because it is elevated for a number of weeks. After this time period, repeat studies for sedimentation rate, C-reactive protein, and other inflammatory mediates may be required. If surgery is required, multiple tissue specimens are sent for culture and microscopic evaluation. As already discussed, an occult infectious process is not excluded by a single negative joint aspirate, and repeat joint aspirations, culture, and blood studies are required.

The initial phase of primary arthrofibrosis occurs within the first few weeks after surgery. The condition at this time period is transient because limitations in knee flexion and extension are usually resolved with conservative measures as long as the patient complies with the recommended program. However, if knee motion deficits are left untreated for a few weeks, the condition becomes more established and eventually requires operative management. Findings include shortening of the posteromedial and posterolateral capsule blocking extension, significant ingrowth of fibroproliferative tissue into the intercondylar notch, shortening of the ACL graft preventing normal anterior tibial translation with extension, obliteration of the suprapatellar pouch, and shortening of the quadriceps muscles limiting flexion. A comprehensive debridement and lysis of adhesions, followed by an inpatient epidural and physical therapy program and many weeks of continued outpatient therapy, may still be successful in achieving significant gains in knee motion. The final phase of arthrofibrosis involves patellar infera and articular cartilage damage, which are exceedingly difficult to treat and the loss of knee motion is usually permanent.

Patients who present with an established arthrofibrosis condition require a comprehensive evaluation, including appropriate radiographs (Fig. 38-6), bone scans, and magnetic resonance imaging (MRI) to determine whether the condition is primary or secondary, as previously discussed. The examination may demonstrate diffuse edema, increased warmth, constant pain, limited patellar mobility (Fig. 38-7), contracture of peripatellar and infrapatellar soft tissues, tenderness in the fat pad, and limits in both extension and flexion compared with the contralateral normal knee (Fig. 38-8). Anterior knee pain, stiffness, pain with attempted knee motion, a flexed-knee gait, and severe quadriceps atrophy are common findings.

Patellar vertical height is determined using the radiographic method described by Caton and coworkers[31] and Linclau.[90] The left side of Figure 38-9 shows that the patellar vertical-height ratio is calculated by dividing line segment A, the distance between the most ventral rim of the tibial plateau and the lowest end of the patellar articular surface, by line segment B, the maximum length of the patellar articular surface. An alternative method described by Blackburne and Peel[17] locates the tibial reference point at an anterior central location on the tibial plateau (shown in Fig. 38-9 as line segment C). Using this method, the patellar vertical-height ratio equals C/B. The senior author (F.R.N.) conducted a study to determine normal right to left patellar vertical-height ratios within the same individual in a group of 51 patients (102 knees).[130] The difference in the vertical-height ratio of

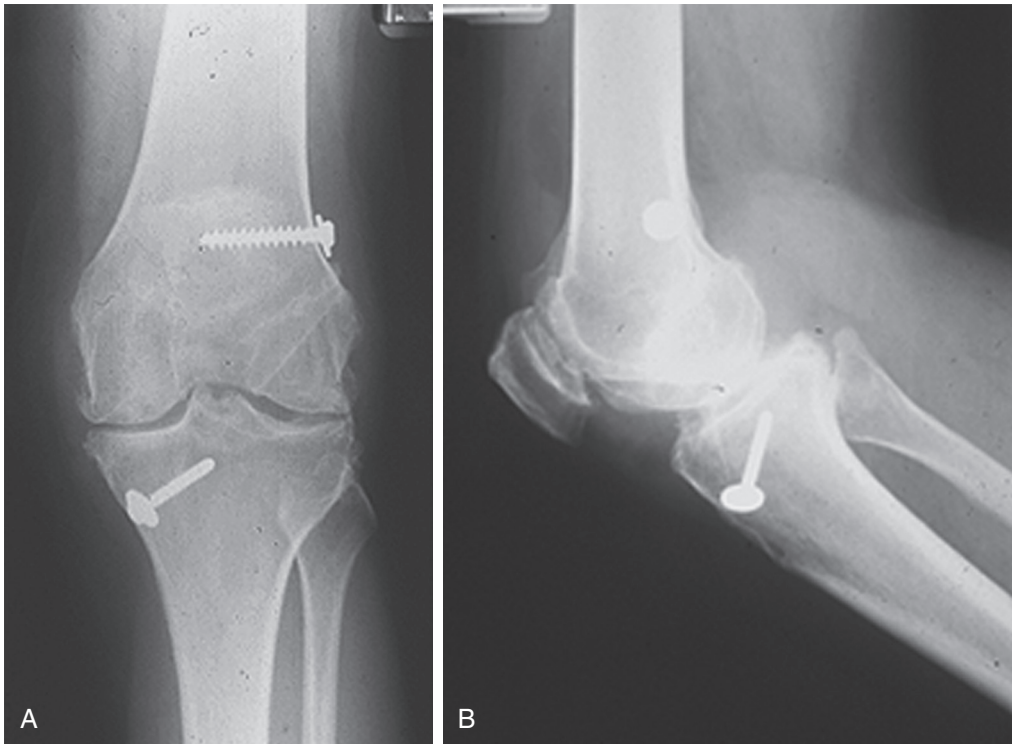


FIG 38-6 Anteroposterior (**A**) and lateral (**B**) radiographs of a knee with a severe flexion contracture and development of advanced joint arthritis after anterior cruciate ligament reconstruction. The patient was not a candidate for surgical soft tissue releases and subsequently underwent total knee arthroplasty.



FIG 38-7 Limited patellar mobility is demonstrated in this patient, referred after undergoing anterior cruciate ligament reconstruction elsewhere. The normal patellar medial glide allows at least 10 to 15 mm medial translation with the knee at 20 degrees of flexion. A normal lateral glide of up to 10 to 15 mm is possible. A loss of either medial or lateral translation occurs with contracture of peripatellar tissues. There is usually a limitation of proximal-distal glide because of an infrapatellar contracture.

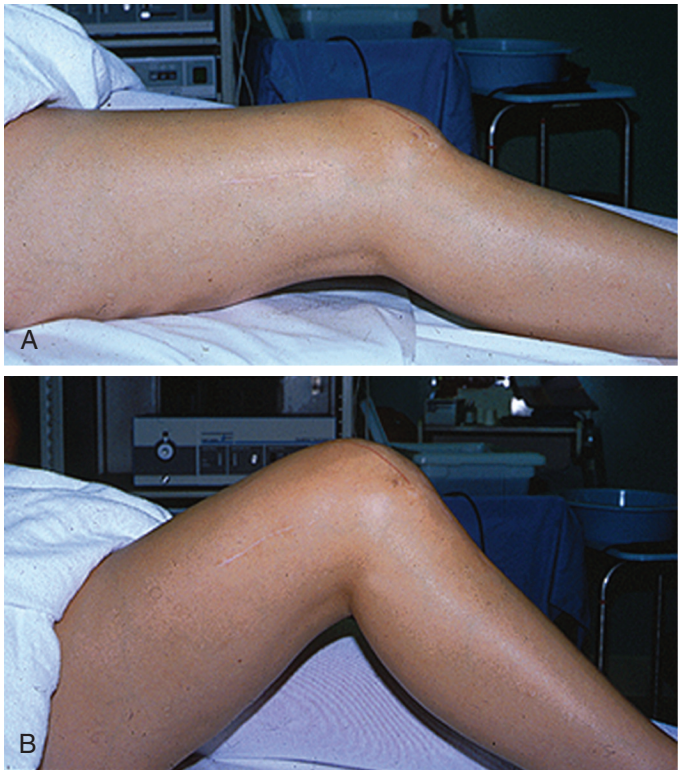


FIG 38-8 A severe limitation of knee extension (**A**) and flexion (**B**) demonstrated after anterior cruciate ligament (ACL) reconstruction in a patient referred for treatment 10 weeks after surgery. An arthroscopic debridement, lysis of adhesions, and posteromedial and capsular releases were required. Unfortunately, the motion deficits were not resolved in the first few weeks after ACL surgery.

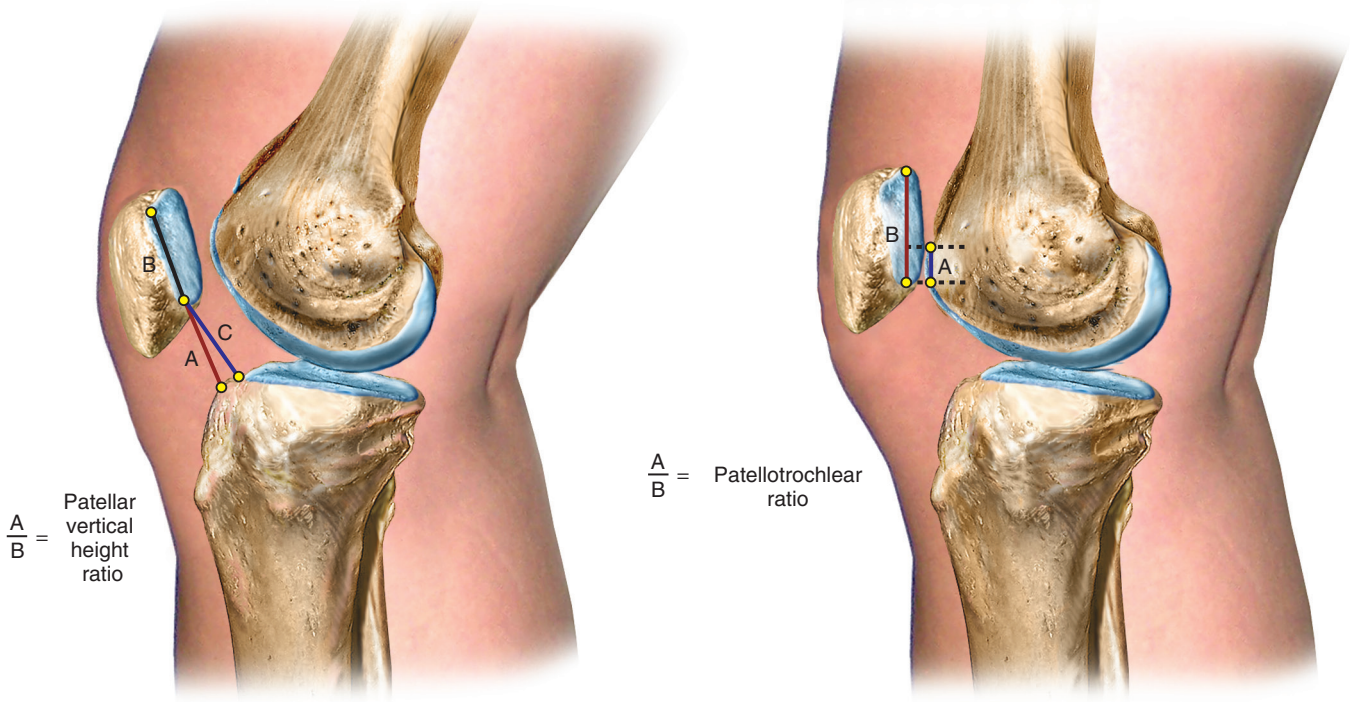


FIG 38-9 Methods used to determine patellar vertical-height ratio on a lateral radiograph. **Left,** The numerator (*line A, Linclau-Caton*) is the distance between the most ventral (anterosuperior) rim of the tibial plateau and the lowest end of the patellar articular surface. The denominator (*line B*) is the maximum length of the patellar articular surface. An alternative numerator (*line C, Blackburne-Peel*) locates the tibial reference point on the middle of the tibial plateau. The patellar vertical-height ratio equals A/B or C/B. **Right,** The numerator (*A*) is the superior-most aspect of the trochlear cartilage that is in contact with *line B*. The denominator (*line B*) is the maximum length of the articular patellar surface. Using this method, the mean index is 32% ± 12%, more than 50% is a patellar infera, and less than 12% is a patella alta.[15]

the patella between these two methods ranged from 0% to 9%, with an average difference of 3%. Large variations existed in the ratios among individual patients (range, 0.75-1.46). Therefore, the diagnosis of patellar infera requires comparison of patellar height ratios compared with those of the opposite knee and subsequent radiographs compared with the same knee at different time periods (Fig. 38-10). A decrease in the vertical height ratio of 14% to 15%, depending on the method used (Table 38-6), indicates a patella infera condition because this amount of difference is greater than 2 standard deviations of the normal difference between knees. An alternative method for the calculation of patellar height is the patellotrochlear index,[15] expressed as a percentage at knee extension (see Fig. 38-9).

MRI is useful in assessing the extent and location of scar tissue formation (Fig. 38-11). The infrapatellar band of scar tissue frequently found in the patellar infera state is just anterior to the fat pad and attaches from the inferior patellar pole to the anterior aspect of the tibia. Obliteration of the fat pad, with the patellar tendon attaching directly to the anterior tibia, is a poor prognostic sign because the patella may adhere to the proximal tibia, which markedly restricts medial-to-lateral mobility. Thick peripatellar tissues are frequently observed. The location of prior ACL or posterior cruciate ligament grafts must be determined. Important signs of an infectious process or unexplained edema and fluid in soft tissues or bone or about fixation implants are specifically evaluated to exclude an infectious etiology.

Patients who present with arthrofibrosis secondary to a cyclops lesion (fibrous fatty notch reactive tissues) or an impinged or improperly placed ACL graft require surgical debridement of the lesion or graft and scar tissue, followed by several months of physical therapy to regain normal knee motion and muscle function. The decision may then be made regarding the necessity for revision ACL reconstruction. In addition, patients with established primary arthrofibrosis require surgical management of the condition, described in detail elsewhere. These two groups of patients will not be successfully managed with conservative treatment measures. However, patients who fail to meet the knee motion goals established after ACL reconstruction (see Table 38-5) and in whom the arthrofibrosis is in the early, transient stage may usually be effectively treated with the exercises and modalities described later. The key is the early detection of the limitation of knee motion, as soon as the seventh postoperative day if 0 to 90 degrees is not demonstrated.

CONSERVATIVE MANAGMENT OF LIMITATION OF KNEE EXTENSION

If the patient has not achieved at least 0 degrees by the seventh postoperative day, she or he is placed into an overpressure extension program. The goal is to produce a gradual stretching of posterior capsular tissues, but not to induce soft tissue tearing and further injury because this could lead to an inflammatory response and worsen the condition. One effective exercise involves hanging weights, in which the foot and ankle are propped on a towel or other device to elevate the hamstrings and gastrocnemius, which allows the knee to drop into

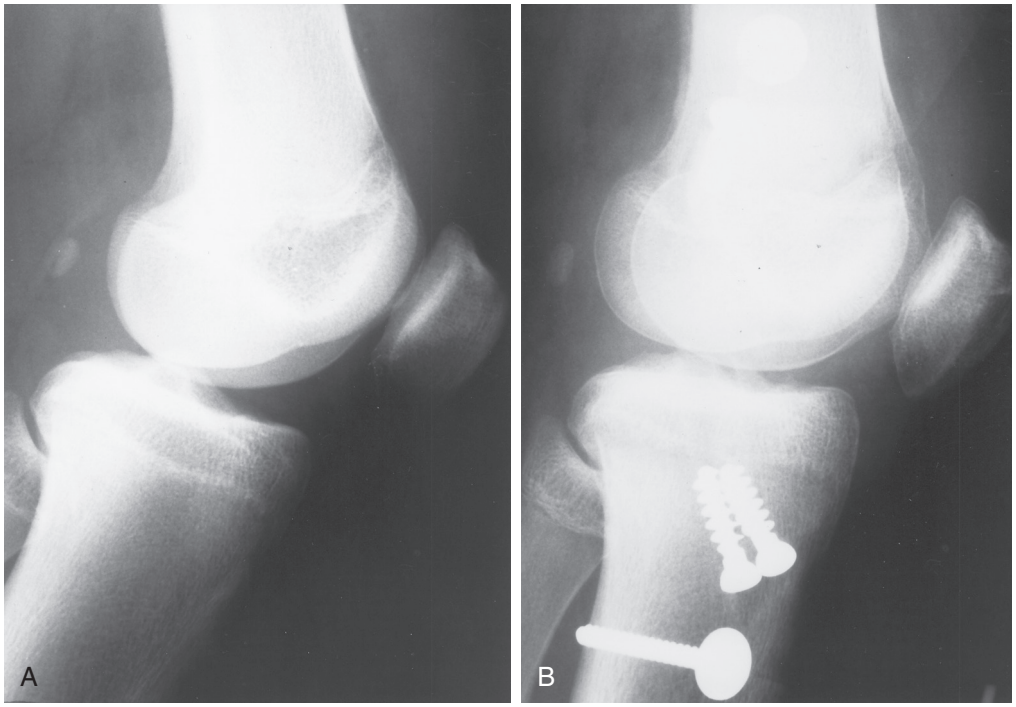


FIG 38-10 Lateral radiographs document a 22% decrease in patellar vertical-height ratio after a combined anterior cruciate ligament reconstruction and medial meniscus repair in a 14-year-old female gymnast. **A,** The injured knee before the reconstruction. **B,** Four weeks postoperative, the patient was referred to our center with significant quadriceps atrophy, difficulty performing knee motion exercises, and limited patellar mobility. The patient was treated with daily physical therapy and required an arthroscopic debridement, peripatellar release, lysis of adhesions, and removal of infrapatellar scar tissue. Nine months postoperative, the patient had regained full knee motion, had no pain symptoms, and had returned to recreational activities. However, the patellar infera remained unchanged. The patient is being followed for signs of patellofemoral arthritis and need for further treatment. (From Noyes FR, Wojtys EM, Marshall MT. The early diagnosis and treatment of developmental patella infera syndrome. *Clin Orthop.* 1991;265:241-52.)

TABLE 38-6 Differences among Three Radiographic Methods of Computing Patellar Vertical Height Ratios

Method	Pairs (*n*)	Knee	Patellar Ligament Length (Range)	Patellar Length (Range)	Ratio (Range)	Difference Right/Left Ratios (Range)	Difference Within 2 SDs (95% of Population)
Linclau[90]	51	Right	3.65 ± 0.46 (2.70-4.70)	3.54 ± 0.37 (2.80-4.20)	1.04 ± 0.13 (0.75-1.36)	–0.0200 ± 0.070 (–0.2100 to 0.135)	15%
		Left	3.69 ± 0.46 (2.90-4.70)	3.51 ± 0.33 (2.70-4.20)	1.06 ± 0.15 (0.80-1.46)		
Blackburne & Peel[17]	51	Right	2.95 ± 0.45 (2.00-4.10)	3.53 ± 0.43 (2.60-4.40)	0.84 ± 0.14 (0.61-1.33)	0.0003 ± 0.060 (–0.1930 to 0.190)	14%
		Left	2.95 ± 0.44 (2.10-3.90)	3.52 ± 0.39 (2.30-4.30)	0.84 ± 0.14 (0.64-1.30)		
Insall & Salvati[77a]	50	Right	4.90 ± 0.45 (4.10-5.90)	4.69 ± 0.43 (4.00-6.20)	1.05 ± 0.11 (0.86-1.28)	0.0140 ± 0.050 (0.1230-0.107)	11%
		Left	4.86 ± 0.44 (4.00-6.20)	4.72 ± 0.42 (4.00-6.20)	1.04 ± 0.10 (0.85-1.26)		

SD, Standard deviation.

full extension (Fig. 38-12, *A*). This position is maintained for 10 to 15 minutes and repeated at least eight times per day. Initially a 10-lb weight is used, which may be progressed up to 25 lb to the distal thigh and knee to provide overpressure to stretch the posterior contracted tissues. Full knee extension is usually obtained by the second to third postoperative week. A commercial extension appliance (see Fig. 38-12, *B*) is also an option.

If these treatment measures are not effective, a drop-out (bivalved) cast (see Fig. 38-12, *C*) is implemented for continuous extension overpressure. The advantage of this technique is that the patient is in control of the process and can apply or remove wedge material as tolerated and may bathe. A hyperextension splint may be used in the same manner; however, we believe that the bivalved cast offers superior benefits. Casting is not recommended in knees that have greater than

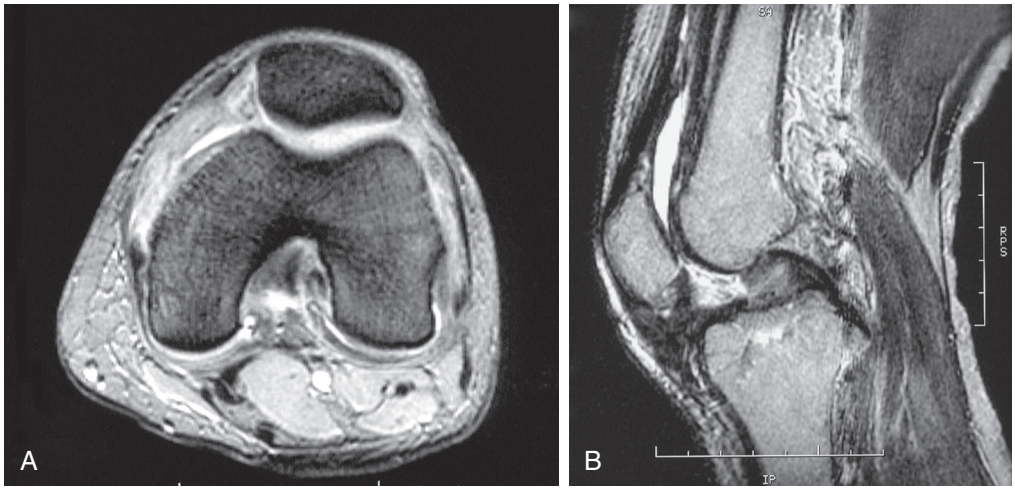


FIG 38-11 Magnetic resonance imaging of a knee with patella infera. **A,** Thickening of the medial and lateral peripatellar tissues. **B,** Note the infrapatellar tissues are replaced with dense fibrotic connective tissue. There is loss of the normal patellar tendon outline because the tendon is encased with scar tissue and attached to the proximal tibia. The infrapatellar scar extends from the inferior pole to the anterior tibia. This patient required arthroscopic debridement of the suprapatellar pouch, followed by open debridement of infrapatellar scar tissue and Z-plasty lengthening of the medial and lateral parapatellar tissues. The decrease in patellar tendon length is permanent.

CRITICAL POINTS Conservative Management of Limitation of Knee Extension

- If at least 0 degrees not achieved by the seventh postoperative day, the patient is placed into an overpressure extension program. Goal is to produce gradual stretching of posterior capsular tissues but not induce soft tissue tearing and further injury because this could lead to an inflammatory response and worsen the condition.
- Hanging weights: foot and ankle propped on a towel to elevate the hamstrings and gastrocnemius allows the knee to drop into full extension; use 10-25 lb weight on distal thigh.
- Bivalved cast (within first 4 weeks) if hanging weight is ineffective. Not used in knees that have more than –12 degrees extension deficit with a hard block to terminal extension or in knees with proliferative ingrowth of fibrous tissue in the femoral notch. These knees require posterior capsulotomy through a limited medial and lateral approach.
- Cylinder cast, if bivalved cast ineffective. Applied at 36-48 hours; anterior wedges used. Convert to night splint for 7-10 days.

a –12 degree extension deficit with a hard block to terminal extension. These knees are usually 3 or more months postoperative, and dense scar tissue has formed posteriorly with posterior capsular contracture requiring surgical releases and debridement. In knees with a rigid block to extension, extension casts have the potential to produce high tibiofemoral compressive forces and articular cartilage damage. Extension casts are also not effective when there is proliferative ingrowth of fibrous tissue in the femoral notch. These cases require arthroscopic debridement.

When indicated, the cast is used within the first 4 weeks for cases resistant to the other overpressure extension modalities. The goal is to resolve all extension problems by 4 weeks postoperatively. In select knees, the extension deficit may return and, accordingly, the drop-out cast is repeated. On occasion, the drop-out cast will not be effective and it is necessary to use a cylinder cast and serial wedges to gain extension. The cast is well padded to prevent skin breakdown. An anterior wedge is used every 12 to 24 hours to gradually achieve extension. The cast is applied for 36 to 48 hours and then removed to resume knee flexion and extension motion exercises. Once extension is regained, the cast is converted into a posterior night splint, which is used for an additional 7 to 10 days. In some knees, full extension is regained but then gradually lost over the course of several weeks. In these cases, a repeat cast application may resolve the problem.

The treatment algorithm for limitations of knee extension is shown in Figure 38-13. The goal is to resolve the loss of knee extension by 4 weeks using the modalities outlined. Frequently, it is necessary to repeat steps in the treatment protocol because the return in a knee extension deficit may occur. It is rare that manipulation or continuous epidural is necessary when the program is followed; however, these steps are provided for the most resistant cases. The most difficult problem is the knee joint that does not respond and, despite the overpressure program, continues to show a lack of full extension. If the lack of knee extension is 10 degrees or less, the overpressure program will usually be successful. However, it is important to identify the knee in which there is a rigid hard block to extension and the deficit is greater than 10 degrees. In these knees, it is better to proceed with a posterior capsulotomy through a limited medial and lateral approach, to be described.

CONSERVATIVE MANAGEMENT OF LIMITATION OF KNEE FLEXION

Because full knee flexion is present at the end of the ACL reconstruction, any limitation in the early postoperative period is because of intraarticular adhesions and contracture of peripatellar tissues and muscle spasm or pain. The early detection of a limitation of flexion (<90 degrees by the seventh postoperative day) necessitates an



FIG 38-12 **A,** Hanging weights. **B,** Extension board. **C,** Drop-out cast.

overpressure flexion program. A rolling stool exercise (Fig. 38-14, *A*) may be done in which the patient sits on a small stool close to the ground, the knee is flexed to the maximum position possible and held in that position for approximately 1 minute or as long as the patient is able to tolerate mild discomfort. Then the patient rolls the stool forward without moving the foot position on the floor to achieve a few more degrees of flexion. The procedure is performed for 10 to 12 minutes and repeated six to eight times a day. Wall slides are another effective exercise to achieve flexion. The patient lies on his or her back and places the foot of the reconstructed knee on a wall as shown in Figure 38-14, *B*. The foot of the opposite leg is used to gently slide the opposite foot and flex the reconstructed knee in a gradual manner. Commercial knee flexion devices (see Fig. 38-14, *C* and *D*) may also

CRITICAL POINTS Conservative Management of Limitation of Knee Flexion

- Overpressure program indicated <90 degrees flexion by seventh postoperative day.
- Rolling stool exercise, wall-slides, commercial knee flexion devices, figure-four exercise usually effective.
- Patients who have <90 degrees by 3-4 weeks require a gentle ranging of the knee under anesthesia (not a forceful manipulation) in which full flexion is easily obtained with only light loads applied.
- Associated peripatellar contracture must be immediately treated to prevent patella infera.
- Knees with no patellar mobility: operative release of tight contracture peripatellar tissues indicated.
- Chronic cases of arthrofibrosis and retinacular contracture usually require open medial and lateral Z-plasty release.

be used as available to further promote overpressure. In addition, a figure-four overpressure exercise is effective (Fig. 38-14, *E*). A 4-inch tubular stocking is used, double wrapped around the foot and ankle, which allows the patient under his or her own power to flex the knee. The patient shown in Figure 38-14, *E* had 90 degrees of flexion, and an arthroscopic release was successful in achieving 135 degrees. After the debridement and placement of an epidural, the surgeon sets a mark on the thigh by gentle pressure to establish the flexion goal for that day. The mark on the thigh in the photograph demonstrates the 135-degree flexion position, which is the overall goal. The mark on the distal portion of the patella in the photograph demonstrates the starting position, which in this case was 90 degrees. The goal of these exercises and modalities is to gradually and passively stretch tissues in a controlled manner while not inducing pain or tearing of tissues. Patients who have difficulty achieving 90 degrees by the third to fourth week require a gentle ranging of the knee under anesthesia (not a forceful manipulation) in which full flexion is easily obtained with only light loads applied. This stretches out early joint adhesions, markedly reduces postoperative pain, and allows the patient to regain motion.

The treatment algorithm for a limitation of knee flexion is shown in Figure 38-15. The first step is to determine whether there is associated contracture of patellar tissues, which makes the treatment more difficult. The loss of knee flexion when there is no peripatellar contracture is more easily resolved. With the treatment protocol shown, it is rare to progress to the necessity for an arthroscopic debridement and release of peripatellar tissues. When there is an associated peripatellar contracture, it is important that the condition be immediately treated because this can result in a patella infera. A conservative patellar mobilization program with oral steroids is performed for 1 week. If the limitation of motion and peripatellar contracture persists, a gentle manipulation under anesthesia is performed; however, no more than "two to three fingers of pressure" is placed at the distal tibia to achieve knee flexion. If more force is necessary, it indicates that the peripatellar contracture is composed of more dense, resistant scar that requires arthroscopic debridement. An aggressive manipulation under higher forces risks damaging the patellofemoral articular cartilage because the tight contracted tissues increase patellofemoral contact forces with knee flexion. Knee flexion is gained but at the expense of possibly damaging the patellofemoral joint. This is also true for pushing knee flexion in the clinic when there is no patellar mobility. Again, an operative release of tight contracture peripatellar tissues is indicated instead of overzealous flexion exercises or a knee manipulation under high flexion loads.

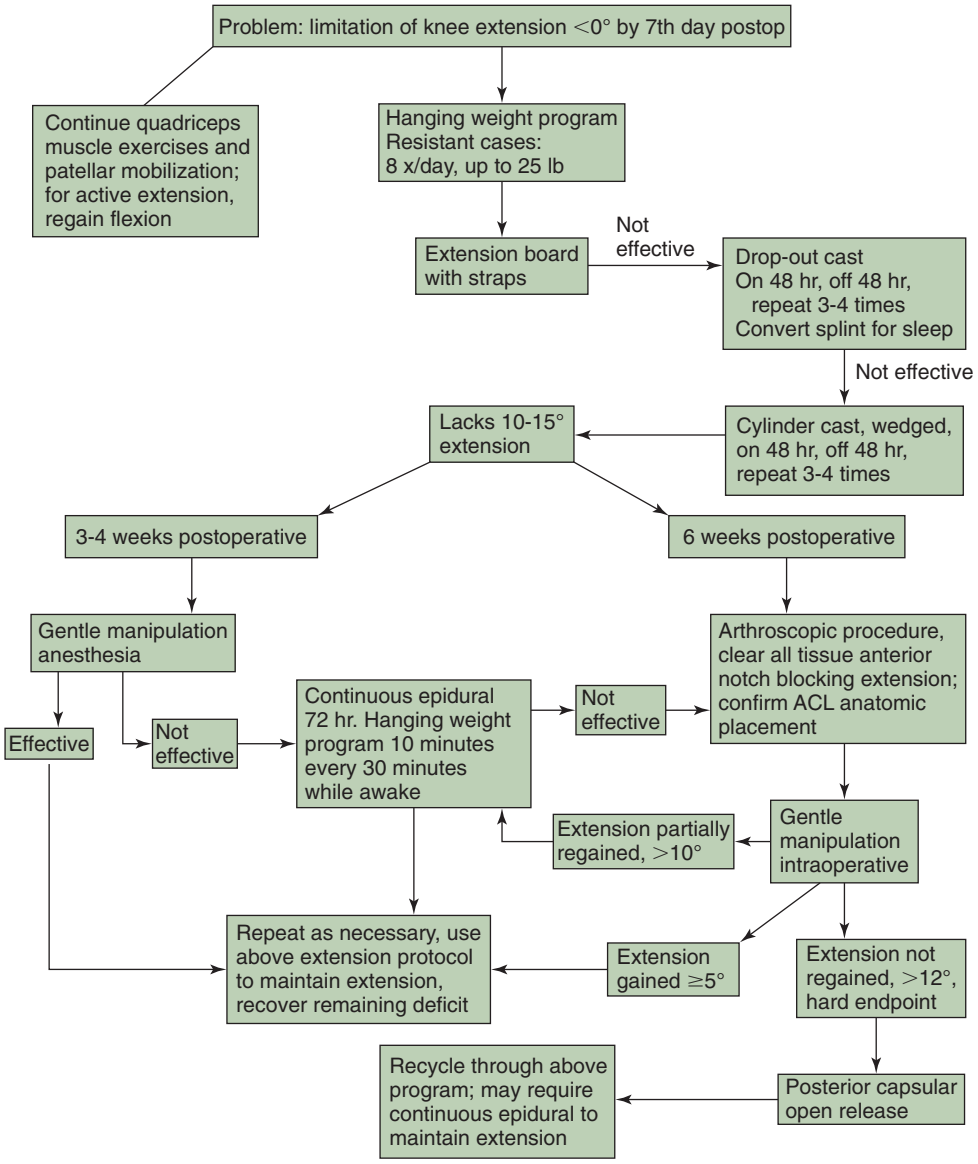


FIG 38-13 Treatment algorithm for limitations of knee extension. *ACL,* Anterior cruciate ligament.

It should be noted that there are select knees, most commonly chronic cases of arthrofibrosis, in which the peripatellar scar tissue is thick and contracted and an attempted arthroscopic release would result in too extensive a release on both the medial and lateral peripatellar tissues. If a major release is necessary, extending to the proximal aspect of the patella, the senior author recommends an open medial Z-plasty release in which the more normal tissue laxity is restored and the abnormal scar tissue is excised. The Z-plasty frequently involves contracted vastus medialis obliquus (VMO) and vastus lateralist obliquus (VLO) tissues. In addition, the Z-plasty procedure prevents the occurrence of a major capsular defect with joint communication to subcutaneous tissues, which is a complication of an extensive medial or lateral arthroscopic release.

ROLE OF ORAL CORTICOSTEROIDS

There is a subset of patients who develop an exaggerated postoperative inflammatory soft tissue response with excessive pain, joint stiffness,

CRITICAL POINTS Role of Oral Corticosteroids

- Indications: knees with exaggerated inflammatory soft tissue response with excessive pain, joint stiffness, soft tissue edema, warmth, and redness about the joint.
- Inflammation not resolved by cryotherapy, antiinflammatory medications, elevation, and compression.
- A 6-day 4-mg Medrol Dosepak is effective if used early. Avoid forceful and aggressive physical therapy.
- Consider oral corticosteroids at elevated doses for 4 weeks if the inflammatory symptoms return or are more severe.
- In cases of severe arthrofibrosis, oral corticosteroids may be required for 2 to 3 months in an effort to avoid repeat surgery.



FIG 38-14 **A,** Rolling stool exercise. **B,** Wall-slides. **C,** Flexion seat. **D,** Knee flexion overpressure device. **E,** Figure-four knee flexion overpressure exercise.

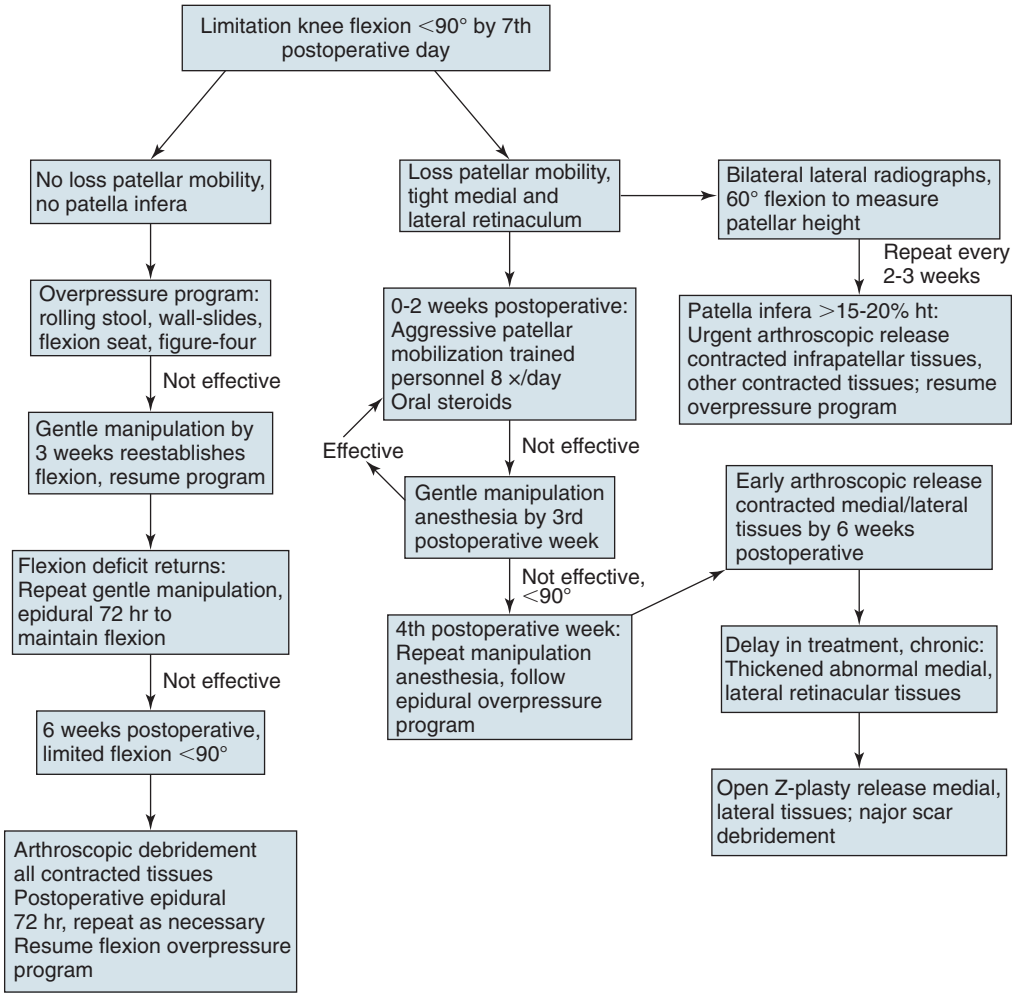


FIG 38-15 Treatment algorithm for a limitation of knee flexion.

soft tissue edema, warmth, and redness about the knee. The inflammation is not resolved by the standard treatment methods of cryotherapy, antiinflammatory medications, elevation, and compression. It is first recommended to use a maximum dose of NSAID for 1 week. If this is not successful, a trial of oral steroids is indicated. It is important that before and during the treatment of these resistant cases, an occult infectious process is ruled out, with appropriate serial diagnostic tests (aspiration, serum inflammatory tests) performed as necessary.

A 6-day 4-mg Medrol Dosepak (methylprednisolone) is effective if used early in the phase. Six tablets are taken on the first day of treatment, five on the second, four on the third, three on the fourth, two on the fifth, and one on the sixth. During this treatment period, forceful and aggressive physical therapy is avoided. Gentle knee motion and lighter overpressure exercises are performed. In select cases, the 6-day dose pack may be repeated.

Another option is to use elevated doses of oral corticosteroids for 4 weeks if the inflammatory symptoms return or are more severe. The usual daily dose is 30 mg in the first week (two tablets taken three times a day), 15 mg in the second (one tablet taken three times a day), 10 mg in the third (one tablet taken two times a day), and 5 mg in the fourth. In cases of severe arthrofibrosis, oral corticosteroids may be required for 2 to 3 months in an effort to avoid repeat surgery. Complications that may arise from prolonged corticosteroid intake include pituitary adrenal suppression, fluid and electrolyte disturbance, hyperglycemia, peptic ulcers, and avascular necrosis. In the most resistant cases, it is necessary to repeat oral steroid cycling on the off days to NSAIDs, which are prescribed at their maximum dosage.

GENTLE MANIPULATION UNDER ANESTHESIA

As already described, a forceful manipulation of a knee with extensive scar tissue is harmful and ineffective in treating the limitation of knee

CRITICAL POINTS Gentle Manipulation Under Antesthsia

- Forceful manipulation of a knee with extensive scar tissue is harmful and ineffective in treating the limitation of motion.
- Patients with a hard stop to knee motion (joint contracture) are treated with arthroscopic debridement, lysis of adhesions.
- A gentle manipulation under anesthesia, done with only mild pressure exerted on the distal leg, is effective if performed within 3-4 weeks postoperatively.
- Supervised physical therapy program required to maintain the knee motion achieved by the manipulation.

motion. A forced manipulation may tear intraarticular and extraarticular tissues and cause excessive tibiofemoral and patellofemoral compression with the risk of fracture, damage to the articular cartilage, rupture of the patellar tendon, and even femoral fracture.[91] Therefore any patient who has a hard stop to knee motion (which represents a joint contracture) is treated with an arthroscopic debridement and lysis of adhesions.

A gentle manipulation under anesthesia, done with only mild pressure exerted on the distal leg, is effective if performed early after ligament surgery, within 3 to 4 postoperative weeks. Even at 6 weeks, there may exist dense scar tissue proliferation in joint soft tissues, and the window of opportunity has been lost to perform an early ranging of motion under general anesthesia. Adequate patellar mobilization must be established before flexing the knee during the procedure to prevent damage to the patellofemoral articular surface. A supervised physical therapy program is required to maintain the knee motion achieved by the manipulation as detailed in the treatment algorithm.

OPERATIVE MANAGEMENT OF SEVERE RESTRICTION OF KNEE MOTION

Arthroscopic Soft Tissue Releases

A demonstration of an arthroscopic technique for debridement of contracted tissues in a knee with arthrofibrosis is shown in Figure 38-16. In this patient, there was a restriction in medial-to-lateral translation (glide) of the patellofemoral joint, with a contracture of the medial and lateral retinaculum. However, approximately 50% of normal patellar mobility was still present, indicating that an arthroscopic technique could be used and an open extensive technique was not necessary. There were limitations of motion at 0/5/90 degrees. The procedure was performed after tourniquet inflation.

Open Z-Plasty, Medial-Lateral Retinacular Tissues

Figure 38-17 demonstrates the operative technique for an open Z-plasty release of the medial and lateral retinacular tissues. An arthroscopic release alone is contraindicated in this case because the release is so extensive (extending above the proximal patella and releasing all medial and lateral soft tissues) that there would be open communication of the joint into the subcutaneous tissues. The principal shown is to preserve the function of the medial and lateral retinacular soft tissues and, as well, debride the tissues to a normal thickness. The Z-plasty open release allows an arthrotomy to thoroughly debride infrapatellar contracted tissues, protect the patellar tendon, and lengthen contracted medial and lateral patellar tissues.

Posterior Medial-Lateral Capsulotomy

The technique for a posterior medial-lateral capsulotomy involves the same exposure as that used for a medial or lateral meniscus repair (Fig. 38-18). On the medial side, the posterior capsule is sectioned at its femoral attachment proximally. On the lateral side, the capsule is sectioned in its proximal aspect just below the attachment of the lateral gastrocnemius to the posterior capsule. The dissection and posterior capsule excision are carried directly over the posterior femoral condyles and not into the posterior intercondylar region because scar tissue may extend to the neurovascular structures. It is often impressive how dense the posterior capsular structures are, and with their release, further gains in knee extension are possible on the operating table. The remaining posterior intercondylar tissues are easily stretched with the overpressure program. The posterior capsule releases are also accompanied with an arthroscopic procedure to remove any tissue that has grown into the notch producing an anterior impingement that would also block extension.

INPATIENT PHYSICAL THERAPY PROGRAM

An inpatient physical therapy program supplemented with a continuous epidural anesthetic, a femoral nerve block, or appropriate analgesics may be used for 3 to 4 days in resistant cases that do not respond to other interventions or in whom limitations of knee motion return after manipulation or arthroscopic debridement. The epidural is regulated to block pain and sensory input, with the goal to retain muscle motor control to allow active knee motion and the overpressure program. The block requires close supervision by an anesthesiologist for levels and medication dosage. The catheter is replaced under fluoroscopy control if the patient expresses insufficient pain relief. If the repeat block fails, pain relief is obtained with a femoral nerve block and analgesics. A skin care and protection program is performed by nursing personnel. The block is maintained for a minimum of 72 hours to allow a gradual overpressure program to stretch contracted soft tissues.

The following measures are taken to avoid deep venous thrombosis and pulmonary embolism. First, a careful analysis is done to detect patients at increased risk, including diabetics; obese individuals; those with venous insufficiency; and patients with a family history or personal history of phlebitis, venous clots, or embolism. These patients are not appropriate candidates for the epidural program owing to the associated inactivity and bedrest. When the epidural is in place, the patient remains mobile and is encouraged to be out of the bed intermittently throughout the day. Antiembolism stockings are worn, and ankle pumps are done for 5 to 10 minutes hourly. The extremity is monitored daily, and a calf venous compression device is used. Aspirin (600 mg daily) is prescribed. The patient is monitored for calf tenderness or leg edema, and an ultrasound examination of both lower extremities is obtained if any suggestion of a deep venous thrombosis exists.

The inpatient overpressure program is contraindicated in patients with open growth plates or disuse osteopenia owing to the increased risk of a fracture. The patient is taught before the epidural how to perform the program and uses the amount of tension applied to the foot-calf stocking to achieve gains in knee flexion. It is important that other individuals such as the family not assist in the overpressure

Text continued on p. 1086

CRITICAL POINTS Inpatient Physical Therapy Program

- An inpatient physical therapy program supplemented with either a continuous epidural anesthetic, femoral nerve block, or appropriate analgesics may be used for 3-4 days in resistant cases who do not respond to other interventions or in whom limitations of knee motion return after manipulation or arthroscopic debridement.
- Contraindicated in patients with open growth plates or disuse osteopenia owing to the increased risk of a fracture.
- Block maintained at least 72 hours to allow a gradual overpressure program to stretch contracted soft tissues.
- Take appropriate measures to avoid deep venous thrombosis.
- Patient is taught before the epidural how to perform the overpressure program.
- Recommend active range of motion program by the patient; continuous passive motion machine rarely required.
- Leg lifts, isometric exercises performed while in the hospital.
- Exercises must be continued after discharge at home 8 times a day, along with supervised therapy program.

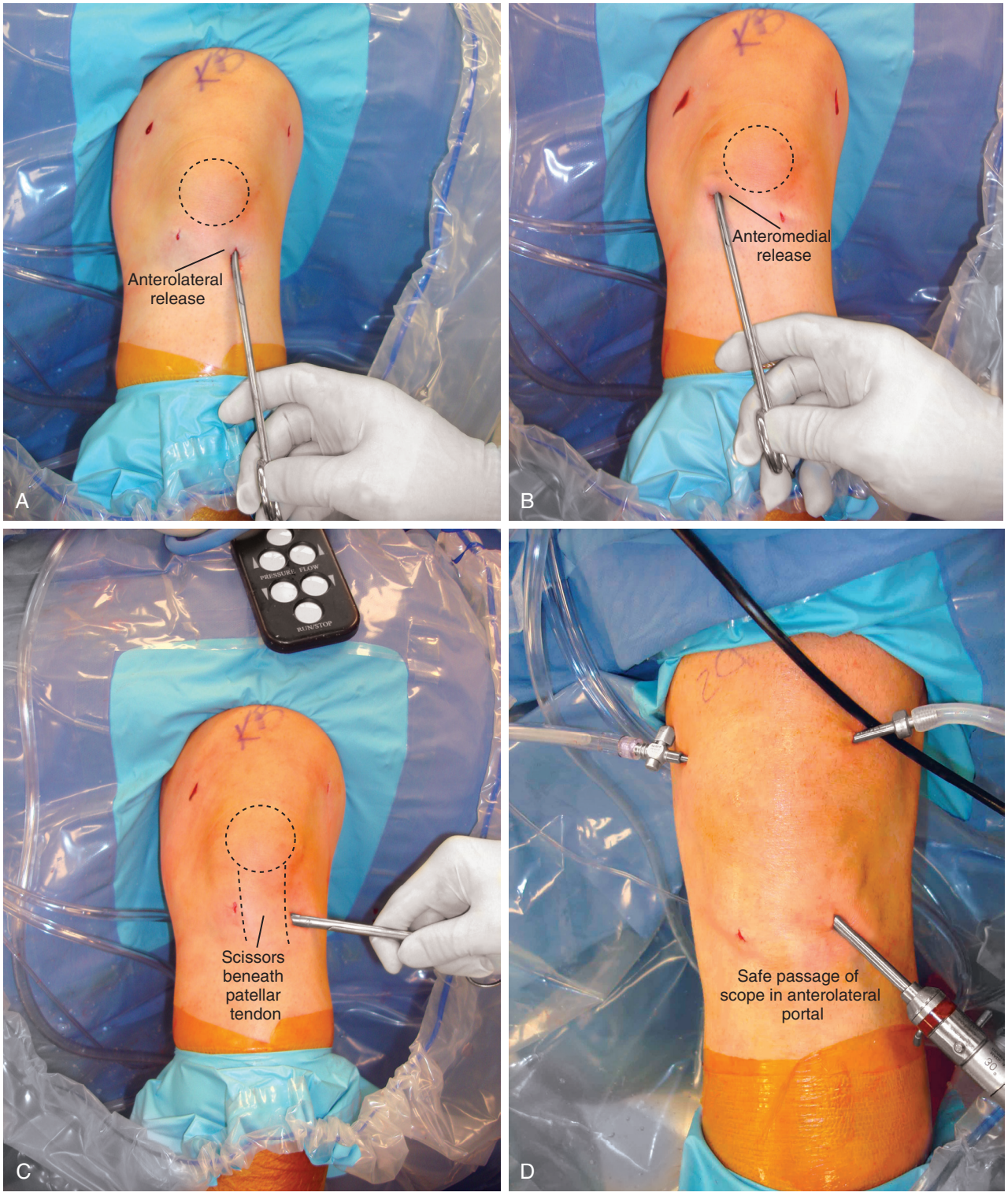


FIG 38-16 **A,** The anterolateral portal is used to transect the lateral retinaculum 15 mm. **B,** The anteromedial portal is used to transect the medial retinaculum 15 mm. **C,** The anterolateral portal is used to place a Metzenbaum scissor beneath the patellar tendon and palpate for an infrapatellar patella–tibial band of scar tissue. The scissor is bluntly pushed posterior to the patellar tendon and through the infrapatellar band to allow fluid to pass into the fatty space behind the patellar tendon. This maneuver protects the patellar tendon during removal of the infrapatellar band, to be described. If a safe plane cannot be established and verified arthroscopically, an open debridement procedure is indicated. **D,** There is now sufficient patellar mobility to pass an arthroscope beneath the patella safely without damaging the patellofemoral cartilage surfaces. If this is not possible, additional medial and lateral releases are performed. The releases at this point are conservative.



FIG 38-16, cont'd **E,** A blunt obturator or shaver is placed into the suprapatellar pouch and translated in a superior and inferior plane to reestablish a space sufficient for the initial arthroscopic debridement. A band of scar extends from the superior patella to the trochlea, and dense suprapatellar adhesions are present. Debridement of suprapatellar scar tissues is performed using an electrocuting device. **F,** The soft tissues and synovium over the anterior femur are not removed to leave a gliding soft tissue surface. **G,** A resection of scar tissue beneath the vastus medialis obliquus and vastus lateralis obliquus may be required because this scar can limit muscle mobility. **H,** The scope is placed in the superolateral portal to view the infrapatellar region and debride an infrapatellar contracture.

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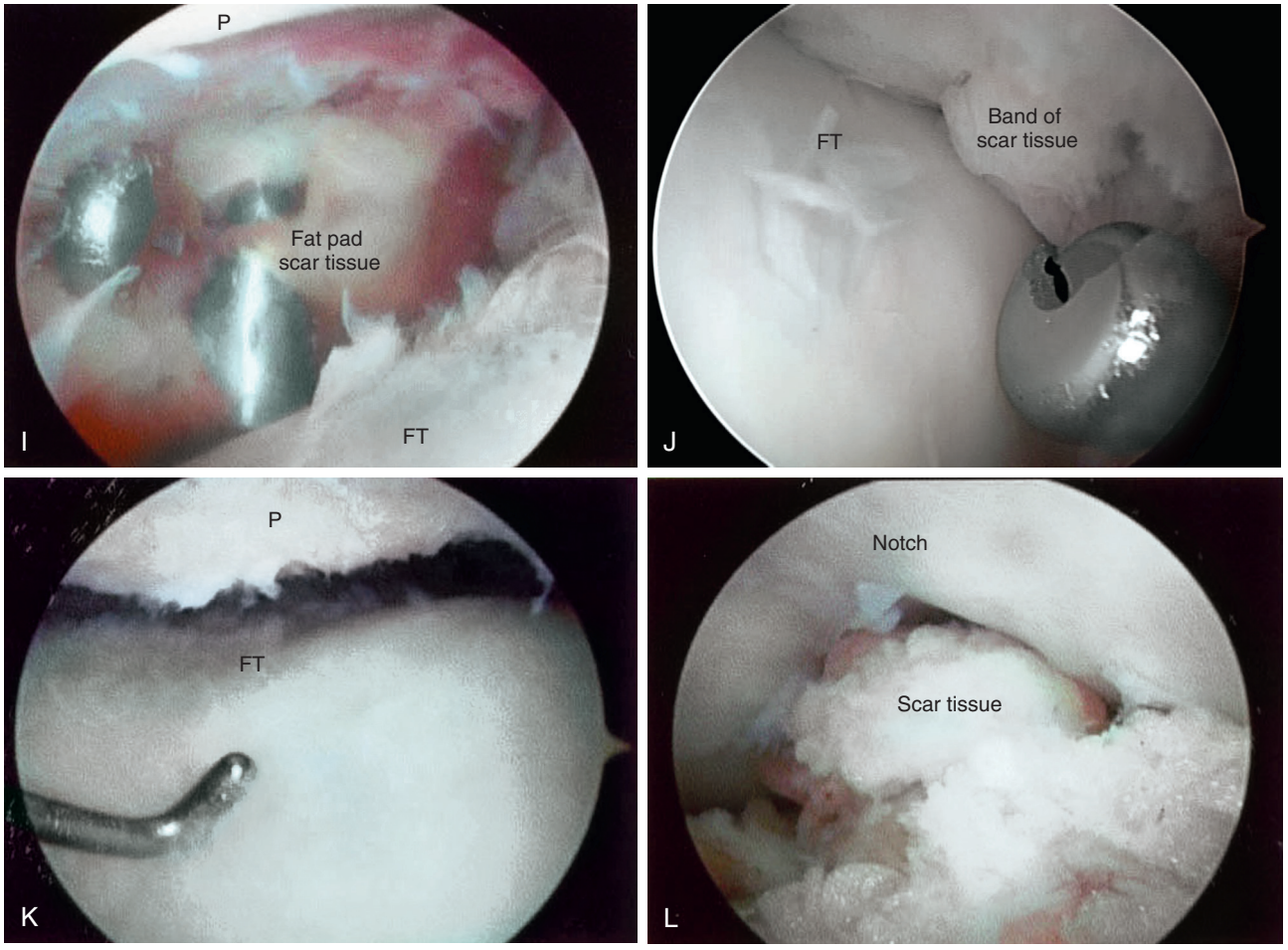


FIG 38-16, cont'd **I,** An arthroscopic view through the superolateral portal shows the fat pad and instruments to remove infrapatellar scar tissue. Care is taken to not transect the anterior medial and lateral meniscus attachments. **J,** With the scope placed alternatively in the anteromedial and anterolateral portals, extensive synovium and scar are removed from the medial and lateral recesses and intercondylar notch. Scar tissue proliferation may block extension on the anterior aspect of the medial and lateral meniscus; this requires removal. **K,** The knee is placed at 30 degrees flexion and sufficient medial and lateral parapatellar contracted tissue and retinaculum are removed to allow for a normal medial-lateral glide. This release rarely extends above the midportion of the patella. In this knee, moderate patellofemoral damage is observed. **L,** Notch ingrowth of tissue removed that may block extension. After completion of the arthroscopic procedure, and verification that no scar tissue remains, the tourniquet is deflated, and meticulous electrocoagulation of bleeding points is performed. The decision to use a drain is based on the ability to control intraarticular bleeding. A gentle ranging of the knee with the patient under anesthesia is performed that is not aggressive in terms of the loads applied. The knee is placed into a bulky compression (cotton-Ace-cotton-Ace) dressing with an ice bladder incorporated into the dressing. *FT,* Fibrous tissue; *P,* patella.

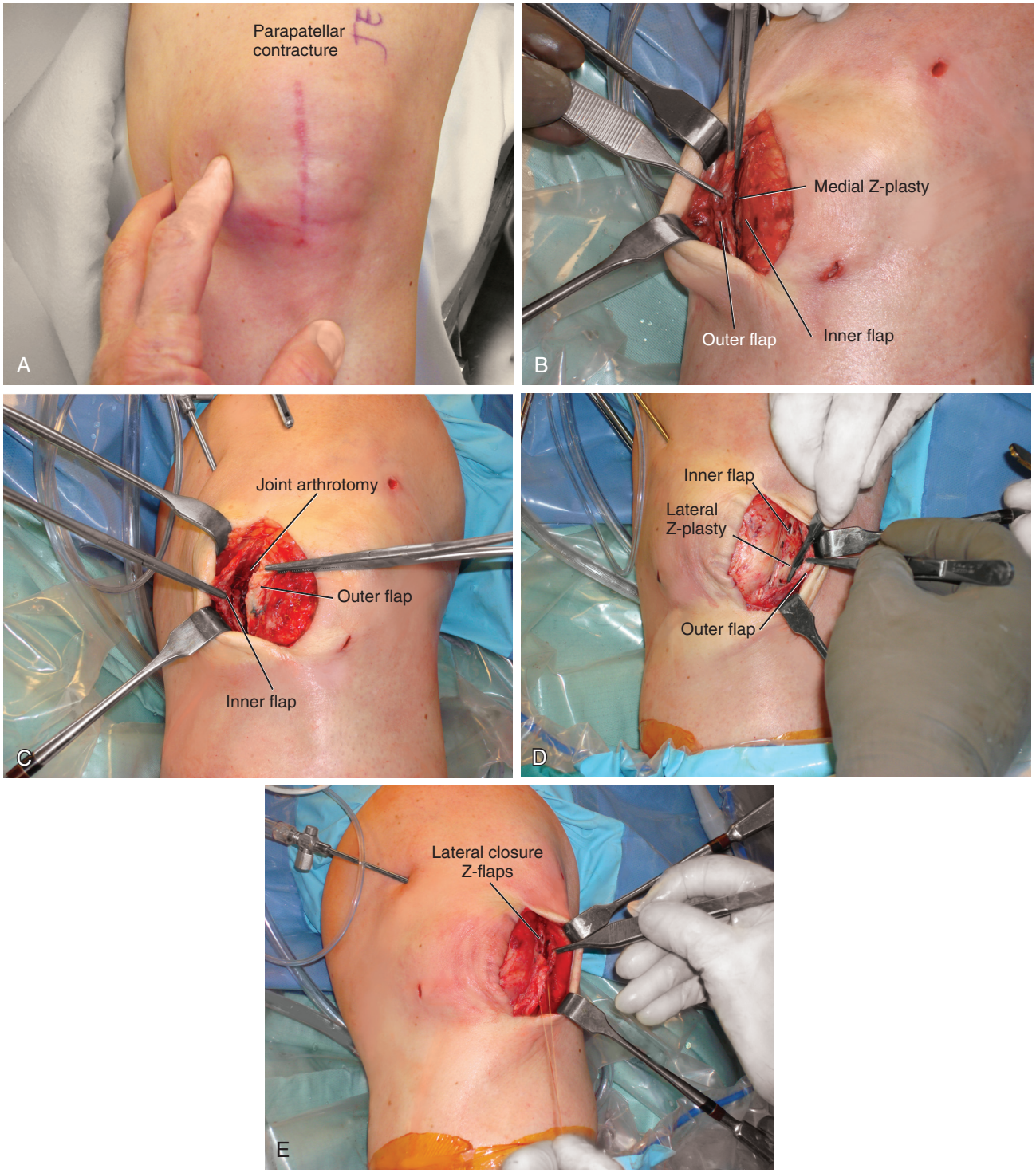


FIG 38-17 Z-plasty operative technique for contracted medial and lateral peripatellar tissues. **A,** Preoperative examination under anesthesia of a patient with established arthrofibrosis discloses a complete lack of patellar mobility, absent medial and lateral glide and an obvious patella infera with shortening of the patellar tendon. The patient's range of motion was 0/0/80 degrees. **B,** Open medial Z-plasty approach. The medial retinaculum and soft tissues are split in a Z-plasty fashion to allow a loose closure and restore a normal medial patellar glide. An arthroscopic procedure was performed just before the open procedure to reestablish the suprapatellar pouch, remove intraarticular adhesions within the suprapatellar pouch and medial and lateral tibiofemoral gutters, and document the condition of the joint. **C,** Completion of medial Z-plasty release shows the medial soft tissue flaps that have been developed. A debridement of infrapatellar scar tissue was performed under direct visualization. **D,** A lateral Z-plasty release of contracted lateral retinacular tissues is performed in a similar fashion. **E,** The loose closure of the lateral Z-plasty release allows restoration of a normal medial glide. A medial and lateral Z-plasty release for contracted soft tissues represents a real key for the successful management of this type of contracture. There is restoration of normal patellar mobility, and most important, the joint soft tissues can be closed.

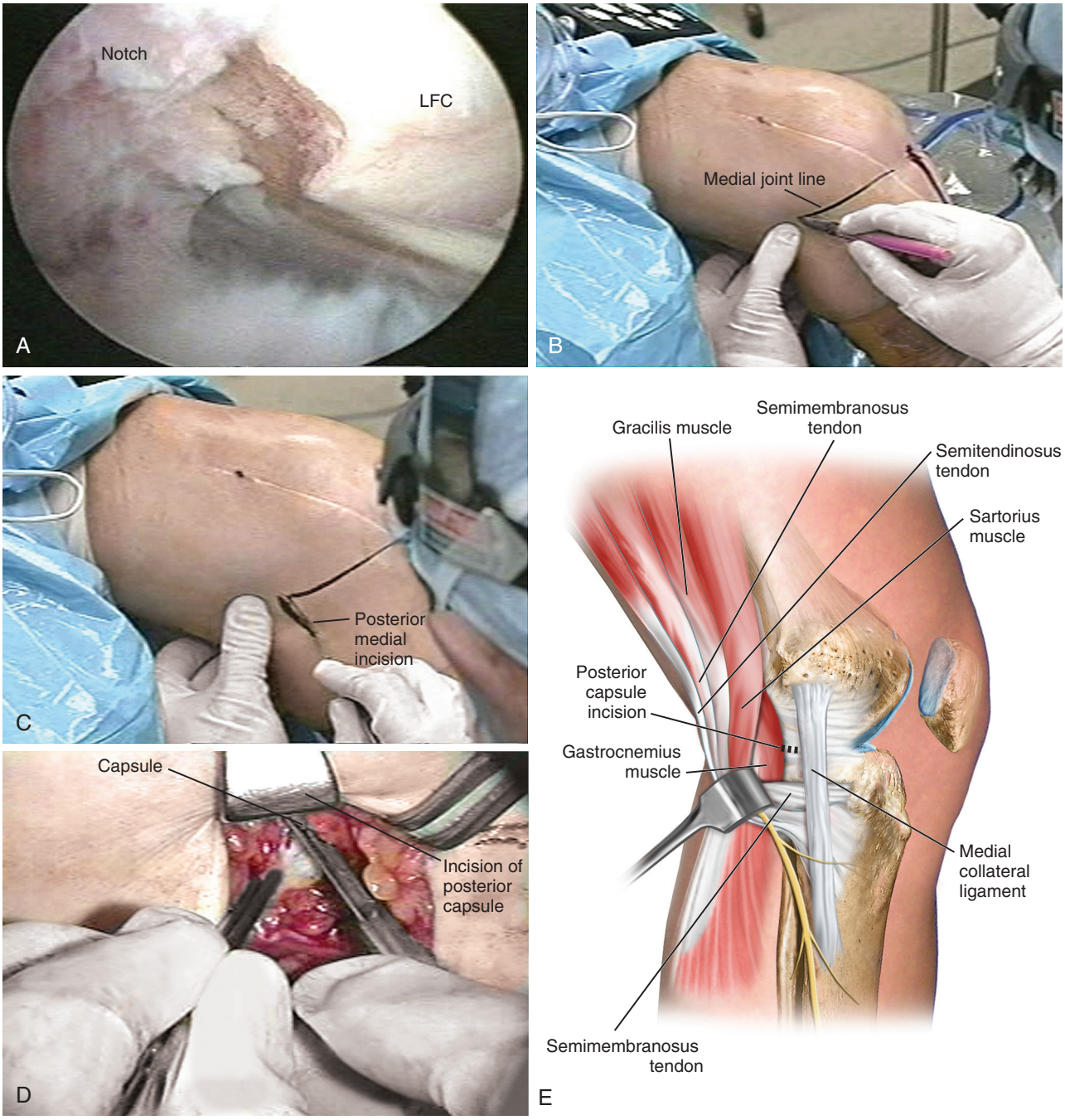
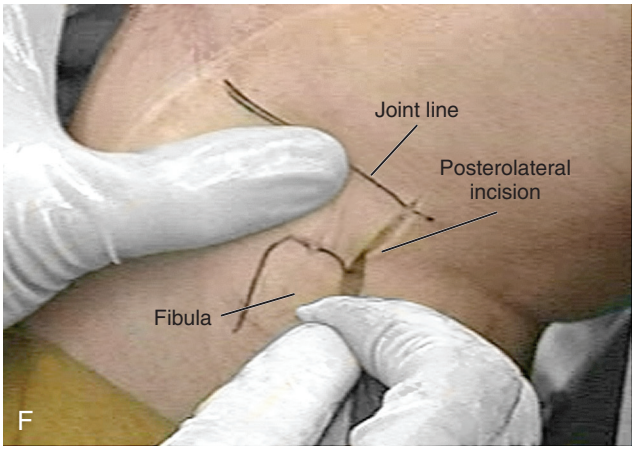
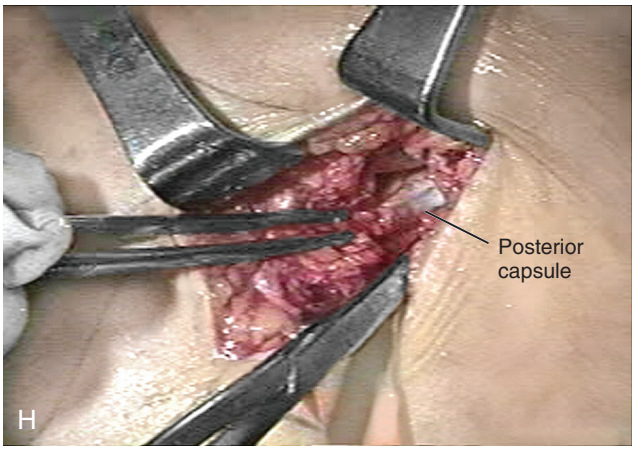
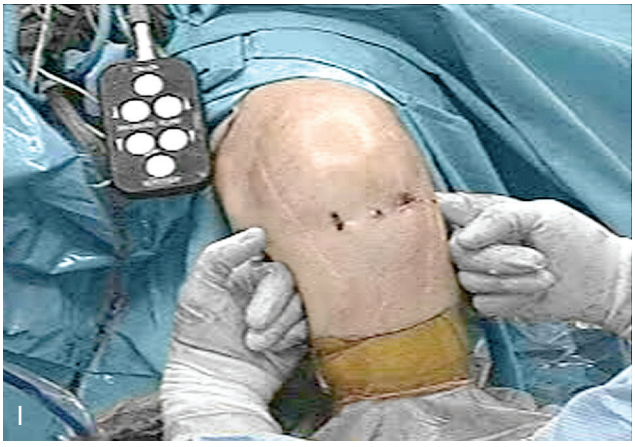


FIG 38-18 Operative photographs of a patient with arthrofibrosis (0/15/80 degrees) requiring an arthroscopic lysis of adhesions, parapatellar releases, and posterior medial and lateral capsulotomy for the 15 degrees flexion contracture. **A,** An arthroscopic lysis of adhesions, removal of scar tissue, and parapatellar releases is performed, as already described. All scar tissue from the notch region is removed and a notchplasty performed as required so that these tissues do not block extension. **B,** The medial joint line is marked. **C,** A posteromedial incision is made. **D,** The approach reflecting the sartorius is used as described for an inside-out medial meniscus repair (see Chapter 23). **E,** A vertical posteromedial capsulotomy is made directly behind the superficial medial collateral ligament. Operative photograph: The surgeon uses a headlamp and the femoral insertion of the posteromedial capsule is identified and transected millimeter by millimeter to the edge of the medial femoral condyle, but not beyond to avoid the neurovascular structures.







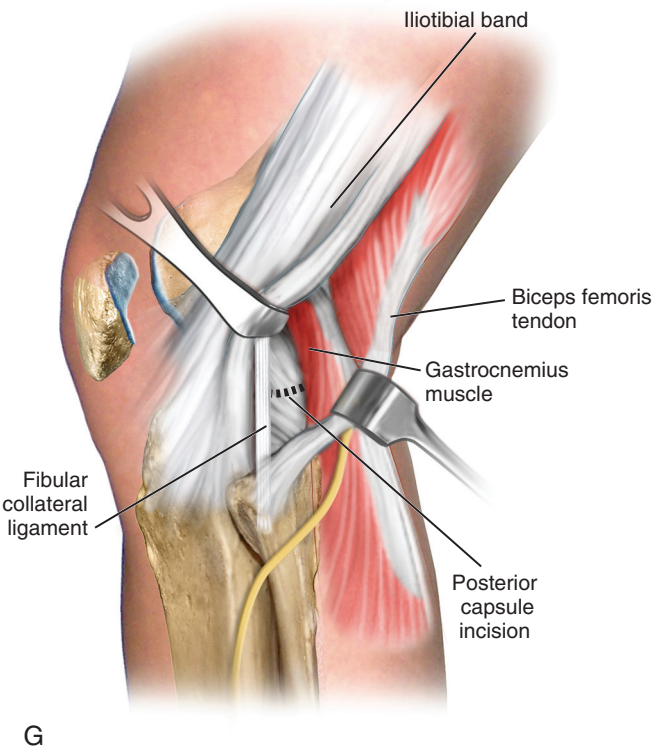
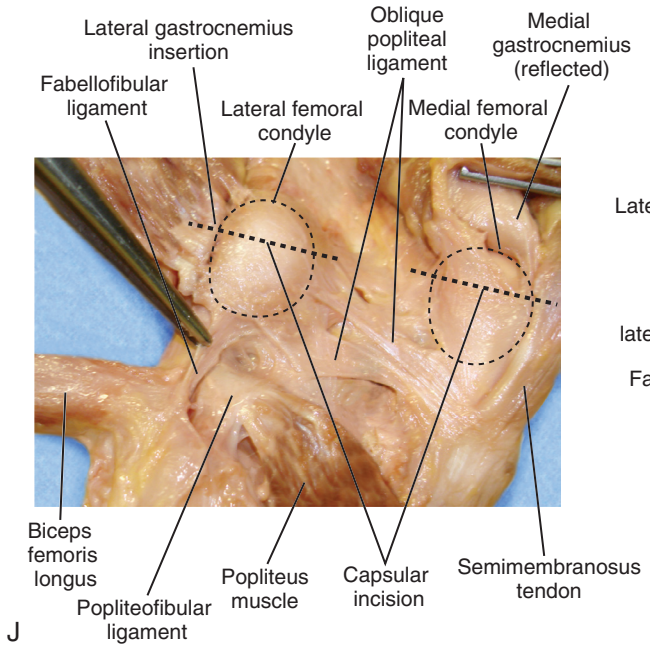


FIG 38-18, cont'd **F,** The posterolateral approach for a capsular release uses the same approach as that for a lateral meniscus repair (see Chapter 23) with a skin incision just distal to the joint line as shown. **G,** The posterolateral capsule anterior to the gastrocnemius tendon is identified. **H,** The posterolateral capsule is carefully incised under direct visualization to the edge of the lateral femoral condyle, avoiding the neurovascular structures. **I,** A finger is placed into the posteromedial and posterolateral incisions, and the central neurovascular structures can be palpated. The central posterior capsule anterior to the neurovascular structures is not released. The finger palpation confirms that the capsule directly posterior to the medial and lateral femoral condyles has been incised, removing this block to extension as the knee is extended.

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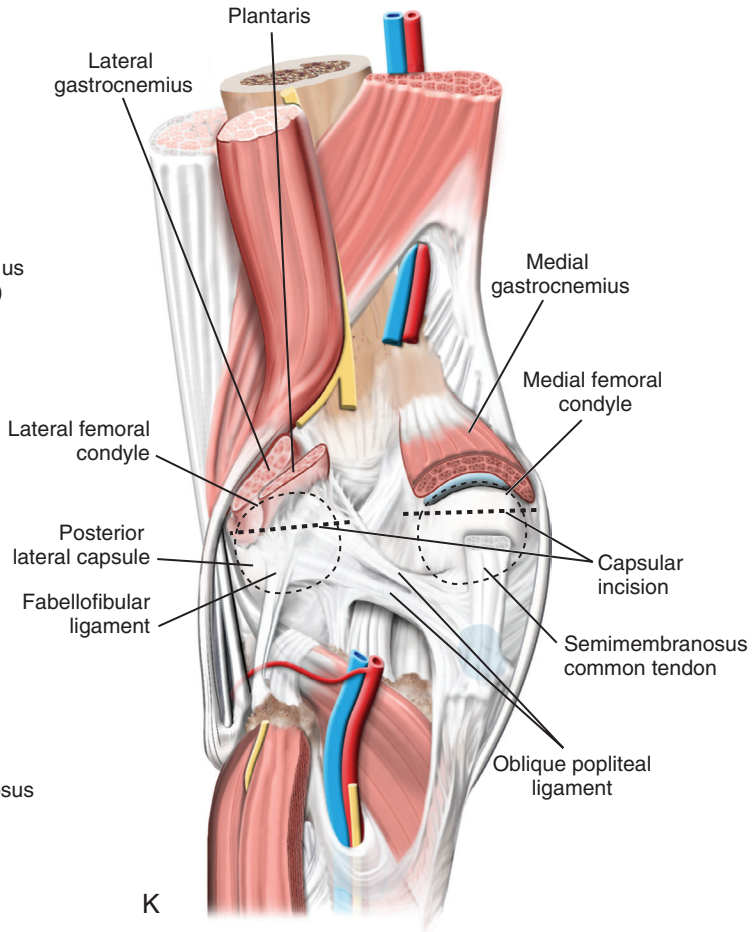


FIG 38-18, cont'd **J** and **K,** The posterior capsular releases. The remaining posterior capsular tissues are gently stretched with the overpressure program to achieve extension. This is a limited cosmetic approach that does not disturb other posterior soft tissues and removes only the contracted posterior capsule as shown by the *dotted line*. *LFC,* Lateral femoral condyle.

flexion, because this would involve a flexion manipulation by untrained personnel.

The overpressure extension (Fig. 38-19) and flexion (Fig. 38-20) exercises are described in Table 38-7. We recommend an active range of motion program performed by the patient instead of use of a continuous passive motion machine. As well, the patient should continue with leg lifts and isometric exercises while in the hospital. It is imperative to control soft tissue inflammation and avoid a hemarthrosis. If soft tissue swelling persists, or thigh muscle pain occurs owing to excessive stretching, a NSAID or steroidal dose pack should be considered. After the epidural, it is routine to obtain a venous ultrasound to exclude venous clot disease.

Upon completion of the inpatient program, the exercises must be continued at home eight times a day. Close supervision by the physical therapist is required because the gains in knee flexion and extension may be reduced rapidly if the regimen is not maintained or if pain and swelling prohibit the patient's ability to perform the exercises.

EXTENDED EPIDURAL FOR PAIN MANAGEMENT

The use of a tunneled epidural catheter in patients who require extended pain management has been described for a variety of diagnoses, including cancer, human immunodeficiency virus, complex regional pain syndrome (CRPS), and TKA.[5,6,29,68,69,148,175] Buvanedran and associates[29] demonstrated the efficacy and safety of placing a tunneled epidural catheter for an average of 49 ± 3 days in 47 patients who underwent knee procedures that were considered high risk for developing a knee motion complication. The procedures were TKA revision, arthroscopy to treat arthrofibrosis, or knee manipulation for arthrofibrosis after TKA. The fluoroscopic-placed catheters were used along with rigorous rehabilitation. There were significant improvements in pain and knee motion following the treatment program, and these improvements remained after removal of the epidural. There only two complications (leaks and disconnects) and no major side effects.

Hartman and coworkers[68] described the use of a tunneled epidural catheter in 9 of 35 patients who underwent revision TKA because of symptomatic knee joint arthrofibrosis that had extended neuraxial pain. Although these authors reported significant improvements in knee motion and the mean Knee Society score for the entire cohort, the results of these 9 patients were not provided separately. All patients except one improved both flexion and extension; however, 34% required additional procedures after the TKA because of continuing arthrofibrosis. The amount of time the catheters were used was not provided. Stanton-Hicks and associates[175] empirically noted that a tunneled epidural catheter was of value in children with CRPS and recommended a period of 4 to 6 weeks of usage along with physical therapy.

The most common complication with tunneled epidural catheters is infection; however, rates appear to vary according to diagnosis.



FIG 38-19 Inpatient extension overpressure exercises include hamstring stretching (**A**) and hanging weights (**B**).

TABLE 38-7 Inpatient Overpressure Extension and Flexion Program Exercises

Extension (Perform First, Before Flexion)

1. Determine weight to be used and pain limits before epidural is begun.
2. Use 15-20-25 lb of weight over the knee with the foot and ankle supported. Progress as tolerated.
3. Use lowest amount of weight to achieve 3 degrees of hyperextension at the third day.

Flexion

1. Perform release of contracted tissues that produce a hard stop to flexion before the overpressure program; protect patellofemoral joint. Expect soft stop to gradually release over 72 hours, producing significant gains in flexion.
2. Mark the affected heel height on the opposite thigh before the epidural is begun to determine the extent of contracture and starting point.
3. Limit the amount of flexion gained over the first 24 hours to prevent muscle and tissue tearing.
4. Perform patellar mobilizations to avoid patella overpressure with knee flexion.
5. Figure-four position in bed; place and hold strap or towel using approximately 15-20 lb of pull on the ankle. Monitor heel-thigh mark on the opposite thigh to determine the gain in flexion.
6. Perform flexion overpressure program every 30 min for 5 min while awake. Goal is to achieve heel height above patella.
7. Physician performs flexion overpressure test to determine whether soft or hard resistance is present and measures knee flexion angle daily.
8. Continue the overpressure program after discharge at home, eight times every 24 hours, using pain control to achieve flexion gained under the epidural.

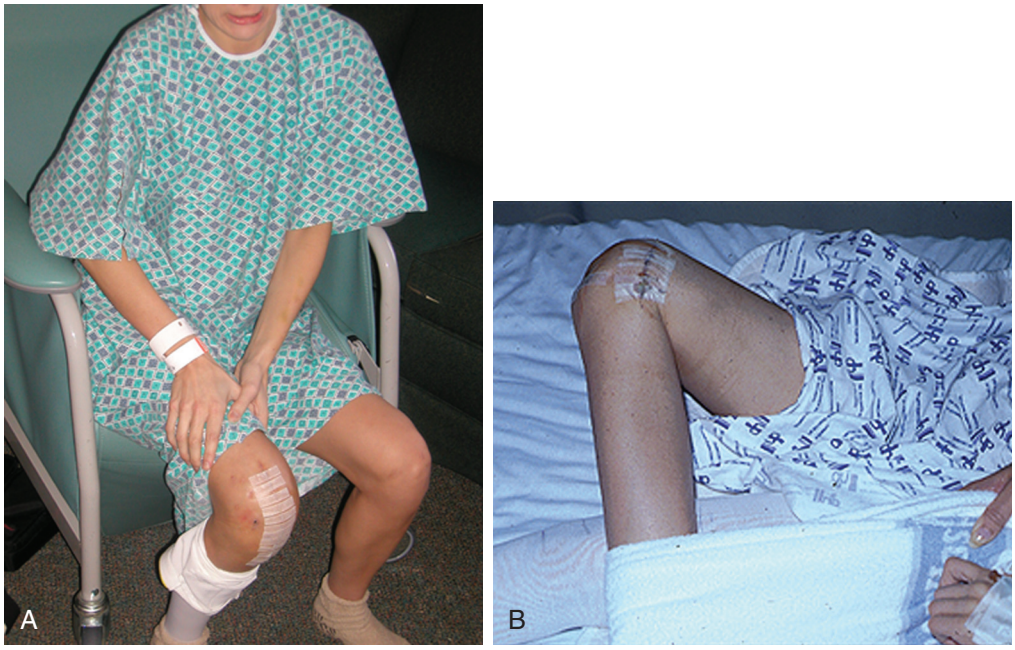


FIG 38-20 In-patient flexion overpressure exercises include rolling stool (**A**) and figure-four with a towel or strap in which the heel is brought up to a predetermined mark on the anterior thigh of the opposite extremity (**B**).

Ruppen and associates[148] conducted a metaanalysis of 12 studies (published between 1983 and 1998) that encompassed 4628 patients who had a catheter in place for at least 7 days. Data pooled from nine studies that focused on cancer patients produced a 2.8% rate of deep infection compared with a rate of 0.48% from three studies of noncancer or both noncancer and cancer (mixed) cohorts. Hayek and colleagues[69] reported on the use of 260 tunneled epidural catheters in 218 patients who had chronic noncancer regional pain, the majority of whom had CRPS. There were 24 epidural space infections; 22 of these patients had CRPS. The epidurals had been used between 11 and 130 days. In addition, 34 others had to be discontinued because of superficial infection or suspicion of infection. These authors reported a significantly increased incidence of infection in patients with neuropathic pain and somatic pain (most of which was adhesive capsulitis of the shoulder) of 24.4% and 6.7%, respectively ($P = .03$). Other potential side effects include numbness or weakness in the lower extremities, dizziness, and discomfort at the insertion site.

DEVELOPMENTAL PATELLA INFERA

The senior author has reported on the complication of developmental patella infera (Fig. 38-21) that occurs after major knee injury or surgery, secondary to contracture of peripatellar and infrapatellar scar tissues and quadriceps weakness.[129,130] This condition may result in permanent shortening of the patellar tendon, patellofemoral arthritis, and severe functional limitations. To prevent this problem, the steps previously described to prevent arthrofibrosis are taken before and after surgery. In addition, the patient is instructed preoperatively on the importance of achieving a voluntary quadriceps contraction as soon as possible after surgery, which is expected to occur by the second postoperative day. Patellar mobility is assessed weekly by the therapist to detect any early contracture. Serial lateral radiographs are taken to detect any decrease in patellar height for patients demonstrating limited patellar mobility or in whom an early arthrofibrotic response is detected (Fig. 38-22). The differences in criteria for determining the presence of patella infera according to published techniques are shown in Table 38-8.

For patients who present with an established patella infera, the treatment algorithm is shown in Figure 38-23. The first principle of treatment is the preoperative preparation of the patient to establish quadriceps muscle function, rehabilitation, and training to avoid a quadriceps shutdown after the surgical procedure. Second, to remove the contracted and scarred tissues either by arthroscopic or open surgery, as already discussed. A number of months of intensive therapy

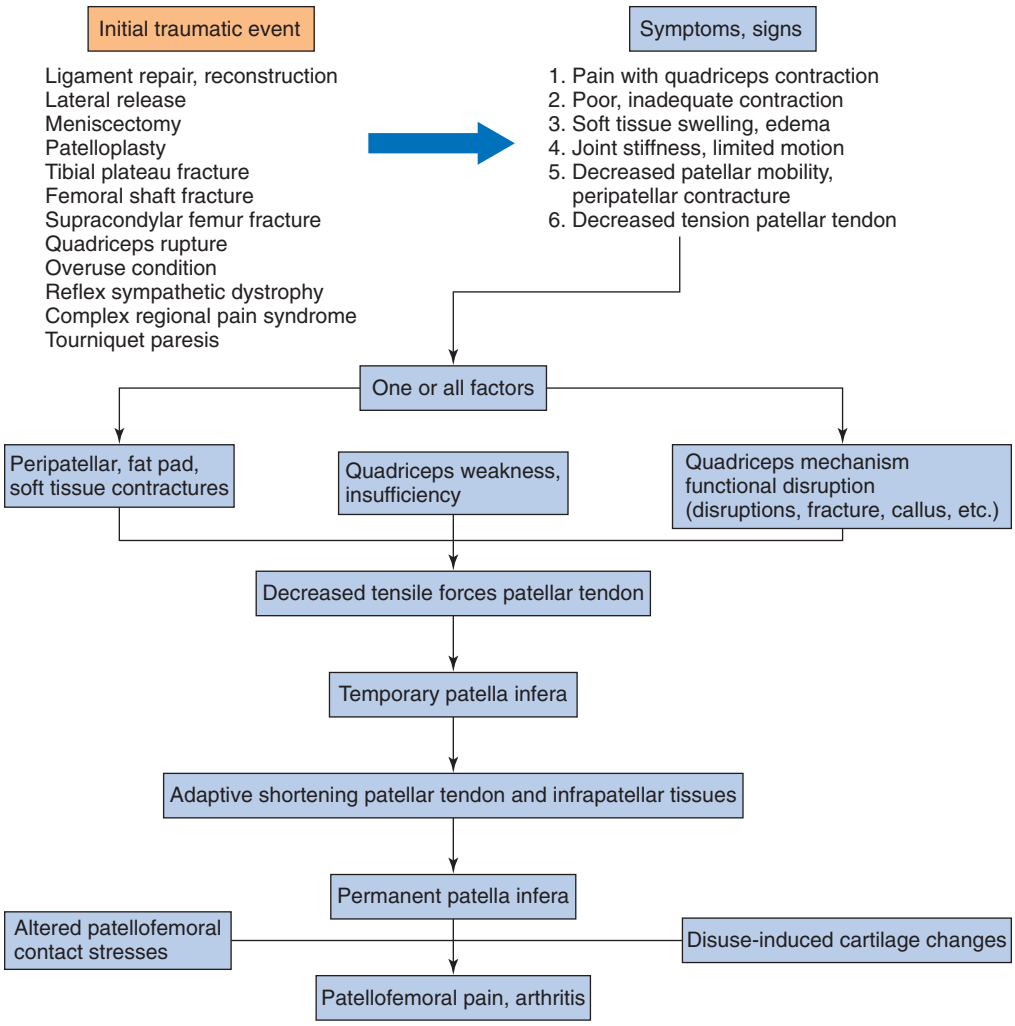


FIG 38-21 Pathomechanics for developmental patella infera, quadriceps insufficiency, patellar tendon shortening, and arthritis. (From Noyes FR, Wojtys EM, Marshall MT. The early diagnosis and treatment of developmental patella infera syndrome. *Clin Orthop.* 1991;265:241-252.)

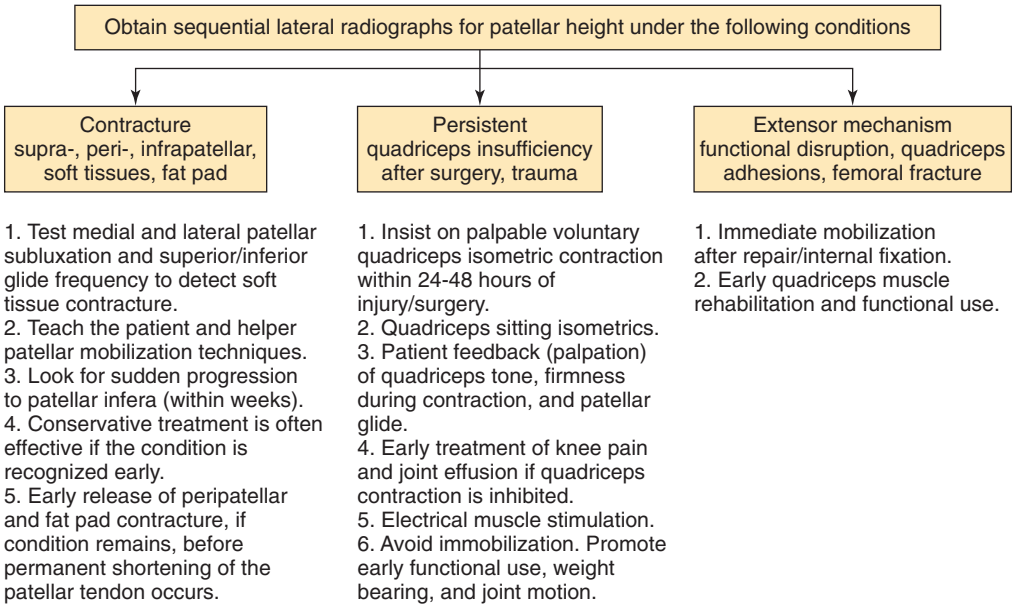


FIG 38-22 Treatment recommendations for avoiding developmental patella infera syndrome. (From Noyes FR, Wojtys EM, Marshall MT. The early diagnosis and treatment of developmental patella infera syndrome. *Clin Orthop.* 1991;265:241-252.)

TABLE 38-8 Published Values for Patellar Height: Normal, Alta, Infera

Study	Technique Source	Normal Mean ± SD (Range)	Alta	Infera
Insall & Salvati[77a] (1971)	Authors' own	1.02 ± 0.13 (0.7-1.3)	>1.2	<0.8
Blackburne & Peel[17] (1977)	Authors' own	0.8 ± 0.13 (0.54-1.06)	>1.2	<0.5
Caton et al[31] (1982)	Authors' own	<1.2	>1.2	≤0.6
Linclau[90] (1984)	Caton et al	1.0 ± 0.08 (0.84-1.16)	>1.2	<0.8
	Blackburne & Peel	0.8 ± 0.10 (0.61-1.01)	>1.0	<0.6
Noyes et al[130] (1991)	Caton et al	1.04 ± 0.13 (0.75-1.36)	NA	≥15%*
	Blackburne & Peel	0.84 ± 0.14 (0.61-1.33)	NA	≥14%*
	Insall & Salvati	1.05 ± 0.11 (0.86-1.28)	NA	≥11%*

*Decrease in patellar height between the involved and the contralateral knee.
NA, Not available; *SD,* standard deviation.

is then required. The final functional limitations are based on residual motion deficits and joint arthritis that are present. A majority of patients with established patella infera have functional limitations.[130] These patients do not desire any further surgery and are willing to live with these limitations, understanding that an eventual arthroplasty procedure may be required. A small percentage of patients with a remaining patella infera and minimal patellofemoral arthritis who have symptoms of anterior knee pain and stiffness may be candidates for restoration of a normal patellotrochlear relationship.

CRITICAL POINTS Developmental Patella Infera

- Occurs secondary to contracture of peripatellar and infrapatellar scar tissues and quadriceps weakness
- May result in permanent shortening of the patellar tendon, patellofemoral arthritis, and severe functional limitations
- Prevention: voluntary quadriceps contraction by second postoperative day, knee motion, patellar mobilization
- Serial lateral radiographs to measure patellar height in patients with limited patellar mobility; early arthrofibrotic response detected
- Treatment established patella infera: preoperative muscle strengthening, rehabilitation. Operative removal contracted and scarred tissues.
- Final functional limitations based on residual motion deficits, joint arthritis

OUR CLINICAL STUDIES

Two studies were conducted to determine the effectiveness of the postoperative rehabilitation program and early diagnosis and treatment of knee motion limitations after ACL reconstruction in preventing arthrofibrosis. In the first study,[126] a group of 207 knees that underwent an ACL bone-patellar tendon-bone (B-PT-B) allograft reconstruction were followed for at least 1 year postoperatively to determine the final amount of knee flexion and extension obtained and document the necessity of treatment interventions. Sixty-nine patients received the operation for an acute ACL rupture and 138 for chronic ACL deficiency. Of the 207 knees, 90 had the ACL reconstruction alone, 52 had a concurrent iliotibial band extra-articular procedure, 52 had a concurrent meniscus repair, and 13 had a concurrent MCL repair.

The investigation found that 189 of the knees (91%) regained normal motion without requiring additional treatment intervention. The remaining 18 required extension casting, gentle manipulation under anesthesia, or (in only three knees) arthroscopic debridement and lysis of adhesions (Table 38-9). There was a correlation among

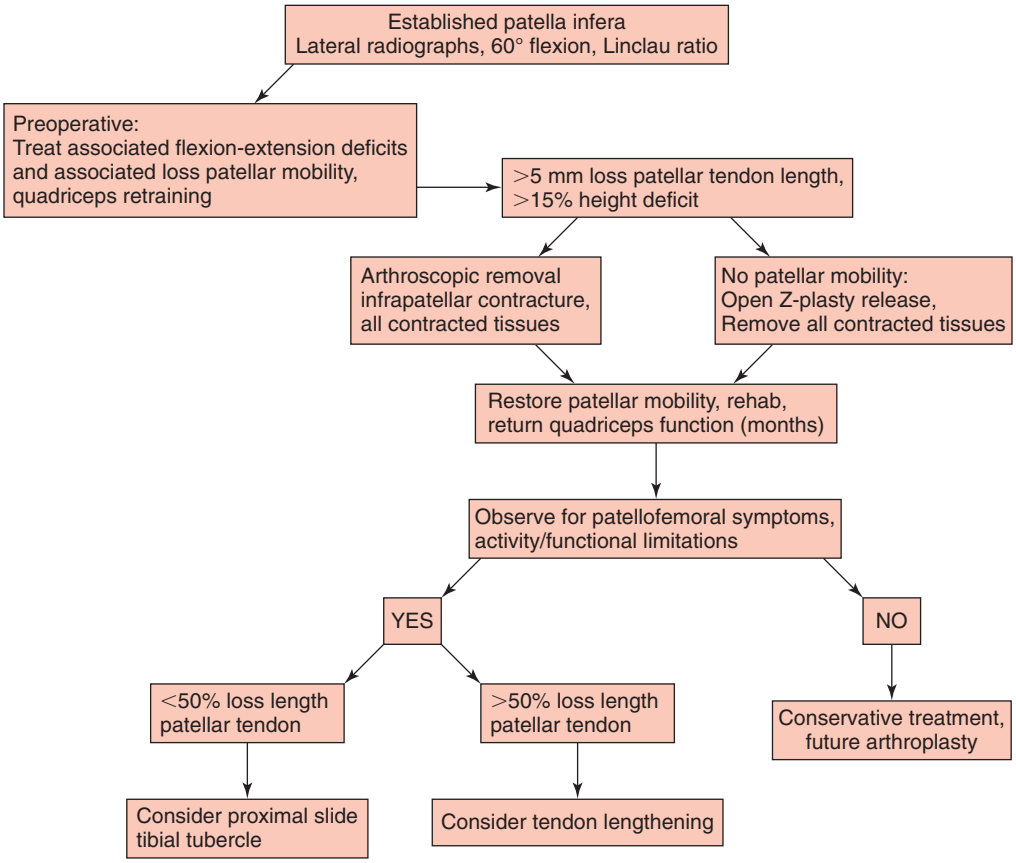


FIG 38-23 Treatment algorithm for established patella infera.

TABLE 38-9 Patients Requiring Treatment Intervention for Knee Motion Limitations After ACL Allograft Reconstruction

Case	Additional Procedures at ACL Reconstruction	Extension Casting	Gentle Manipulation Under Anesthesia	Arthroscopic Debridement
1	Meniscus repair, EA	Yes	Yes	
2	None	Yes	Yes	
3	Meniscus repair	Yes	Yes	
4	Meniscus repair	Yes	Yes	
5	MCL repair		Yes (×2)	Yes
6	EA	Yes		
7	Meniscus repair		Yes	
8	None	Yes		
9	Meniscus repair, EA		Yes	
10	Meniscus repair	Yes		
11	Meniscus repair	Yes		
12	None	Yes		
13	EA		Yes	
14	MCL repair		Yes	
15	Meniscus repair	Yes		
16	Meniscus repair, EA	Yes	Yes	
17	MCL repair, meniscus repair	Yes	Yes	Yes
18	None		Yes	Yes

ACL, Anterior cruciate ligament; *EA*, iliotibial band extraarticular procedure; *MCL*, medial collateral ligament.

TABLE 38-10 Results of Arthroscopic Debridement for Arthrofibrosis After ACL Allograft Reconstruction

Case	Week Release Performed After ACL Reconstruction	ROM Before Release (Degrees)	ROM After Release (Degrees)	Week Manipulation Performed After Release	Complications, Final Outcome
5	9	5-80	5-100	12, 16	Knee infection: open drainage; patella infera because of noncompliance with rehabilitation program
17	32	10-90	5-105	None	Continued contracture owing to noncompliance with rehabilitation program
18	7	8-89	0-100	9	Achieved full knee motion

ACL, Anterior cruciate ligament; *ROM*, range of motion.

concurrent procedures and the incidence of patients requiring additional treatment because 4% in the ACL alone subgroup, 10% in the iliotibial band extraarticular subgroup, 12% in the meniscus repair subgroup, and 23% in the MCL subgroup required intervention. The timing of surgery had no effect on the necessity for treatment intervention.

Extension casts were applied to 6 knees between 4 and 12 weeks postoperatively, and all regained normal extension. A gentle manipulation under anesthesia was performed in 9 knees between 3 and 13 weeks postoperatively. All achieved full flexion, and all but two achieved full extension; two knees lacked 5 degrees of extension at follow-up. Arthroscopic debridement was done in three knees; the details and results are shown in Table 38-10. At follow-up, full knee motion was present in 98%, 1% had a 5 degree limitation of extension, and 1% had a permanent contracture.

We conducted a second study[125] comprising 443 knees that underwent ACL B-PT-B autograft reconstruction. The operations were performed for acute/subacute ACL ruptures in 161 patients and for chronic ruptures in 283 patients. All were followed for an average of 2.1 years (range, 1-7.2 years) postoperatively. Concurrent procedures done in 224 knees included meniscus repairs in 194 knees, proximal advancement of the posterolateral structures in 32 knees, an autograft reconstruction of the fibular collateral ligament (FCL) in 4 knees, a repair or reconstruction of the MCL in 9 knees, and a proximal patellar realignment in 17 knees.

No correlation existed between concurrent procedures and the incidence of patients requiring addition treatment in this study. The percentages of patients requiring additional treatment intervention were 6% in the ACL alone subgroup, 5% in the FCL reconstruction/posterolateral advancement subgroup, 8% in the meniscus repair subgroup, 18% in the proximal patellar realignment subgroup, and 22% in the MCL subgroup. The timing of surgery had no effect on the necessity for treatment intervention.

The investigation found that 98% of the knees regained normal motion, and 2% had mild losses of extension of 5 degrees. In 23 knees, treatment intervention was required (Table 38-11), which was successful in treating the limitation of knee flexion or extension (Table 38-12). The 2% (seven knees) that had mild losses of extension refused treatment intervention.

Extension casts were applied to nine knees an average of 13 weeks postoperatively. All of these knees regained normal extension. A gentle manipulation under anesthesia was performed in nine knees a mean of 6.4 weeks postoperatively, and all achieved full knee flexion. Arthroscopic debridement was done in three knees, which also successfully restored normal knee motion. There was no statistically significant increased risk for knee motion problems for six variables studied, including gender, injury chronicity, condition of the articular cartilage at reconstruction, location of physical therapy, whether or not prior surgery had been performed, and whether or not a prior ACL reconstruction had been performed.

CRITICAL POINTS Our Clinical Studies

Study 1

- *n* = 207 knees ACL B-PT-B allograft reconstruction followed at least 1 year postoperatively.
- 189 (91%) regained normal motion without additional treatment intervention:
  - 6 extension casting
  - 9 gentle manipulation under anesthesia
  - 3 arthroscopic debridement and lysis of adhesions
- Correlation concurrent procedures and incidence of patients requiring treatment:
  - 4% ACL alone
  - 10% ACL + iliotibial band extra-articular
  - 12% ACL + meniscus repair
  - 23% ACL + MCL
- At follow-up, full knee motion was present in 98%, 1% had a 5 degrees limitation of extension, 1% had a permanent contracture.

Study 2

- *n* = 443 knees ACL B-PT-B autograft reconstruction followed mean 2.1 years (range, 1-7.2 years) postoperatively.
- Treatment intervention required 23 knees, all successfully resolved.
- Concurrent procedures and incidence of patients requiring treatment:
  - 6% ACL alone
  - 5% ACL + FCL reconstruction/posterolateral advancement
  - 8% ACL + meniscus repair
  - 18% ACL + proximal patellar realignment
  - 22% ACL + MCL
- 98% regained normal motion, and 2% (refused additional treatment) had mild losses of extension of 5 degrees.

TABLE 38-11 Patients Requiring Treatment Intervention for Knee Motion Limitations After ACL B-PT-B Autograft Reconstruction

Case	Additional Procedures at ACL Reconstruction	Steroid Dose Pack	Extension Casting	Epidural, Inpatient Physical Therapy	Gentle Manipulation Under Anesthesia	Arthroscopic Debridement
1	None	Yes	Yes			
2	None		Yes			
3	None		Yes			
4	Meniscus repair		Yes			
5	Meniscus repair		Yes			
6	MCL reconstruction		Yes			
7	Meniscus repair		Yes			
8	Advance PLS		Yes			
9	None	Yes	Yes			
10	Meniscus repair		Yes	Yes	Yes	
11	None	Yes	Yes		Yes	
12	Advance PLS, meniscus repair	Yes	Yes	Yes	Yes	
13	Meniscus repair, PR				Yes	
14	None	Yes			Yes	
15	PR				Yes	
16	PR	Yes			Yes	
17	Meniscus repair				Yes	
18	Meniscus repair				Yes	
19	Meniscus repair	Yes	Yes	Yes	Yes	Yes
20	MCL, meniscus repair			Yes	Yes	Yes
21	Meniscus repair	Yes				Yes
22	None			Yes		
23	None			Yes		

ACL, Anterior cruciate ligament; B-PT-B, bone-patellar tendon-bone; *MCL*, medial collateral ligament; *PLS*, posterolateral structures; *PR*, proximal realignment.

TABLE 38-12 Results of Treatment Intervention

Case	Treatment Intervention	Weeks Postoperative Intervention Applied	ROM Before Treatment (Degrees)*	ROM After Treatment*	Weeks Postoperative Full ROM Achieved
1	Extension cast	8, 15, 16	–7 (extension loss)	0/0/157	18
2	Extension cast	6, 28, 45	–5 (extension loss)	0/0/142	46
3	Extension cast	7	–3 (extension loss)	0/0/140	16
4	Extension cast	30	–3 (extension loss)	0/0/144	35
5	Extension cast	3	–7 (extension loss)	5/0/152	10
6	Extension cast	20	–3 (extension loss)	0/0/140	22
7	Extension cast	15	–5 (extension loss)	1/0/148	19
8	Extension cast	12, 36	–3 (extension loss)	5/0/146	48
9	Extension cast	20	–5 (extension loss)	0/0/137	23
10	Manipulation	7	0/–3/110	0/0/136	13
11	Manipulation	5	0/–3/95	0/0/142	12
12	Manipulation	7	0/–5/110	2/0/138	22
13	Manipulation	6	0/0/90	0/0/140	9
14	Manipulation	12	0/–3/118	5/0/140	18
15	Manipulation	4	0/0/97	0/0/136	6
16	Manipulation	5	0/0/96	0/0/147	9
17	Manipulation	5	0/–5/60	0/0/141	22
18	Manipulation	7	0/0/73	0/0/135	19
19	Scope, release	7	0/–10/121	0/0/140	17
20	Scope, release	14	0/0/90	10/0/126†	NA‡
21	Scope, release	10	0/0/126	0/0/135	16
22	Inpatient rehabilitation	48	0/–20/120	3/0/138	48
23	Epidural	20	0/–3/115	0/0/137	NA‡

*Values are for passive hyperextension/zero point/flexion.
†Equal to the opposite normal knee.
‡Not available, patient lived out of town, but full at the 2-yr follow-up evaluation.
NA, Not available; *ROM,* range of motion.

The data from the two investigations on 650 knees showed that 6% of the patients required and agreed to treatment intervention for a knee motion problem. At the final follow-up evaluation, 2% lacked normal knee motion (nine knees lacked 5 degrees of extension and two had permanent contractures). An extension cast was applied in 2%, gentle manipulation under anesthesia was done in 3%, and arthroscopic debridement was performed in fewer than 1%. The percentages of all 650 knees requiring additional treatment intervention were 5% in the ACL alone subgroup, 5% in the FCL reconstruction/posterolateral advancement subgroup, 10% in the meniscus repair subgroup, 10% in the extraarticular subgroup, 18% in the proximal patellar realignment subgroup, and 23% in the MCL subgroup.

OTHER AUTHORS' CLINICAL STUDIES

Several authors have reported on the outcome of the treatment of arthrofibrosis following ACL reconstruction, as well as other procedures and injuries (Table 38-13). These studies help identify risk factors for a limitation of knee motion discussed previously, including a delay in initiating treatment, performing acute knee ligament reconstruction or multiple ligament reconstructions, and use of immobilization after surgery. Although authors usually reported that significant gains were obtained in knee motion, most found that the many patients had permanent losses of flexion and/or extension and had more complaints of pain and limitations compared with patients who did not have this complication.

TABLE 38-13 Clinical Studies Treatment of Arthrofibrosis

Study	*N*	Follow-up (yr)	Causes, Incidence Rate	Pretreatment ROM (Degrees)	Mean Time to Treatment	Treatment	Post-Treatment ROM (Degrees)	Comments
Said et al[150] (2011)	27	Mean 4.2 (range, 1.6-6.1)	Knee ligament reconstructions	Flexion mean 94 ± 28; extension loss mean –5 ± 6	4 mo (range, 1-32 mo)	Manipulation (14) or arthroscopic release (13) (4+ posterior capsular release)	Flexion mean 132 (100-155); extension loss mean 1 (range, –2 to 3)	Predictors of poor outcome: >6 mo from reconstruction to surgical release, global arthrofibrosis
Vander Have et al[184] (2010)	32	Range 0.5-2	Displaced tibial eminence fracture in children (aged 8.4-16.3 yr) with open growth plates treated with reduction and internal fixation	Flexion loss mean 60 (range, 20-90); extension loss mean 20 (range, 10-40)	20 wk (range, 18-24 wk)	Arthroscopic debridement (24) or manipulation (8)	29 patients motion within 5 of opposite knee, 3 patients loss extension	Manipulation alone not recommended; 3 patients distal femoral fractures and growth arrest
Biggs-Kinzer et al[16] (2010)	33	Mean 1.2	ACL reconstruction in 27, other surgery in 6	Involved knee mean 0/8/117, opposite knee mean 5/0/147	Not provided	Arthroscopic debridement, postoperative protocol beginning day of surgery to regain flexion	26 patients normal/nearly normal, 3 abnormal, 4 several abnormal	3 patients patella infera; IKDC Subjective Knee scores significantly better in knees with normal motion
Bonutti et al[19] (2008)	41	Mean 1 (range, 0.5-2)	Knee arthroplasty in 21, cruciate injury or reconstruction in 9, distal femur fracture in 2, multiple operations in 9	Flexion mean 84 (range, 30-110), extension loss mean –15 (range, –65 to –3)	17 wk (range, 6-57 wk)	Static progressive stretch with JAS Knee Device for mean 9 wk (range, 3-27 wk)	Flexion 108 (range, 65-135), extension mean loss –6 (range, –45 to 0)	Mean total gain 33 arc of motion; 93% satisfied with device
Rue et al[147] (2008)	23	Mean 0.8 (range, 0.3-2)	ACL reconstruction	Flexion deficit mean 31 (range, –2 to 55)	6.1 wk (range, 4-12 wk)	Single Medrol Dosepak	Mean flexion improved mean 29 (range, 0-60)	5 treatment failures, no complications; return to normal motion in 78%
Wang et al[187] (2006)	22	Mean: 3.7 (range, 2-5.2)	Fracture in 20 (17 treated with ORIF, 2 external fixators, 1 dynamic hip screw), ACL reconstruction in 2	Flexion mean 27 (range, 5-45); 2 patients loss extension (range, 5-10)	2.9 yr (range, 0.3-11.5 yr)	Mini-open and arthroscopic debridement in all, quadriceps tendon lengthening in 16, CPM	Flexion mean 115 (range, 75-150) 3 patients loss extension (range, 5-15)	All but 1 satisfied with outcome

Continued

TABLE 38-13 Clinical Studies Treatment of Arthrofibrosis—cont'd

Study	N	Follow-up (yr)	Causes, Incidence Rate	Pretreatment ROM (Degrees)	Mean Time to Treatment	Treatment	Post-Treatment ROM (Degrees)	Comments
Mayr et al[101] (2004)	223	Mean 4.3	ACL reconstruction	Extension loss: <3: 12.1% 3-5: 25.5% 6-10: 26.1% >10: 35.7%	1.5 yr	Scope, debridement	Extension loss: <3: 63.7% 3-5: 26.8% 6-10: 5.1% >10 3.2% Mean flexion 127	88% x-ray signs DJD. Risk factors: acute ACL reconstruction, preoperative irritated knee (swelling, effusion, hyperthermia), limited motion before ACL reconstruction
Millett et al[107] (1999)	8	Mean 4.7 (range, 0.7-9.4)	ACL reconstruction in 4, multiligament reconstruction in 3, meniscectomy post septic arthritis in 1	Mean extension 18.7 (range, 15-20), mean flexion 81 (range, 40-130)	1 yr (range, .5-1.6 yr)	Open debridement, soft tissue release, CPM, custom drop-lock extension brace	Mean extension 1.25 (range, 0-5), mean flexion 125 (range, 110-145)	Risk factors: acute ACL reconstruction, multiligament reconstruction. Seven had prior scope/ debridement that failed. All salvage knees.
Reider et al[143] (1996)	11	Mean 1.8 (range, 0.7-5.6)	ACL reconstruction	Extension loss mean 19.6 (range, 7-35)	1 yr (range, 0.5-3.2 yr)	Scope, debridement	Mean loss extension 2 (range, 0-6)	All patients immobilized in flexion for mean 6 wk after ACL reconstruction. No cases of patella infera.
Lobenhoffer, et al[92] (1996)	21	Mean 1.5 (range, 0.5-3.1)	Ligament reconstruction in 58%, fractures in 30%, infection in 12%	Extension loss mean 17 (range, 10-30)	0.5-7 yr	Scope, open posterior capsulotomy	Mean loss extension 2 (range, 0-5)	All chronic, all had at least 1 prior arthroscopic debridement that failed
Shelbourne et al[163] (1996)	72	Mean 2.9 (range, 2.3-9.6)	ACL reconstruction	5/0/143 (range, 0/0/130 to 10/5/156)	12.5 mo (range, 2.4-60 mo)	Scope, debridement, removal ACL graft if required, extension cast for types 2, 3, 4 arthrofibrosis	*Full extension:* Type 1: 88% Type 2: 81% Type 3: 80% Type 4: 69% *Full flexion:* Types 1 and 2: 100% Type 3: 53% Type 4: 19%	Arthrofibrosis defined as any symptomatic limitation in knee motion compared with opposite knee

ACL, Anterior cruciate ligament; *CPM*, continuous passive motion; *DJD*, degenerative joint disease; *IKDC*, International Knee Documentations Committee; *ORIF*, open reduction internal fixation.

ILLUSTRATIVE CASES

Case 1 A 42-year-old woman presented 7 months after an open reduction internal fixation of a patellar fracture and 4 weeks of immobilization with a severe patella infera, marked by a Linclau ratio of 60% of the left knee (compared with 97% on the opposite knee, Fig. 38-24, *A*). She complained of muscle weakness, pain, and limitations with activities of daily living. She had a range of motion of 0/10/95 degrees and a significant decrease in patellar mobility in both medial-lateral and superior-inferior directions. Physical examination showed an obvious patella infera, with mild patellofemoral crepitus. An isokinetic evaluation revealed a 75% deficit in quadriceps peak torque compared with the contralateral side. She underwent 2 months of rehabilitation because of this severe quadriceps muscle weakness.

The patient was then treated with an open release of scar tissue, which completely obliterated the suprapatellar pouch. Dense scar was

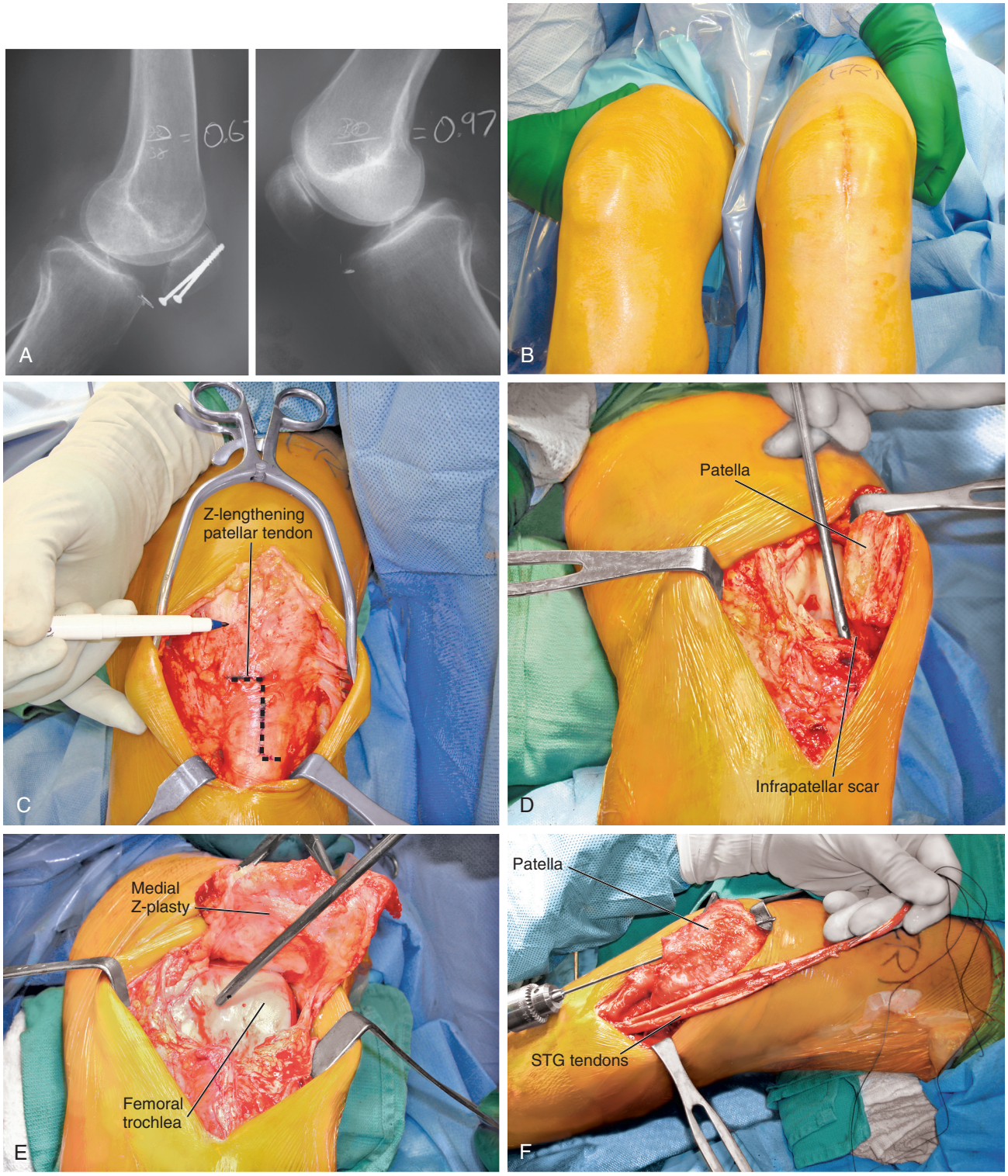


FIG 38-24 Case 1. **A,** Preoperative lateral radiographs demonstrate patella infera. **B,** Preoperative appearance of the left knee. The skin mobility was sufficient and did not contraindicate surgery. **C,** The line for the incision of the Z-plasty lengthening of the patient's patellar tendon. **D,** Extensive resection of infrapatellar scar tissue was required. **E,** Appearance of the femoral trochlea shows intact articular cartilage. An extensive medial Z-plasty release was performed. **F,** Placement of a central patellar tunnel for later passage of semitendinosus and gracilis (STG) tendons from a distal-to-proximal direction. *Continued*

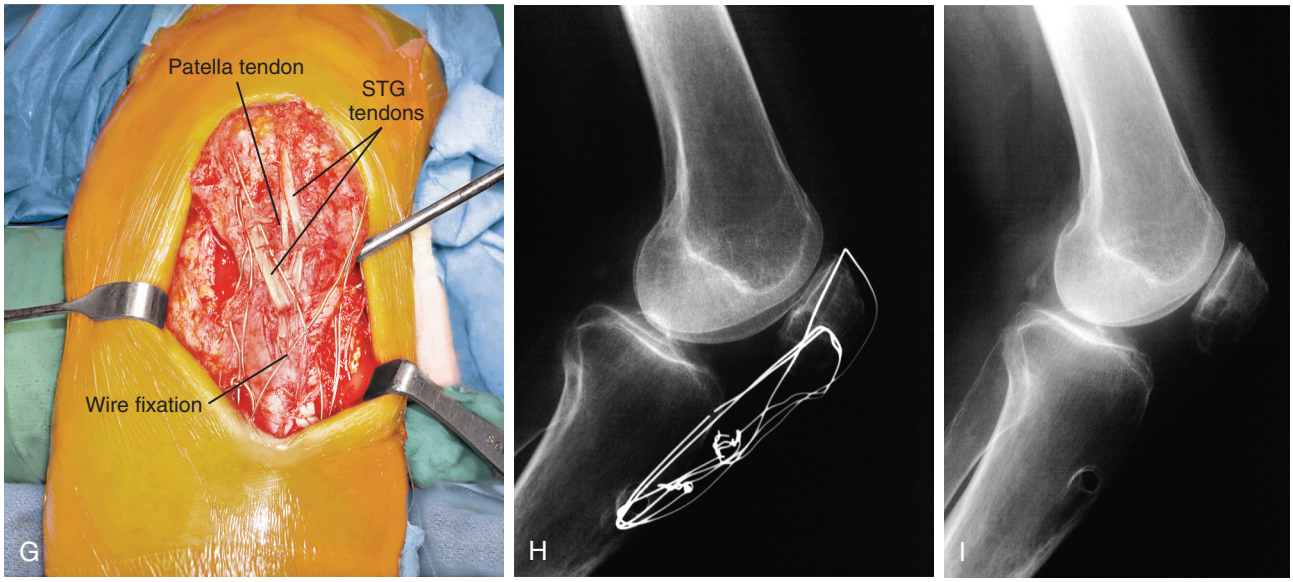


FIG 38-24, cont'd **G,** Final appearance of patellar tendon reconstruction. The patient's patellar tendon was reapproximated after the Z-plasty lengthening. The STG tendons were passed from the inferior to the superior pole and brought distally along the medial retinaculum to further augment the medial portion of the patellar tendon. In this case, the advantage of using the patient's own patellar tendon added significant soft tissues so that further augmentation was not required. **H,** Postoperative radiograph shows three internal fixation wires that provide stabilization and allow immediate range of motion. **I,** Radiograph shows restoration of normal patellar height after removal of internal fixation wires. The patient was asymptomatic with activities of daily living and able to perform light recreational activities. The final range of motion was normal (0/0/135 degrees).

present in the medial and lateral gutters, the medial and lateral joint lines, and intercondylar notch. After the procedure, the patient underwent 3 days of inpatient physical therapy on the epidural overpressure program described previously. Her knee motion improved to 0/0/100 degrees.

Two months later, the patient continued to have symptoms and minimal improvement. Therefore, the decision was reached to perform a patellar lengthening procedure. Figures 38-24, *B* to *G* demonstrate the tendon lengthening. A Z-plasty lengthening of the patient's patellar tendon was performed along with an augmentation using a four-strand semitendinosus-gracilis autograft. Internal fixation with wire was used to initiate immediate knee motion. The procedure was successful in restoring a normal patellar height (Fig. 38-24, *H* and *I*). The goal was to buy time until the patient eventually requires a patellofemoral arthroplasty, which is possible with normal patellar height.

Case 2 A 33-year-old woman presented with severe patellar infera (Linclau ratio, 29%) 4 months after resection of a ganglion cyst, which was growing under her patellar tendon. A portion of the patellar tendon was damaged in the procedure, and the patient was treated with 5 weeks of plaster immobilization, which resulted in severe quadriceps atrophy and severely contracted peripatellar and joint soft tissues. This represented a salvage knee condition because the patient had significant loss of function of the lower extremity. The range of motion was 0/10/75 degrees. She underwent 6 weeks of intense preoperative rehabilitation for muscle strengthening and then a skin expansion procedure (Fig. 38-25, *A* and *B*). Because this patient had no remaining patellar tendon to use in a Z-plasty fashion to incorporate into the reconstruction, she underwent a combined allograft-autograft patellar tendon lengthening procedure (see Fig. 38-25, *C* to *G*). The patient required intensive rehabilitation for 6 months.

At the most recent follow-up evaluation, 2 years postoperatively, the patient had equal Linclau ratios of 85% (see Fig. 38-25, *H* and *I*) and a range of motion of 0 to 120 degrees. She has no symptoms with activities of daily living or swimming and, although pleased with her condition, realizes that in the future a patellofemoral arthroplasty may be required.

Our comments: The salvage procedure of lengthening the patellar tendon was performed in this young patient to buy time before an anticipated total knee replacement. The benefit of reestablishing the normal patellar height (see Fig. 38-25, *H* and *I*) allowed a return of moderate lower limb function, with the added benefit at the time of the total joint procedure of retaining patellofemoral joint function.

Case 3 A 42-year-old woman sustained an acute anterior cruciate ligament rupture to the right knee, which was treated 4 weeks later with an anterior tibialis allograft reconstruction. Before surgery, the patient had achieved 0/0/100 degrees of knee motion. Postoperatively, she experienced significant problems with quadriceps muscle atrophy and failed to gain more than 100 degrees of knee flexion. A manipulation under anesthesia was performed 2 months postoperatively in which 0/0/120 degrees was achieved; however, the patient gradually reverted back to 0/0/90 degrees of motion.

The patient presented to our center 5 months after surgery with complaints of stiffness, tightness, failure to achieve more than 90 degrees knee flexion, and a flexed knee gait. On physical examination, she had a stable knee with negative Lachman and pivot shift test results. There was significant muscle atrophy, and the patient was unable to actively perform an isometric quadriceps contraction. She ambulated with limited knee flexion. The patellofemoral joint was markedly restricted, with no medial or lateral glide and an obvious patella infra position.

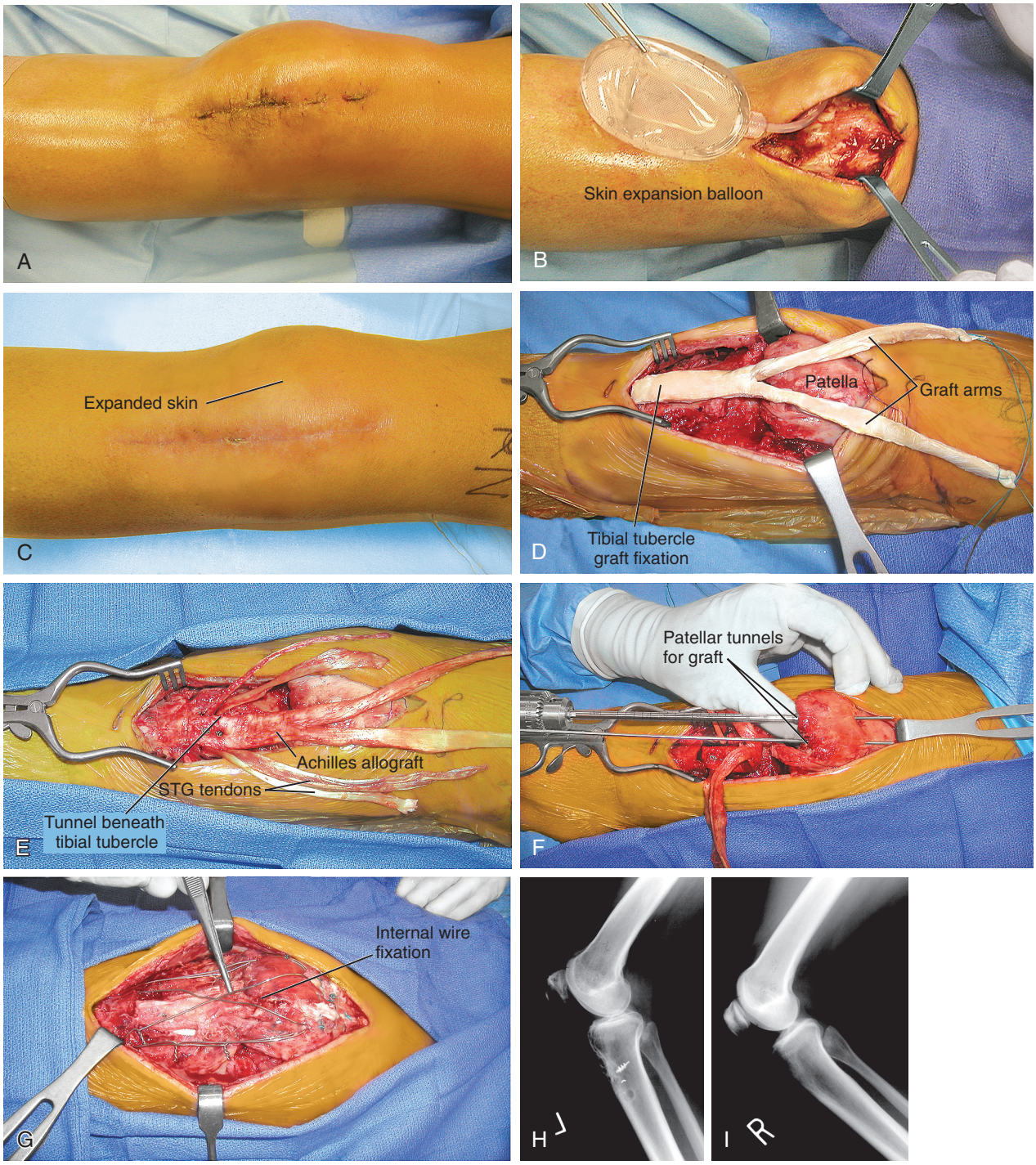


FIG 38-25 Case 2. **A,** Preoperative appearance of skin contracture. It is necessary to obtain more normal skin and soft tissue before the patellar tendon–lengthening procedure. Otherwise, there would be an increased risk of a complication of skin breakdown and infection. **B,** Placement of the skin expansion system at surgery. The expansion system may be placed either through the prior incision or through limited medial and lateral incisions using two balloons to avoid the primary incision. **C,** Appearance of expanded skin over the anterior aspect of the knee joint after 4 weeks of skin expansion. The balloon was removed through a small incision before the operative procedure. Extra redundant skin and subcutaneous tissue is shown, and a scar revision was performed. **D,** Operative photograph shows an Achilles tendon allograft for reconstruction of the patellar tendon. The bone portion of the graft is fixated at the tibial tubercle. The two arms of the graft are placed through separate patellar tunnels and sewn into the quadriceps tendon proximally. **E,** A semitendinosus and gracilis autograft harvest is performed. The tendons are passed beneath the tibial tubercle and the Achilles tendon–bone allograft. **F,** Placement of two patellar tunnels. **G,** Final tendon-lengthening construct. The Achilles tendon has been secured both proximally and distally. The semitendinosus-gracilis autograft tendons are placed through the proximal tibia adjacent to the tibial tubercle. Both tendon arms are passed medially and laterally and secured to the peripatellar tissues to augment the allograft tendon reconstruction. Two wire loops are placed through the tibial tubercle to the midpoint of the patella. A third wire is crossed from the tibial tubercle over the superior portion of the patella and passed beneath the quadriceps tendon patella insertion as a tension band. The height of the patella is adjusted to the normal opposite side using intraoperative fluoroscopy. **H** and **I,** Postoperative lateral radiographs of both knees show retention of the normal height of the patella in the left knee (**H**) compared with the right knee (**I**).

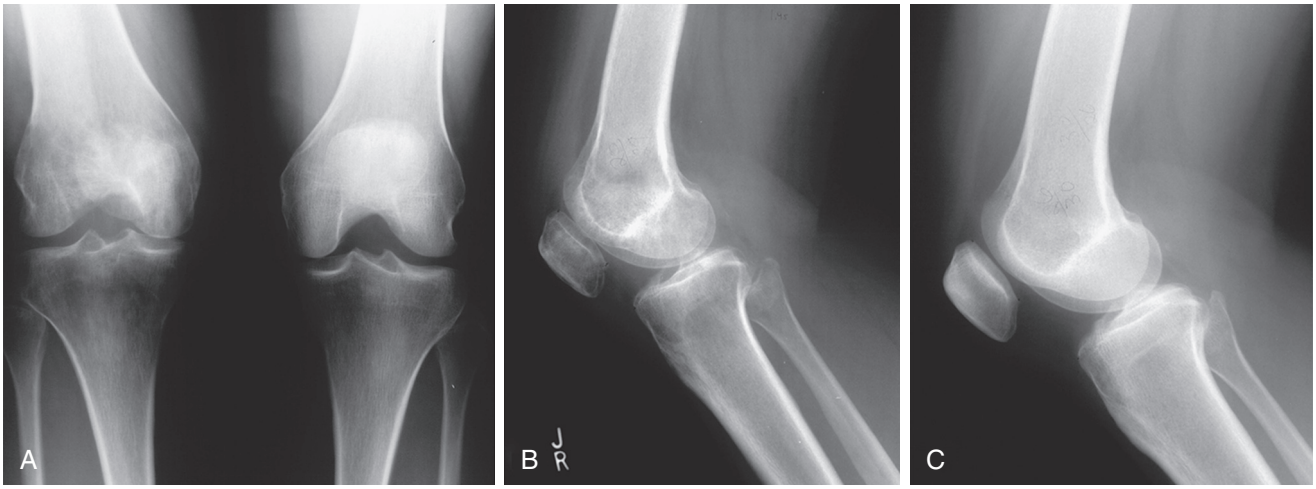


FIG 38-26 Case 3.

Standing posteroanterior radiographs showed a decrease in the height of the patella and osteopenia (Fig. 38-26, *A*). Lateral radiographs with the knee flexed showed an obvious patella infra, with a 68% Linclau ratio on the involved side see (Fig. 38-26, *B*) compared with the opposite side of 87% (see Fig. 38-26, *C*). The patient underwent Z-plasty lengthening of the medial and lateral retinacular structures to restore patellar mobility, an arthroscopic suprapatellar debridement to open the synovial pouch, and removal of infrapatellar contracture. The patellar tendon shortening was permanent. The patient underwent 3 months of intensive rehabilitation, muscle strengthening, and gait retraining and achieved 0/0/125 degrees of motion, with restoration of patellar mobility.

Our comments: This case demonstrates the importance of maintaining normal patellar mobility postoperatively. Any limitation of patellar mobility should be treated by 3 weeks postoperatively using the programs discussed in this chapter. The lack of motion after surgery, with inadequate rehabilitation, contributed to the postoperative problem. It is not advisable to perform a manipulation at 8 postoperative weeks in a knee where the joint contracture is well established. Arthroscopic debridement and appropriate lysis of adhesions are instead indicated. Overpressure flexion exercises are contraindicated until release procedures are performed to restore patellar mobility; otherwise, high patellofemoral forces exist with forced flexion and possible articular cartilage damage. If treated early, loss of patellar tendon length and patella infra and associated patellofemoral cartilage damage could possibly have been avoided in this knee. The contracture of the medial and lateral parapatellar tissues was so severe that an open Z-plasty release was required.

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Video Content

Video 7-4
Video 11-1
Video 11-2
Video 11-3
Video 24-3
Video 24-4
Video 30-1

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39

Knee Pain of Neural Origin

A. Lee Dellon

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VIDEO CONTENT

Video 1-1 The Key to the Knee: A Layer-by-Layer Demonstration of Medial and Anterior Knee Anatomy

INTRODUCTION

Nerves related to the knee include not only those that go in the skin about the surface of the knee joint but also mixed (motor and sensory) nerves that pass the knee on the way to their targets distal to this joint. In addition to these well-known nerves are those that innervate the knee joint. Each is at risk of injury when there is (1) blunt force directed at the knee, (2) a stretch/traction injury to the musculoskeletal system of the knee joint, or (3) an inversion sprain to the ankle or when (4) open or arthroscopic knee surgery has been performed. Although it is intuitively clear that a joint is innervated, the exact pathways of this innervation are curiously omitted from the classic and even the newer anatomy texts. For the human knee, the innervation pattern was not found to be described until 1994, during my search for an etiology of knee pain unrelated to musculoskeletal dysfunction.[25] The approach to knee pain described in this chapter closely follows the approach developed for wrist pain,[8,16,20] which preceded my interest in knee pain. This led to a subsequent similar approach to shoulder pain[1,3] and ankle pain.[6,13,29]

CRITICAL POINTS Introduction

Nerves are at risk of injury from:
- Blunt force directed at the knee
- Stretch/traction injury of the knee joint
- Inversion sprain to the ankle
- Open or arthroscopic knee surgery

Approach: knee pain that exists after musculoskeletal treatment is of neural origin.
- Decide whether pain is coming from direct damage to the cutaneous nerves about the knee or from an injury to one of the nerves arising within the knee joint structures themselves.
- Partial joint denervation is an approach in which the joint afferents that transmit a pain message are interrupted.

The approach described in this chapter considers knee pain that exists after musculoskeletal treatment to be of neural origin. The physician caring for these patients must consider whether the pain is coming from direct damage to the cutaneous nerves about the knee, such as a neuroma of the infrapatellar branch of the saphenous nerve, or from an injury to one of the nerves arising within the knee joint structures themselves. A further source of knee pain caused by nerve injury is an injury to a nerve far away from the knee, such as the lateral femoral

cutaneous nerve, or a nerve that is simply going past the knee on its way to some other distal target. The concept of partial joint denervation is presented as an approach in which those joint afferents that transmit a pain message are interrupted, thereby stopping the pain and preserving the musculoskeletal components of the joint. A Charcot-type joint is not created because the deafferentation is partial instead of total.

PERIPHERAL NERVE ANATOMY RELATED TO THE KNEE

Innervation of the Human Knee Joint

The innervation of the human knee joint is remarkably constant.[25] On the medial aspect (Fig. 39-1), the femoral nerve branch that innervates the vastus medialis continues past its motor point and exits deep and distal to the muscle. At this point, it lies deep within the medial retinaculum and becomes related to the medial recurrent geniculate artery and vein. This structure is termed the *medial retinacular nerve*. Both nerve and vessels continue directly adjacent to the vastus medialis and superficial to the synovium to enter the ligamentous structures of the medial aspect of the knee. These fibers also continue toward the midline of the knee to innervate the undersurface of the patella (see Fig. 39-1).

On the lateral aspect of the knee (Fig. 39-2), a branch of the sciatic nerve leaves the popliteal fossa, travels laterally and anteriorly, emerges deep within the biceps tendon and enters the space beneath the lateral retinaculum. In this location, the nerve is adjacent to the superior lateral geniculate artery and vein. This structure is termed the *lateral retinacular nerve*. Both structures, the nerve and vessels, are immediately distal to the vastus lateralis and superficial to the synovium. The nerve enters the ligamentous structures of the lateral aspect of the knee (which have not yet been further defined histologically) and travels to the midline to innervate the undersurface of the patella.

Anteriorly, another source of innervation is derived from the femoral nerve innervation of the vastus intermedius. This nerve continues on the surface of the periosteum to innervate the tissues around the prepatellar bursa. Finally, posteriorly, branches from the sciatic nerve enter the posterior knee joint capsule to provide innervation (see Fig. 39-2).

Innervation of the Proximal Tibiofibular Joint

Although many patients complain of "knee pain," they may be pointing or referring to the region distal and lateral to the knee, which is the articulation between the fibular head and the tibia. This joint space is likely to be injured from fractures of the fibula or lateral tibial plateau or from high tibial osteotomy or a Maquet operative procedure. It is innervated by the common peroneal nerve (see Fig. 39-2). As the common peroneal nerve travels from the popliteal fossa to the fibular head, it gives off a small (~1 mm in diameter) nerve that may enter

CRITICAL POINTS Peripheral Nerve Anatomy Related to the Knee

- Innervation of human knee joint
- Innervation of proximal tibiofibular joint
- Common peroneal nerve
- Deep peroneal nerve
- Superficial peroneal nerve
- Proximal tibial nerve
- Lateral femoral cutaneous nerve
- Saphenous nerve

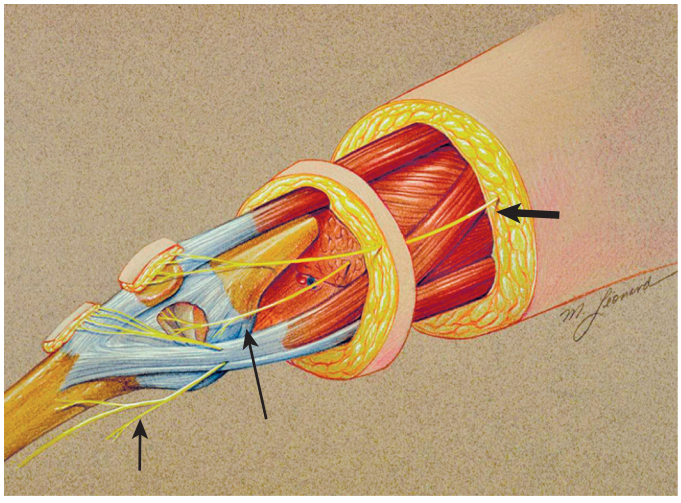


FIG 39-1 Medial view of the innervation of the knee. The skin overlying the patella is innervated by the medial cutaneous nerve of the thigh, a branch of the saphenous nerve (*thick arrow*). The medial joint structures are innervated by a branch of the femoral nerve, the medial retinacular nerve, which, after innervating the vastus medialis, continues distal and then anterior to this muscle to enter the ligamentous structures of the knee joint (*long thin arrow*). This nerve lies superficial to the synovium and deep to the medial retinaculum. The saphenous nerve's infrapatellar and distal branches are shown in their most common variation (*short thin arrow*). (Courtesy Dellon.com.)

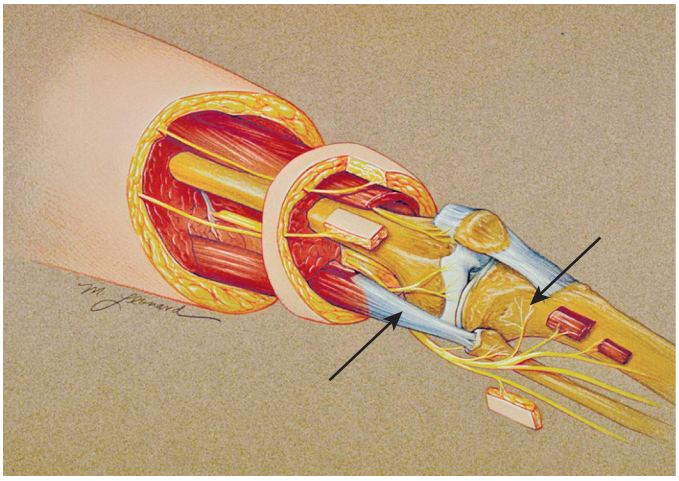


FIG 39-2 Lateral view of the innervation of the knee. The innervation of the skin in this area represents the terminal branches of the lateral femoral cutaneous nerve. The lateral joint structures are innervated by a branch of the sciatic nerve that comes from the popliteal fossa, goes deep to the biceps tendon to enter the joint, termed the *lateral retinacular nerve* (*bottom arrow*). The nerve passes just distal to the vastus lateralis and then lies superficial to the synovium and deep to the lateral retinaculum as it enters the joint. The branches of the sciatic nerve to the posterior knee joint capsule are shown next to the femur posteriorly. The branch to the prepatellar bursa is shown on the anterior surface of the femur as it exists the vastus intermedius. The innervation of the proximal tibiofibular joint is shown as branches proximal and distal to the fibular head, arising from the common peroneal nerve (*top arrow*). (Courtesy Dellon.com.)

the space posterior to the fibular head. The common peroneal nerve gives off a second innervating branch immediately as it curves anterior to the fibular head at the junction with the fibular neck. This branch is also approximately 1 mm in diameter. The next branch of the common peroneal nerve goes to the tibialis anterior, which is a critical motor branch. In the operating room, the only way to identify the branch to the joint is to stimulate it electrically. No motor function will be elicited when the branch is stimulated. This is a critical step. This small branch often looks like epineurium.

Common Peroneal Nerve

The common peroneal nerve is the lateral branch of the sciatic nerve. It can most often be identified as a distinct branch even to the sciatic notch. Therefore, in the thigh, there is clearly a common peroneal nerve even though it may be referred to as the sciatic nerve. In the distal thigh, the common peroneal nerve courses laterally, approaches the fibular head, and continues anteriorly to cross the fibular neck and enter the leg. As the common peroneal nerve approaches the fibular neck, it clearly divides into the superficial and the deep peroneal nerve, increasing in size as increased epineurium is required to ensheath these two branches (Fig. 39-3). The critical anatomic sites that can cause compression have long been appreciated to occur where the common peroneal nerve crosses the fibular neck, requiring division of the fascia of the peroneus longus fascia.[35] With increasing experience, it has become evident that three other anatomic factors must be considered. A fibrous band exists beneath the peroneus longus in 20% of cadavers, but this band is present (and ranges from 5 to 15 mm in width) in 80%

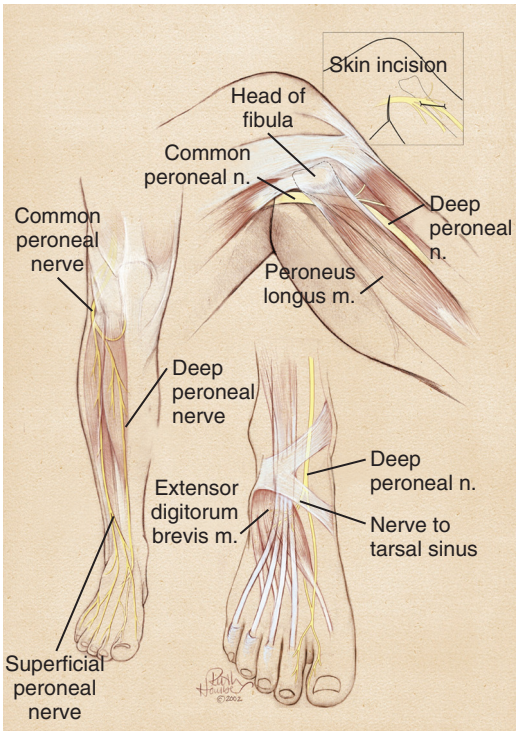


FIG 39-3 Common peroneal nerve enters the leg at the fibular head and divides into the deep and superficial peroneal nerves. *Inset,* The typical incision for the decompression of the common peroneal nerve. The superficial peroneal nerve entrapment site as it exits from the deep fascia is noted laterally, and the deep peroneal nerve entrapment site is illustrated beneath the extensor hallucis brevis tendon. (Courtesy Dellon.com.)

of patients requiring neurolysis.[14] The surgeon must identify the common peroneal nerve by elevating it from the fibular neck; determine whether or not fibrous thickening in the lateral gastrocnemius muscle fascia is present; and finally, be certain that the overall entrance into the anterior and lateral compartments is sufficiently large.

Deep Peroneal Nerve

The deep peroneal nerve arises over the fibular neck as a discrete fascicle. It can be dissected proximally by microtechnique if necessary. Immediately after crossing the fibular neck, it gives off tiny branches to the tibialis anterior and the toe extensor muscles. In so doing, the deep peroneal nerve effectively tethers the common peroneal and its distal branches from having too much excursion. This predisposes the common peroneal nerve and its branches to stretch/traction injuries. The entrapment site for the deep peroneal nerve is at the ankle, the "anterior tarsal tunnel," which is a rare site for compression unless there has been a direct injury at this location. A more common site for compression is over the dorsum of the foot where the tendon of the extensor hallucis brevis represents the anatomic structure causing the compression. A portion of the tendon of the extensor hallucis brevis is excised in the region of the deep peroneal nerve (see Fig. 39-3).[5]

Superficial Peroneal Nerve

The superficial peroneal nerve arises over the fibular neck from the common peroneal nerve. It can be dissected proximally by microdissection if required. The motor innervation to the foot everters arises within the first 1 to 2 cm distal to the neck of the fibula. The known site of entrapment for this nerve is the region where it transitions from deep fascia into the subcutaneous tissues in the distal third of the leg. The typical division into its dorsomedial and dorsolateral branches occurs just proximal to the ankle in approximately 75% of patients (see Fig. 39-3). In my experience, it is now clear that in at least 25% of cadavers and patients coming to surgery, this division can occur in the proximal third of the leg.[2,39] This creates the situation in which the superficial peroneal nerve may be found in both the anterior and its most usually described location, the lateral compartment. Indeed, the superficial peroneal nerve may be present in just the anterior compartment or within the septum between the two compartments.[40] The anatomic variability means that any surgical approach to this nerve must open both the anterior and the lateral compartments.

Proximal Tibial Nerve

Although the tibial nerve (like the common peroneal nerve) arises at the sciatic notch as the medial component of the sciatic nerve and is often clearly a distinct nerve in the thigh, the only well-described site for tibial nerve compression was at the medial ankle in the tarsal tunnel.[31] It is now evident that the tibial nerve can be compressed in a site more proximal than the tarsal tunnel, and this site (just distal to the knee) is best described as the proximal tibial nerve, to distinguish it from the tarsal tunnel region. Tibial nerve compression in the popliteal fossa has been described related to the presence of compartment syndrome or space-occupying masses, such as a popliteal artery or a Baker cyst.[26,34] Although anatomy texts clearly depict a fibrous arch or soleal sling from which the soleus muscle arises, only recently has there been an anatomic study describing the relationship of this sling to the proximal tibial nerve (unpublished data). This sling lies at a mean distance of 9.3 cm (range, 7-13 cm) from the middle of the popliteal fossa and causes a visible narrowing of the tibial nerve over a length of 1.5 cm in 55% of the cadavers, with a severe constriction being found in 2% of the specimens. With injury to the knee, especially one

associated with postoperative bleeding into the popliteal fossa, tibial nerve compression at this proximal site must be considered as a source of symptoms of numbness in the plantar aspect of the foot, with proximal referral to the knee region.

Lateral Femoral Cutaneous Nerve

The lateral femoral cutaneous nerve has a great deal of anatomic variability related both to its location at the anterior superior iliac crest[2] and to its innervated skin territory. If the location is within the inguinal ligament instead of inferior to it, the lateral femoral cutaneous nerve is at risk for compression or stretch/traction injury during falls, while wearing tight belts, during a seatbelt injury, or during manipulation of the knee with the patient on the operating room table. From Figure 39-4, it can be noted that compression of the lateral femoral cutaneous nerve can produce symptoms that include numbness or pain about the lateral aspect of the knee.[37] This nerve, or the femoral nerve itself, can be injured during regional anesthesia given for knee surgery.[22]

Saphenous Nerve

The saphenous nerve is a branch that arises from the femoral nerve in the proximal thigh. Its cutaneous branches to the skin below the knee are well described and lie in a position to be injured directly from either a medial ankle arthroscopy portal or the midline incisions used for many surgical approaches to the knee. These branches can be directly injured by blunt trauma as well. Less well recognized is the nerve to the skin overlying the patellar itself. This is a branch of the femoral nerve, which may include sensory contribution from the obturator nerve joining within Hunter's canal. The medial cutaneous nerve of the thigh (see Fig. 39-1) approaches from the medial aspect of the knee compared with the vertical approach taken by the anterior femoral cutaneous nerves.[1] Even less well appreciated is that the saphenous nerve can be compressed in the distal thigh within Hunter's canal. This is called *adductor canal syndrome*, which is rare in the absence of direct trauma to the region. Entrapment of the saphenous nerve in this location can present as medial knee pain.[36]

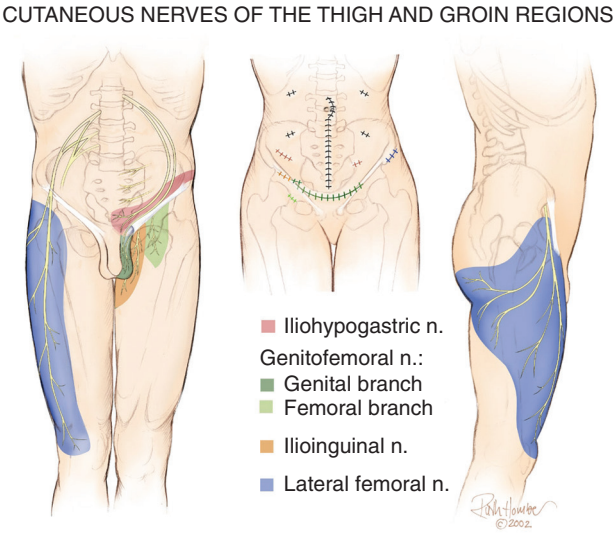


FIG 39-4 Skin territory innervated by different nerves related to the groin. The lateral femoral cutaneous nerve territory is shown in *blue* and extends distally to the knee. Compression or stretch/traction injury of this nerve can be perceived as knee pain. (Courtesy Dellon.com.)

CLINICAL EVALUATION OF KNEE PAIN OF NEURAL ORIGIN

It is critical to obtain the history of knee pain. Knee pain does not arise de novo but because of a history of some type of sports event, overuse activity, new activity, or actual direct injury to the knee. The knee injury may be blunt or open. Surgery should also be considered as a source of trauma. Many patients with knee pain caused by musculoskeletal problems awake from their reconstructive knee surgery to have a different pain or paralysis. These are known complications of knee surgery that should be recognized as such and referred for appropriate treatment in a timely manner. The determination of whether or not the pain is made worse by certain positions of the body or leg or by certain activities is important for a correct diagnosis. Certainly, most knee pain unrelated to structural impairment will be relieved by nonoperative treatment. But when pain persists beyond a reasonable timeframe of 3 to 6 months, the diagnosis is most consistent with pain of neural origin.

The physical examination is directed at identifying one or more sources of neural origin of the pain. First, the clinician should try to distinguish whether any skin territories are dysesthetic or painful when touched lightly. If so, these areas should be outlined. The most common distribution is that of the infrapatellar branch of the saphenous nerve; the second most common is the skin over the patella itself. These areas might be numb, indicating loss of sensation (Fig. 39-5). Once the pattern is identified, examine proximally along the course of the given nerve, observing for a trigger spot, which is either a true end-bulb neuroma or an in-continuity nerve lesion. The hypothesis is made that this nerve or these nerves are the source of the cutaneous pain; a diagnostic nerve block will be required to confirm this hypothesis.

The physical examination is then directed to the joint afferents. Palpation is done deeply on the spot located just distal to the vastus medialis muscle, through the medial retinaculum to elicit pain from the medial retinacular nerve. Next, palpation is repeated on the area located just

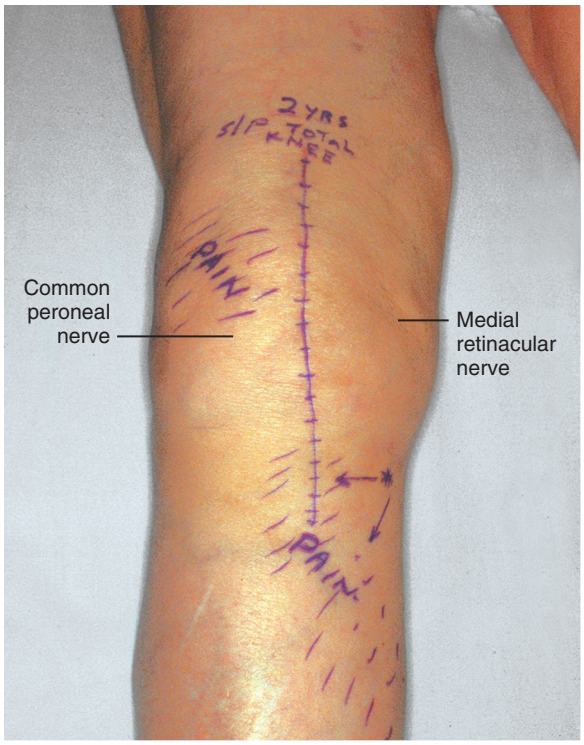


FIG 39-5 Demonstration of the sites to palpate a tender medial and lateral retinacular nerve in a patient with joint pain.

CRITICAL POINTS Clinical Evaluation of Knee Pain of Neural Origin

- History is critical.
- Determine whether pain is made worse by certain positions of the body or leg or by certain activities.
- If pain persists beyond a reasonable timeframe of 3 to 6 months, diagnosis is most consistent with pain of neural origin.
- Distinguish whether any skin territories are dysesthetic; observe for trigger spot.
- Joint afferents: palpate medial and lateral retinacular nerves. To determine whether knee pain is because of an injury to one or both of the joint afferents, conduct diagnostic nerve block. Determine whether effective.
- If block is not effective, look for more rare sources of nerve pain: anterior femoral cutaneous nerve, another branch of the infrapatellar saphenous nerve, Tinel's sign over lateral femoral cutaneous nerve, or motor function of the common peroneal nerve.

distal to the vastus lateralis muscle, through the lateral retinaculum, to elicit pain from the lateral retinacular nerve (Fig. 39-5). The hypothesis is made that the knee joint pain is caused by an injury to one or both of the joint afferents; a diagnostic nerve block will be required to confirm this hypothesis. The medial cutaneous nerve to the thigh and the medial retinacular nerve can be blocked at the same area. Ten minutes after the nerve blocks, the patient is instructed to walk in the hallway, climb and descend a few steps, and even kneel on a padded chair (Fig. 39-6). A reduction of 5 points on a visual analog scale, for example, from 10 to 5, where 10 represents the worst pain, is confirmation that sufficient relief of pain has occurred to permit surgery for partial knee denervation and resection of cutaneous neuromas.

If the nerve blocks just described have not reduced the pain level to less than 5 points or the blocks were not effective, the physical examination should proceed to include other more rare sources for the nerve pain. In a patient with a knee replacement, the remaining pain may stem from an anterior femoral cutaneous nerve found in the proximal portions of the incision or another branch of the infrapatellar saphenous nerve, which can have many branches, including more distal branches.

Finally, the groin should be examined to search for Tinel's sign over the lateral femoral cutaneous nerve. The patient will be noted to sit with the lower extremity extended at the hip joint (Fig. 39-7). The midthigh should be examined to search for Tinel's sign over Hunter's adductor canal. This is most effectively done with the patient supine and the affected leg externally rotated at the hip, leaving the knee bent. This stretches the adductor muscle group over the saphenous nerve. Then gentle palpation over the canal produces a distal radiating painful response (Fig. 39-8).

If the pain is below the knee joint and located laterally, examine for tenderness in the proximal tibiofibular joint space. If this is present, a nerve block can be done directly into this space without blocking the common peroneal nerve.

If pain is accompanied by complaints of the leg "giving out," the foot dragging, or a "footdrop," the motor function of the common peroneal nerve must be evaluated by manual muscle testing. The common peroneal nerve must be palpated or percussed at the fibular neck, with tenderness (even without distal radiation) considered a positive sign for nerve entrapment.

INDICATIONS FOR PARTIAL KNEE DENERVATION

Knee pain that persists for more than 6 months despite musculoskeletal nonoperative and operative treatment is considered chronic. By definition, patients with chronic pain require appropriate management. The diagnosis of knee pain of neural origin should be considered before sending a patient for pain management or, at the least, be considered and evaluated with nerve blocks by a pain-management physician. Certainly, before any consideration is given for a peripheral nerve or spinal stimulator for pain relief, the physician should contemplate treating the peripheral nerve pain generators directly by resection or decompression, as described in this chapter.

CRITICAL POINTS Indications for Partial Knee Denervation

- Knee pain more than 6 months.
- Persistent knee pain in athletes after ligamentous repair or knee arthroscopy.
- Persistent pain after knee reconstruction related to other disorders.
- Patient who has severe degenerative knee pain, but who is "too young" for a hemi- or total knee replacement.
- Patient with persistent knee pain after total knee arthroplasty, in the absence of loosening, malalignment, or infection.

In the athlete, persistent knee pain after ligamentous repair or knee arthroscopy is an indication to determine whether the pain is caused by a traction injury to the nerves that innervate the knee joint, a stress/traction injury, or compression of nerves that cross the knee. Medial knee pain can be related to a groin pull if the contracted adductor muscles create an adductor canal syndrome.

In the patient who has had knee reconstruction related to other disorders, persistent pain must be considered as related to a cutaneous neuroma or an injury to the joint afferents.

In the patient who has severe degenerative knee pain, but who is "too young" for a hemireplacement or total knee replacement, consideration should be given to diagnostic nerve blocks. Although partial joint denervation will not change the underlying osteoarthritic process, it may provide the patient some degree of relief until she or he ages sufficiently to enter the age bracket considered appropriate for an arthroplasty.

In the patient with persistent knee pain after total knee arthroplasty (TKA), in the absence of loosening, malalignment, or infection, pain of neural origin clearly must be evaluated, as described in this chapter.

PREOPERATIVE PLANNING

The first consideration is to make the correct diagnosis. The pain must be identified as coming from either an injured joint afferent as proven by a successful nerve block, an injured cutaneous nerve as proven by a successful nerve block, or a nerve entrapment as demonstrated by the history and physical examination.

The second consideration is that all structural musculoskeletal problems have been treated either nonoperatively, operatively, or both as documented in the referring letter from the orthopaedic surgeon.

The third consideration is the presence of lumbosacral disk disease. Appropriate imaging, electrodiagnostic studies, and subspecialty referral must be completed before peripheral nerve surgery is conducted.

The fourth consideration is the existence of a neuropathy, either diabetic or idiopathic. If the patient has complaints related to the feet, the presence of neuropathy should be evaluated. In addition to the history and physical examination, my preferred approach is to obtain



FIG 39-6 Demonstration of the use of local anesthesia to block the suspected joint and cutaneous afferents in the patient with knee pain. A mixture of 0.5% bupivacaine (Marcaine) and 1% lidocaine (Xylocaine), each without epinephrine (*upper left*), is used to conduct the local block at the two sites indicated in Figure 39-5 to block the joint afferents most likely to be the source of joint pain. Additional blocks would also be done of cutaneous afferents. After the block, the patient should be able to climb stairs and kneel without the previous pain (as shown). There should be a reduction of at least 5 on the 10-point Likert scale in order for this block to be considered successful enough to recommend a partial knee denervation. If there is significant residual pain after the block, additional nerves causing this pain should be identified.

CRITICAL POINTS Preoperative Planning

- Identify pain as coming from either an injured joint afferent, an injured cutaneous nerve, or a nerve entrapment.
- All structural musculoskeletal problems have been treated either nonoperatively, operatively, or both.
- Treat lumbosacral disk disease if present first.
- Determine whether neuropathy exists.
- Consider general health condition of patient, vascular status of limb.
- Educate patient regarding postoperative pain, success rate, and therapy required.

nonpainful and noninvasive neurosensory testing with the Pressure-Specified Sensory Device (PSSD) (Sensory Management Services, LLC).[4,7,38] The PSSD documents the presence of a neuropathy and a nerve entrapment, providing a basis for decompression of the common or superficial peroneal nerve or both (dorsomedial and dorsolateral foot sensibility sites). This device also documents the presence of tibial nerve dysfunction by evaluating the medial calcaneal and medial plantar nerves (heel and hallux pulp skin test sites). This is especially helpful in a patient with postarthroplasty palsy, in whom the PSSD evaluation can document whether the involved nerves demonstrate a nerve regeneration pattern and warrant further observation or, in the absence of that pattern, whether or not neurolysis is indicated at the 3-month timeframe.[9]

The fifth consideration is the medical condition of the patient with regard to the risks of general anesthesia.

The sixth consideration is the vascular status of the limb. The peripheral nerve surgery is done with the use of a tourniquet. Currently, it is not recommended to use a tourniquet in the presence of a leg that has had a bypass grafting procedure.[21]

The seventh consideration is to inform the patient that after a denervation procedure, a neurectomy of a peripheral nerve, or a decompression, there may be unusual and sometimes painful postoperative sensations. These are because of either nerve regeneration in

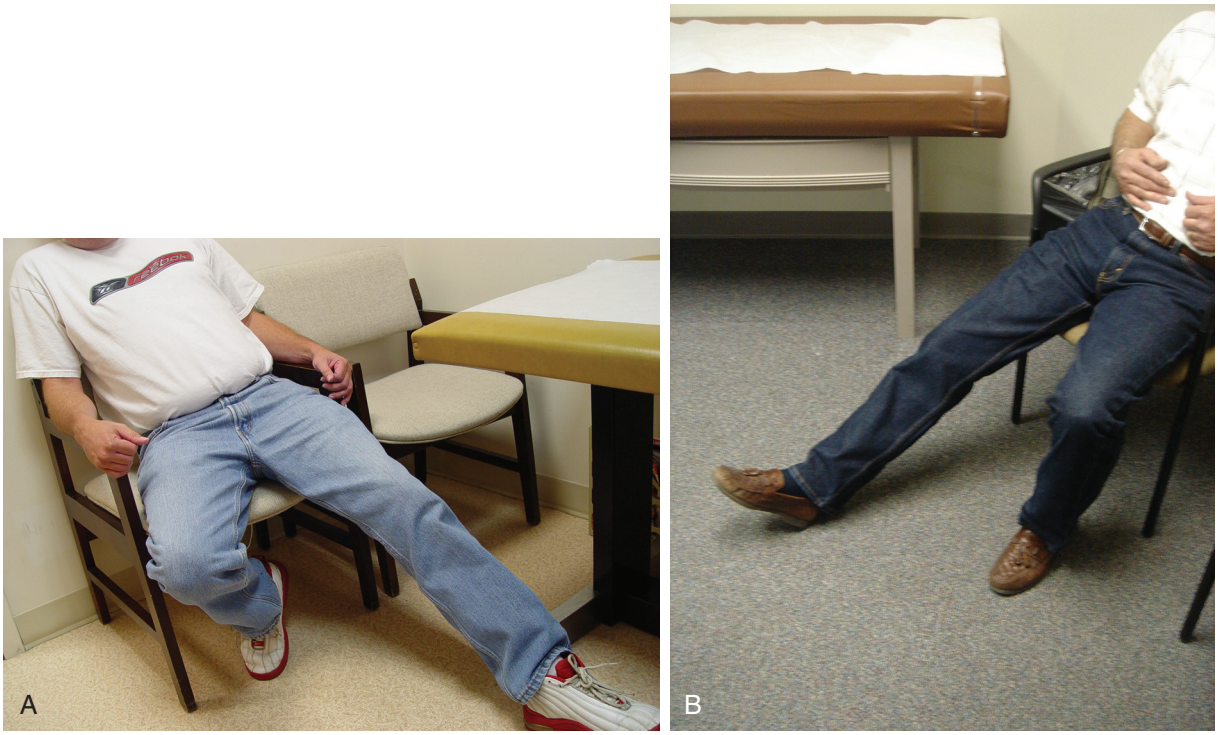


FIG 39-7 Clinical sign of compression of the lateral femoral cutaneous nerve (meralgia paresthetica). Two examples are shown. The patient can be observed to be sitting with the lower extremity on the painful side extended at the hip. Hip flexion increases pressure on the lateral femoral cutaneous nerve as it exits through the site of compression. Shown are a left (**A**) and a right (**B**) lateral femoral cutaneous nerve compression.

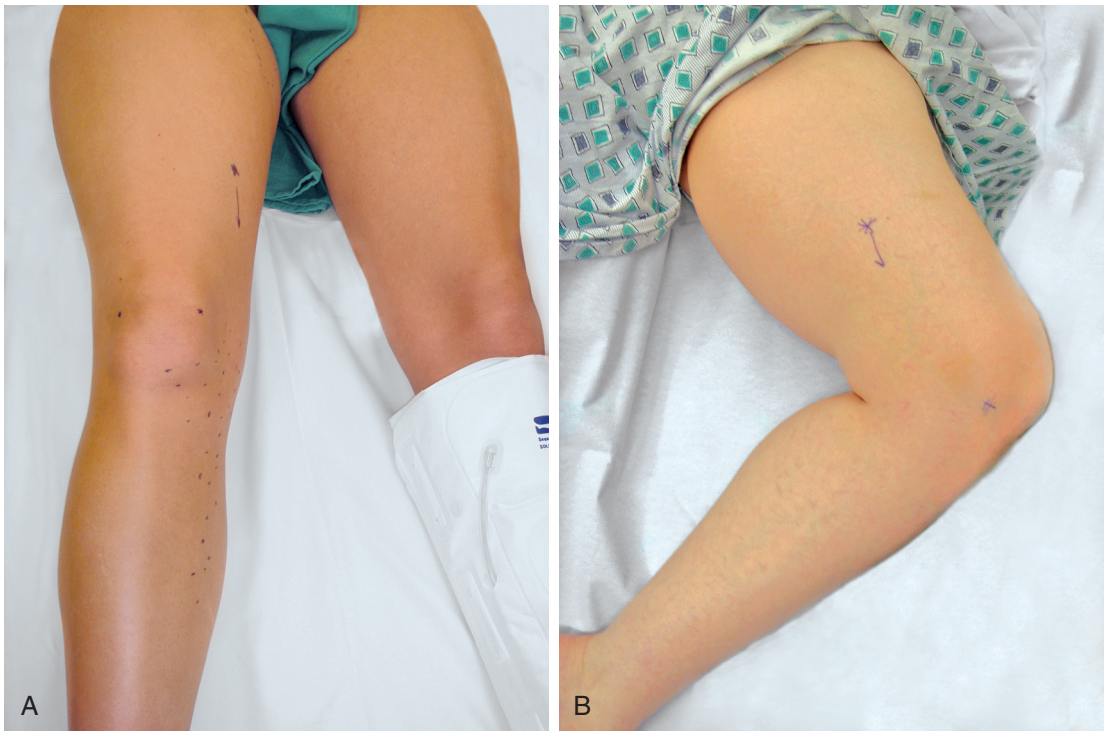


FIG 39-8 Location of the distally radiating Tinel's sign in the patient with compression of the saphenous nerve in Hunter's canal. **A**, Site in a right thigh. **B**, Site in a left thigh. Tinel's sign is marked, and distal radiation into saphenous skin territory is noted.

the case of a nerve decompression or collateral sprouting in the case of a resection of a cutaneous nerve. Some patients perceive that the knee area is swollen, although no visible effusion is present. Postoperatively, the patient should be prepared to participate in aquatic therapy pool sessions two to three times a week for 3 weeks and perform water walking to desensitize the skin and help reorganize the cortical maps.[10]

The eighth consideration is to inform the patient that not all of the original knee pain may be resolved. Small nerves have many anatomic variations, and although in some patients the preoperative block suggests that all pain has been relieved, there may still be a small branch (e.g., the infrapatellar branch of the saphenous nerve) that will require a second operation to remove. A second operation may be necessary in approximately 10% of patients.

With regard to postoperative care, the patient ambulates immediately. This facilitates gliding of any nerves that have been decompressed and minimizes the risk of venous thrombosis. Once the sutures are removed, the patient begins water therapy. With regard to postoperative wound healing, in an obese individual, the lipid substances may come out of the fat cells into the subcutaneous tissue. The biologic process to absorb this often results in a firm, warm area in the fat that may appear to be cellulitis. This responds to topical warmth and antiinflammatory medication. If it is difficult to distinguish this from a bacterial problem, a course of antibiotics may be necessary.

Finally, the patient must be told that peripheral nerve surgery will not alter the stiffness present in the knee joint. Once pain has been relieved, the patient's range of motion (ROM) and strength can again be addressed by the orthopedic surgeon and the physical therapist.

OPERATIVE TECHNIQUES

The operative techniques for partial knee denervation described later have been previously published.[17-19] For each patient, a tourniquet is used and set at a pressure of 300 mg Hg. If the leg is quite large or exceptionally muscular, this pressure can be increased to 325 mm Hg. It is critical to note that the leg is *not* completely exsanguinated. Deliberately, some venous blood is left in the region around the knee by not wrapping the Ace bandage tightly. The small amount of blood left in all the recurrent geniculate artery and veins is helpful in identifying the small joint afferents that lie next to these structures and the larger nerves, such as the infrapatellar branch of the saphenous nerve. A bipolar coagulator and Loupe magnification (×3.5) are used. Intravenous antibiotic prophylaxis is given before inflating the tourniquet. A femoral nerve block is *not* done owing to the risk of injury to the femoral nerve, but rather bupivacaine (Marcaine) 0.5% is infiltrated into the skin edges of the incisions at the end of the surgical procedure. The dressing consists of Xeroform gauze over the incision followed by sterile 4 × 4 inch gauze, which is held in place with Kling and covered with a stockinette. Then an Ace wrap is applied firmly and left in place for 30 minutes to counteract the reactive hyperemia attendant to use of the tourniquet.

Finally, the concept of minimizing the risk of recurrent neuroma pain must be understood. Because the sensory nerves remain alive once divided owing to their intact nucleus in the dorsal root ganglion, nerve regeneration will occur in every joint afferent or cutaneous afferent that is divided. Alteration of the microenvironment of the nerve by implanting the proximal end of a divided sensory nerve into an innervated motor environment results in the absence of formation of a true neuroma.[32] Implanting a sensory nerve into an innervated muscle after resecting the painful neuroma or after interruption of that nerve function by division of that nerve results in predictable pain relief without recurrent neuroma for upper[15,30] and lower extremity[12,28,29] peripheral nerves. The location chosen to place the divided nerve is explained for each operation described later.

CRITICAL POINTS Operative Techniques

- Intravenous antibiotic prophylaxis
- Tourniquet used, leg not completely exsanguinated
- Femoral nerve block not done owing to risk of injury to femoral nerve.
- Bupivacaine (Marcaine) 0.5% is infiltrated into skin edges of incisions at end of surgical procedure
- Dressing: Xeroform gauze over incision followed by sterile 4 × 4 inch gauze held in place with Kling and covered with a stockinette; Ace wrap applied firmly, left in place for 30 minutes
- Operative procedures
- Lateral denervation of knee joint
- Medial denervation of knee joint
- Resection of infrapatellar branch of saphenous nerve
- Resection of medial cutaneous nerve of thigh
- Neurolysis of common peroneal nerve
- Denervation of proximal tibiofibular joint
- Neurolysis of superficial peroneal nerve
- Neurolysis of proximal tibial nerve
- Neurolysis of lateral femoral cutaneous nerve
- Neurolysis of saphenous nerve in Hunter's canal

Lateral Denervation of the Knee Joint

An incision is outlined lateral to the patella, beginning over the distal muscle belly of the vastus lateralis. This muscle sometimes has a slight distal split, and the surgeon must be sure to remain distal to the most distal portion of the vastus lateralis muscle. The iliotibial band (lateral retinaculum) is divided longitudinally for approximately 1.5 cm. Immediately adjacent to the muscle belly are small recurrent vessels and a 1- to 1.5-mm nerve that go from beneath the biceps tendon and the iliotibial band and across the synovium into the lateral joint and infrapatellar structures. This nerve is infiltrated with bupivacaine 0.5% down beneath the iliotibial band and the nerve and vessels are cauterized toward the patella to prevent bleeding and placed under traction. Subsequently, they are cauterized deep beneath the iliotibial band to prevent further bleeding. The portion between the two cauterized sites is sent to pathology. The iliotibial band (lateral retinaculum) is repaired with two figure-eight sutures of 2-0 braided nonabsorbable material (Fig. 39-9).

Medial Denervation of the Knee Joint

An incision is outlined medial to the patella beginning over the distal muscle belly of the vastus medialis. The thin medial retinaculum is divided longitudinally for approximately 1.5 cm. Immediately adjacent to the muscle belly are the small recurrent vessels and a 1- to 1.5-mm nerve that goes from beneath the vastus medialis and across the synovium into the medial joint and infrapatellar structures. This nerve is dissected proximally beneath the retinaculum until it exits from beneath the muscle. It is infiltrated with bupivacaine 0.5% down beneath the vastus medialis and the nerve and vessels are cauterized toward the patella to prevent bleeding and placed under traction, then cauterized deep beneath the vastus medialis to prevent further bleeding. The portion between the two cauterized sites is sent to pathology. The medial retinaculum is repaired with two figure-eight sutures of 3-0 braided nonabsorbable material (Fig. 39-10).

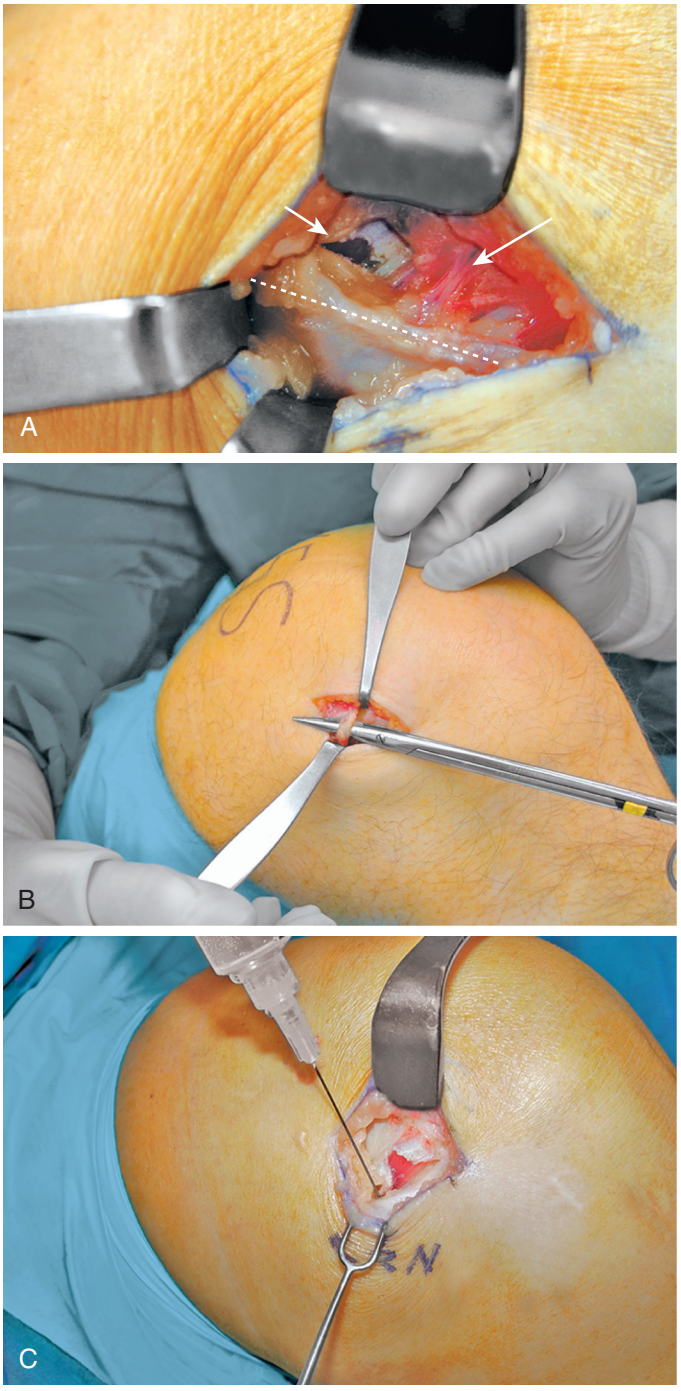


FIG 39-9 Lateral knee denervation. **A**, Incision is shown, lateral to the patella, centered over the tender site shown in Figure 39-5. The *short arrow* indicates the vastus lateralis. The iliotibial tract is incised (*dotted line*) to demonstrate the lateral retinacular nerve (*long arrow*) adjacent to the superior lateral geniculate vessels. **B**, The lateral retinacular nerve. **C**, The nerve is first infiltrated with local anesthetic, cauterized distally and proximally, and then divided proximally below the level of the iliotibial band so that the nerve drops into the popliteal fossa.

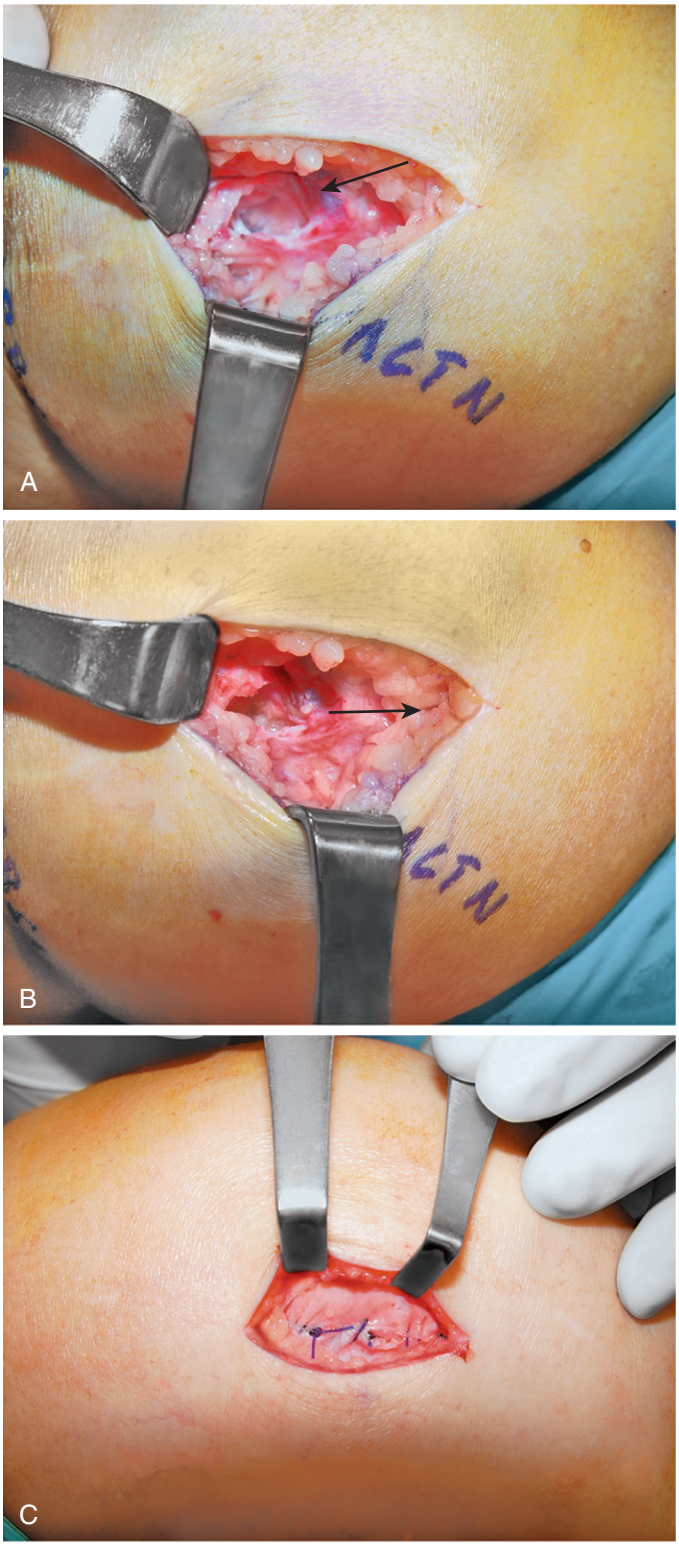


FIG 39-10 Medial knee denervation. **A**, Incision is shown, medial to the patella, centered over the tender site shown in Figure 39-5. The medial retinaculum is opened. The *arrow* points to the medial retinacular nerve adjacent to the recurrent medial recurrent geniculate vessels. **B**, The nerve has been resected. The *arrow* points to the direction in which, beneath the medial retinaculum, the nerve has been implanted into the vastus medialis muscle. **C**, Closure of the medial retinaculum.

Resection of the Infrapatellar Branch of the Saphenous Nerve

The saphenous nerve exits Hunter's canal in the distal thigh to become the medial cutaneous nerve of the thigh, the infrapatellar branch of the saphenous nerve, and the distal saphenous nerve. The infrapatellar branch crosses the insertion of the adductor tendons into Gerdy's tubercle beneath the deep fascia. There may already be two branches at this level. Ultimately, several terminal branches cross from medial to lateral across the region of the tibial tuberosity to innervate the lateral knee skin. The skin proximal to this laterally is the terminal zone of innervation of the lateral femoral cutaneous nerve. Although the numbness is lateral, the damage to the nerve usually occurs in the axial line of the knee from an incision or medially from a scope portal. The site of Tinel's sign medially is around Gerdy's tubercle. An incision is made longitudinally across Tinel's sign. The dissection is carried deep into the fascia where one or more branches are noted by the blood in the vein that accompanies the nerve branch. A thorough proximal and distal search must be done to identify more than one branch. This is the most common location for a missed remaining painful nerve. The nerve is infiltrated with bupivacaine 0.5% proximally, the distal end cauterized to minimize bleeding, a segment resected for pathology, and the proximal end dissected. There is usually a clear tunnel where this nerve has transversed along or through the sartorius or other adductor muscle or tendon. The proximal end of the divided nerve, after cauterization to prevent bleeding, is turned blindly into these muscles and implanted there, proximal to the popliteal crease (Fig. 39-11).

Resection of the Medial Cutaneous Nerve of the Thigh

The medial cutaneous nerve goes to the skin overlying the patella. This skin is traditionally shown as being innervated by an anterior femoral cutaneous nerve coming vertically down the leg. However, the skin is actually innervated by a branch of the saphenous, which approaches this region medially. Indeed, the same tender location for the medial retinacular nerve is the location of this nerve. The clinical clue is that the skin of the patella is dysesthetic. The medial nerve block will block both of these nerves. An incision is used to approach the medial retinacular nerve. There will be blood in the immediate subcutaneous tissue from the small vein that accompanies this nerve. The nerve is cauterized distally, and the proximal end is dissected medially across the surface of the vastus medialis. The nerve is injected with bupivacaine 0.5% proximally. A small window is opened into the fascia of the vastus medialis. The proximal end of the nerve is implanted loosely into this muscle (Fig. 39-12).

Neurolysis of the Common Peroneal Nerve

An oblique incision is made going from the location of the popliteal fossa distally across the fibular neck overlying the palpable and tender common peroneal nerve. In the immediate subcutaneous tissue, the surgeon should be aware that the lateral cutaneous nerve of the calf can be present as a branch of the common peroneal nerve. Injury to this nerve will cause a postoperative painful incision. In addition, this nerve can become adherent to the biceps tendon, which also causes postoperative pain beneath the incision proximally.

The deep fascia is opened. In patients who do not have a neuropathy but who sustained trauma, this fascia will be adherent to the common peroneal nerve, which will be white with an area of inflammation and swelling as the peroneus longus muscle is approached. In patients with neuropathy, particularly those with glucose intolerance or actual diabetes, the common peroneal nerve will be yellow and resemble a neuroma. Be aware of these cases and handle the fat beneath the fascia with great care because it is usually the nerve. The dissection must release the nerve into the popliteal fossa, especially in the case of trauma or joint replacement. The usual compression site, however, is beneath the peroneus muscles. As the surgeon evaluates the common peroneal nerve approaching the fibular head and crossing the fibular neck, two or more tiny branches that go around the fibular head to innervate the proximal tibiofibular joint will be observed. Because the peroneus fascia is the main site of compression, divide the peroneus longus fascia transversely and from the fibula head distally, cauterizing the edges. If there is a septum between muscle groups, divide this septum, being careful on its deep surface. Retract the muscle; dividing the muscle is not necessary. In 20% of cadavers, but in 80% of patients, there will be another band of varying width and thickness deep into the muscle and overlying the nerve across the fibular neck.[12] This is the site of compression, and this band is resected. Next, look beneath the nerve for fibrous bands on the lateral gastrocnemius muscle; if they are present, cauterize and resect them. Check the passageway of the common peroneal nerve beneath the muscles and into the leg. If this is tight, divide the fascial origins of the muscle at the fibula by cautery. This completes the neurolysis of the common peroneal nerve (Fig. 39-13).

Denervation of the Proximal Tibiofibular Joint

In the preceding section, the small branches to the proximal tibiofibular joint were observed. The safest way to denervate this joint is to perform a complete neurolysis of the common peroneal nerve. Then, using a disposable nerve stimulator, stimulate the deep and the superficial peroneal nerves to demonstrate a "positive control." Stimulate the small branches purported to go the proximal tibiofibular joint. If no muscle twitches, these are indeed the correct nerves, and they may be resected back to the common peroneal nerve and submitted to pathology. Do not inject bupivacaine into these nerves because this is likely to create a motor block and cause worry in the recovery room until it wears off (Fig. 39-14).

Neurolysis of the Superficial Peroneal Nerve

Symptoms related to compression of the superficial peroneal nerve are numbness, tingling, or pain radiating from the midlateral lower leg to the top of the foot.

The most important concept here is that the superficial peroneal nerve in at least 25% of patients will have a branch in the anterior compartment.[2,39] Therefore, in addition to opening the lateral compartment, the anterior compartment must be opened. The incision is made approximately 4 cm long, centered on the site of the positive Tinel's sign. The most common location for the incision is 10 to 15 cm proximal to the lateral malleolus. In the subcutaneous tissue, look for a small bulge in the fascia or fat protruding from the fascia because this may be the transit site of the superficial peroneal nerve from deep to superficial to the fascia. There may be a small branch to the skin right at this point that must be preserved. Create a longitudinal opening in the lateral compartment. Even if a nerve is found, a longitudinal opening in the anterior compartment must be made. In addition, transversely cut the fascia to visualize all the way anteriorly. The fascial edges must be cauterized because they are well vascularized and can be a source of postoperative bleeding. The septum between the two compartments is another site in which a branch or the entire superficial peroneal nerve may be located. Do not just simply cut across this region.[40] The goal is to leave the superficial peroneal nerves surrounded only by muscle because



FIG 39-11 Resection of the infrapatellar branch of the saphenous nerve. **A**, A woman 9 years after total knee arthroplasty whose knee is shown from medial aspect demonstrating sites of pain over the anterior femoral cutaneous nerve (proximally), over the medial cutaneous nerve of the thigh (and medial retinacular nerve), and over the infrapatellar branch of the saphenous nerve. **B**, The infrapatellar branch is noted at the medial aspect of the knee, near the tibial tuberosity, at which site it is usually painful to touch. The nerve is infiltrated with local anesthetic prior (**C**) and then cauterized and divided (**D**). **E**, The proximal end of the nerve is dissected and implanted into an adductor muscle medially (location denoted by the finger at the popliteal fossa). **F**, A search must be made proximally for other infrapatellar branches. One is shown here in the incision used to resect the medial cutaneous nerve of the thigh and the medial retinacular nerves.



FIG 39-12 Resection of the medial cutaneous nerve of the thigh. A 23-year-old with a direct injury to the knee resulting in pain over the patellar region. **A**, Site of Tinel's sign and nerve block that eliminated the pain. **B**, Medial cutaneous nerve of the thigh demonstrated by the scissors' tips in the subcutaneous plane. **C**, This is superficial to the medial retinaculum. **D**, The nerve has been divided distally and dissected proximally and is held by a clamp. **E**, A window is made in the fascia over the vastus medialis into which the proximal end of the nerve will be implanted.

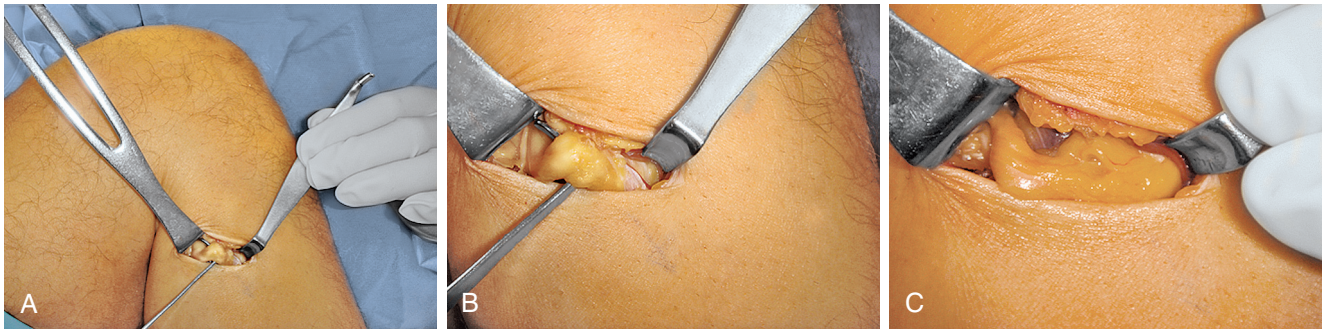


FIG 39-13 Decompression of the common peroneal nerve. **A**, The incision is noted on a right knee, overlying the fibular head and angling toward the popliteal fossa. **B**, The peroneus fascia has been released superficially and the muscles retracted anteriorly. The common peroneal nerve is infiltrated by fat in this patient with diabetes and is compressed by the fibrous band deep to the retracted muscle. **C**, The fibrous band has been excised. The nerve is noted to be indented at the site and to have lost its fascicular markings, consistent with severe compression.

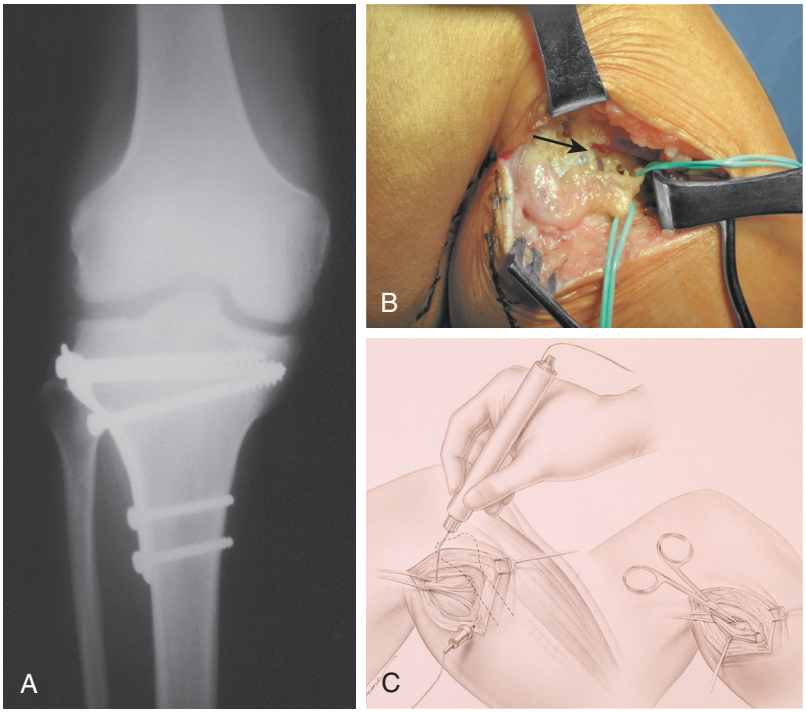


FIG 39-14 Denervation of the proximal tibiofibular joint. **A**, Example of surgery in the region of the proximal tibiofibular joint that can cause pain in this region, typically after a high tibial osteotomy or tibial plateau fracture. **B**, The common peroneal nerve has been decompressed, with the normal common peroneal nerve proximally, and a vessel loop is placed about its major branches, the deep and superficial peroneal nerves. The *arrow* marks a branch that innervates the proximal tibiofibular joint. **C**, Electrical stimulation will give no motor response, and this small branch can be resected. There may be a more proximal branch as well.

this guides the proximal and distal extent of the fascial releases (Fig. 39-15).

Neurolysis of the Proximal Tibial Nerve

An incision approximately 12 cm long is made medially in the calf just anterior to the medial head of the gastrocnemius muscle. The center of the incision is made at the level of the tender proximal tibial nerve, approximately 9 cm distal to the popliteal crease. The deep fascia is opened and the medial gastrocnemius muscle is dissected bluntly from the soleus muscle. The plantaris tendon and the popliteus muscle will be seen. The tibial nerve and the popliteal vein will be observed to pass anterior to the fascial origin or arch or sling of the soleus muscle. A large clamp placed deep to this arch demonstrates the tight area. The soleus muscle fibers may require dissection to reveal the fibrous arch.

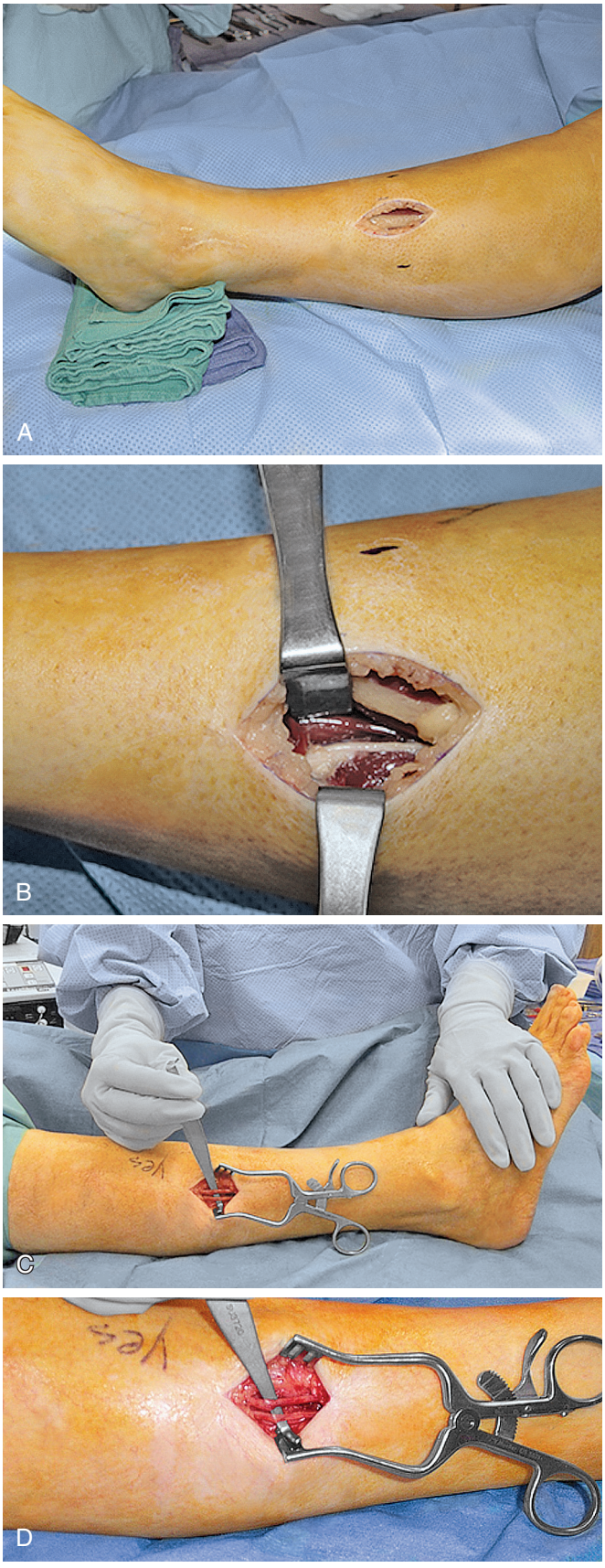


FIG 39-15 Neurolysis of the superficial peroneal nerve. An incision is made over the lateral aspect of the leg at the site of Tinel's sign. Whereas the superficial peroneal nerve is in the lateral compartment in 75% of patients, it can be in just the anterior compartment (**A** and **B**) or in both the anterior and the lateral compartments (**C** and **D**). For this reason, a fasciotomy of both compartments must be done for each patient. The neurolysis is continued until the nerve is distally in the subcutaneous tissue and is proximally surrounded by muscle. In some patients, a portion of the septum between the two compartments must be excised.

If there has been bleeding in this area, this dissection can be difficult. The soleal arch must be completely divided. Usually, a notch in the tibial nerve will be identified (Fig. 39-16).

Neurolysis of the Lateral Femoral Cutaneous Nerve

A tender spot exists just anterior to the anterior superior iliac crest. An incision approximately 4 cm long is made just cephalad to this area and deepened into the subcutaneous tissue. The inguinal ligament is identified and carefully divided, millimeter by millimeter, adjacent to the anterior superior iliac crest while the surgeon looks for the compressed lateral femoral cutaneous nerve. The nerve is narrowed, yellow, and inflamed and often does not look like a nerve. The nerve must be released into the thigh and then proximally until it enters the pelvis. Proximally, this entails dividing portions of the internal oblique fascia. Where this dissection stops, the surgeon should take care not to divide the deep circumflex iliac artery and vein. If the lateral femoral cutaneous nerve is too badly damaged by the compression, it may need to be resected with the proximal end allowed to lie within the pelvis (Fig. 39-17).

Neurolysis of the Saphenous Nerve in Hunter's Canal

A 6 cm incision is made longitudinally at the site of Tinel's sign of the saphenous nerve in the adductor canal. The dissection goes deep until the fascia connecting the vastus medialis to the adductor longus is identified. The length of this tunnel is between 6 and 8 cm. Small nerves will be in this vicinity. They need to be stimulated, because some are not saphenous branches but motor branches. Once the fascia is released, the saphenous nerve will be present as one or more branches. Deep within them will be the superficial femoral artery (Fig. 39-18).

OUR CLINICAL STUDIES

If a patient obtains relief of knee pain after a block of any combination of joint or cutaneous afferents, there is a 90% chance that he or she should also obtain good to excellent relief of his or her knee pain postoperatively.[17-19] Patients who achieve less than a satisfactory result either have another nerve that requires removal or have confounding problems such as a central mechanism for their chronic pain, drug addiction, or legal issues related to work or an accident.

The first group of patients selected for partial knee denervation were chosen from a group who had undergone a TKA but had persistent pain for greater than 6 months that was unrelated to loosening, malalignment, or infection.[19] In this study, the orthopedic surgeons completed a preoperative Knee Society Function Score, ROM, and pain assessment in 15 patients. The author independently performed the partial knee denervation, whereas the orthopedic surgeons conducted the postoperative assessment. To be selected for surgery, each patient had to achieve a reduction of 5 points on a visual analog scale for pain after undergoing selective nerve blocks. A total of 45 nerves were

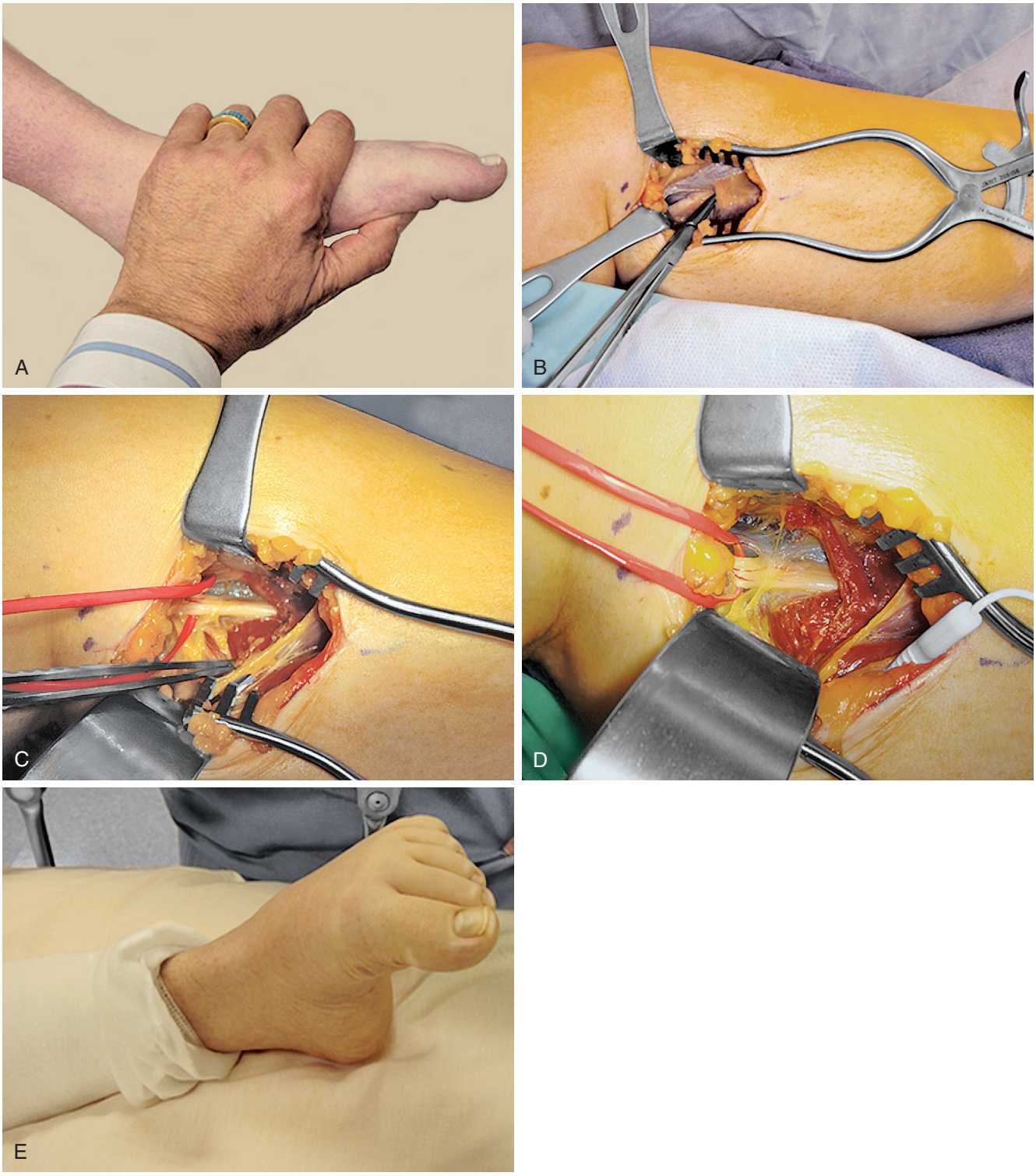


FIG 39-16 Neurolysis of the proximal tibial nerve. Compression of the tibial nerve proximally or distally will decrease sensibility in the plantar aspect of the foot. **A**, However, with a proximal compression versus a tarsal tunnel syndrome, the patient may lose the ability to flex the big toe. **B**, The medial incision is used to expose the space between the medial gastrocnemius muscle and the soleus. **C**, The clamp identifies the compression site of the tibial nerve by the fibrous arch of the soleus muscle. **D**, The nerve has been decompressed, and a difference in appearance of the nerve at this site is noted. **E**, In the recovery room, the patient regained the ability to flex the big toe.

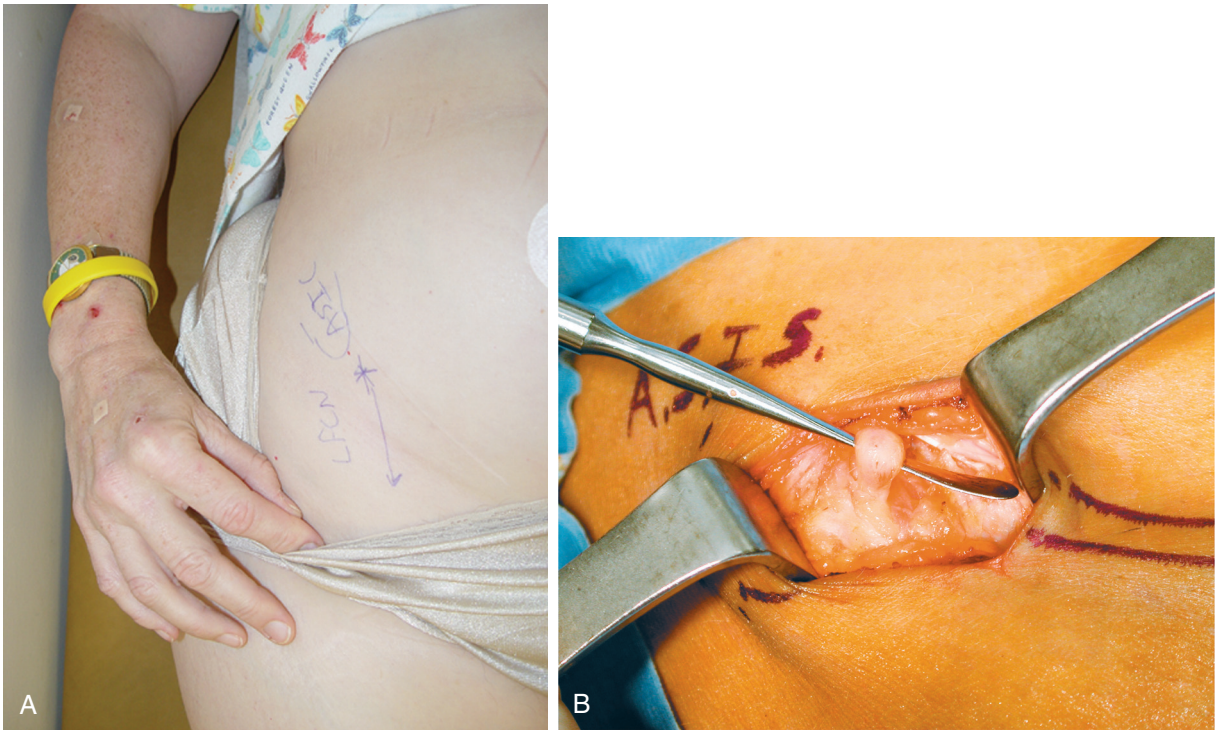


FIG 39-17 Neurolysis of the lateral femoral cutaneous nerve. **A**, Typical site of tenderness of the lateral femoral cutaneous nerve, just medial to the anterior superior iliac crest. **B**, A decompressed right lateral femoral cutaneous nerve is elevated by the instrument after division of the inguinal ligament from above and below. Additional neurolysis is required more proximally for the internal oblique fascia.

CRITICAL POINTS Our Clinical Studies

Study 1

- 45 nerves resected in 15 patients after total knee arthroplasty
- All patients subjective improvement immediately postoperative, maintained 6 to 16 months.

Study 2

- 70 patients after total knee arthroplasty, knee trauma, tibial osteotomy
- 86% satisfied with results
- Knee Society score: preoperative mean, 51 points (range, 40-62 points); follow-up mean, 82 points (range, 15-100 points)

Study 3

- 344 patients after total knee arthroplasty, knee trauma
- All had multiple nerves resected.
- 70% excellent (no remaining pain), 20% good (some pain remained, but no medication was required), 5% some improvement (surgery helped, but pain medication still required), and 5% no improvement.

resected in the 15 patients including (in each patient) both the medial and the lateral retinacular nerve and the infrapatellar branch of the saphenous nerve. All patients reported subjective improvement in the immediate postoperative period, which was maintained at a mean follow-up of 12 months (range, 6-16 months). It was concluded that selective knee denervation is indicated in the management of intractable knee pain of neuroma origin after TKA.

The next series reported consisted 70 patients.[18] Some of these patients had persistent knee pain after TKA, but the indications were extended to include those with chronic pain after knee trauma or tibial osteotomy. In patients with TKA, aseptic loosening, sepsis, ligamentous instability, malalignment, and polyethylene wear were systematically ruled out as the source of pain by the orthopedic surgeons. In patients with non-TKA pain, arthrosis, synovitis, ligamentous instability, and meniscal derangement were excluded as a source of pain. All candidates for the procedure had a successful selective nerve block. Sixty of the 70 patients (86%) were satisfied with the denervation procedure as judged by direct questioning and a reduction in their preoperative pain visual analog score of 5 or more points. The average Knee Society Score improved from a preoperative mean of 51 points (range, 40-62 points) to a follow-up mean of 82 points (range, 15-100 points). Forty-nine patients (70%) had final Knee Society objective scores greater than 80 points. There was no difference in patient satisfaction whether the follow-up period was less than 2 years or more than 2 years. Selective knee denervation is indicated in the management of intractable knee pain after exhaustion of traditional approaches to any structural or infectious etiologies and after successful selective nerve block.

In 2000, a series of 344 patients reviewed.[17] Of these, 255 had a previous TKA, and 89 had knee trauma. Most patients had several nerves removed; none had only one nerve resected. All required removal of the medial and the lateral retinacular nerves, and the majority also required removal of the medial cutaneous nerve of the thigh and the infrapatellar branch of the saphenous nerve. The nerves least often removed were the anterior femoral cutaneous and the distal saphenous nerve. Approximately half of the patients, especially those who had sustained knee trauma, required a neurolysis of the common peroneal nerve. The proximal tibiofibular joint required denervation in patients with fractures of the fibula or tibial plateau and who had undergone a Maquet procedure or a high tibial osteotomy. The results for the entire series were 70% excellent (no remaining pain), 20% good

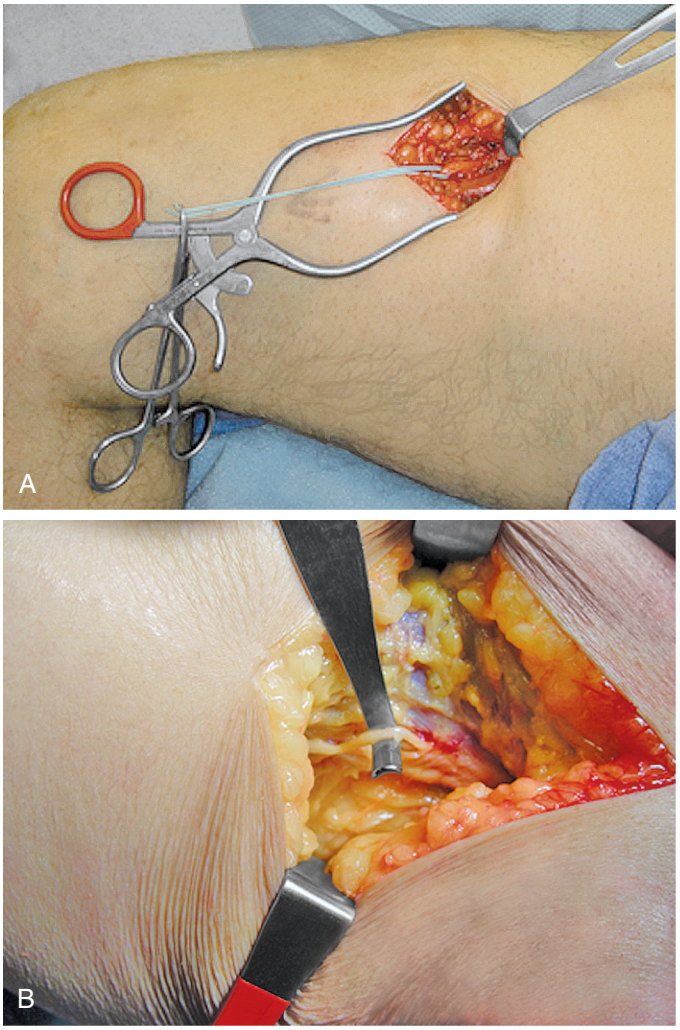


FIG 39-18 Neurolysis of the saphenous nerve in Hunter's canal. **A**, The location of the incision is clear. The entire fascial band from the vastus medialis to the adductor magnus has been released. The large single saphenous nerve is noted. **B**, In this view, a single small saphenous nerve branch is seen emerging from the fascia of Hunter's canal before its release.

(some pain remained, but no medication was required), 5% some improvement (surgery helped, but pain medication still required), and 5% no improvement. No patient was neurologically downgraded or made worse. No knee implant or hardware was exposed. No patient had to be hospitalized to treat infection. The abnormal sensibility, which is usually decreased sensibility, remained to some degree in everyone after a cutaneous nerve was removed.

A review of knee denervation patients on our office computer from January of 2000 through December of 2006 included 405 patients. Although this large group of patients had not been reviewed at this time, the overall experience with the diagnosis, intraoperative management, and postoperative outcomes remained the same as those obtained in our 2000 review data.[16]

OTHER AUTHORS' CLINICAL STUDIES

In contrast to the vast literature on relief of acute knee pain with femoral, obturator, or even lateral femoral cutaneous nerve blocks (more than 120 references cited in PubMed between 2006 and 2008), with the exception of one surgeon in Germany,[23,24] there have been no reported studies of partial knee denervation. Between May 1995 and June 1999, Fromberg and Hempfling[24] performed partial denervation using the "Dellon technique" described in this chapter in 45 knees. The investigations of Fromberg and Hempfling included patients with direct knee injury as well as those who had knee joint replacement. Thirty-four patients were followed, 11 with bilateral knee pain, whose ages ranged from 25 to 86 years (mean, 34 years). At follow-up 6 to 18 months postoperatively, 70% of the patients reported "a reduction in pain," and after 4 years, 50% "still confirmed a positive result." Complications included 1 hematoma and 2 seromas, which resolved with conservative management.

A recent study evaluated the innervation of the patella in 30 knees of 15 formaldehyde-fixed cadavers.[33] A nerve from the vastus medialis (which is the nerve described previously[1]) entering the patella "superomedially" and a nerve "from the vastus lateralis entering the patella superolaterally" were identified. The origin of these nerves was not described. The superolateral nerve "from the vastus lateralis" was most likely the nerve described previously that originates from the sciatic nerve and crosses in front of the vastus lateralis.[25] This anatomic study in fixed cadavers confirms the author's observations reported in 1994.[25] Maralcan and coworkers[33] confirmed that these nerves were patellar pain afferents by performing a local anesthesia block in 32 knees of 20 patients with patellofemoral pain. They observed a significant difference between the visual analog scale scores before and after local anesthetic injections ($P < .01$). Their observations appear to confirm that knee pain can be of neural origin from the medial and the lateral retinacular nerves, as described previously.[17-19,25]

CRITICAL POINTS Other Authors' Clinical Studies

***Fromberg and Hempfling*[24]**

- $n = 45$
- 70% reported "a reduction in pain" 6 to 18 months postoperative
- After 4 years, 50% "still confirmed a positive result"

***Maralcan et al.*[33]**

- Local anesthesia block in 32 knees of 20 patients with patellofemoral pain
- Significant difference between the visual analog scale scores before and after local anesthetic injections
- Confirmed that knee pain can be of neural origin from the medial and the lateral retinacular nerves

REFLEX SYMPATHETIC DYSTROPHY OF THE KNEE

In 1986, Katz and associates[27] defined reflex sympathetic dystrophy of the knee as diffuse pain, often accompanied with skin color changes, in patients who did not allow their knee to be touched and exhibited all the characteristics of what today is termed *complex regional pain syndrome*. These authors reported on 5 patients from a series of 662 primary total knee arthroplasties (0.8%) who demonstrated, in addition to pain, marked limitation of flexion. They stated that the traditional bone scan and osteopenia that were used as criteria for diagnosing reflex sympathetic dystrophy in the hand were difficult to aid in diagnosing this disease in patients who had TKA (Fig. 39-19). A lumbar sympathetic block was believed to be more helpful in making the diagnosis.

With the vision of hindsight, I now maintain that this condition is related to the combination of joint and cutaneous neuromas. However,

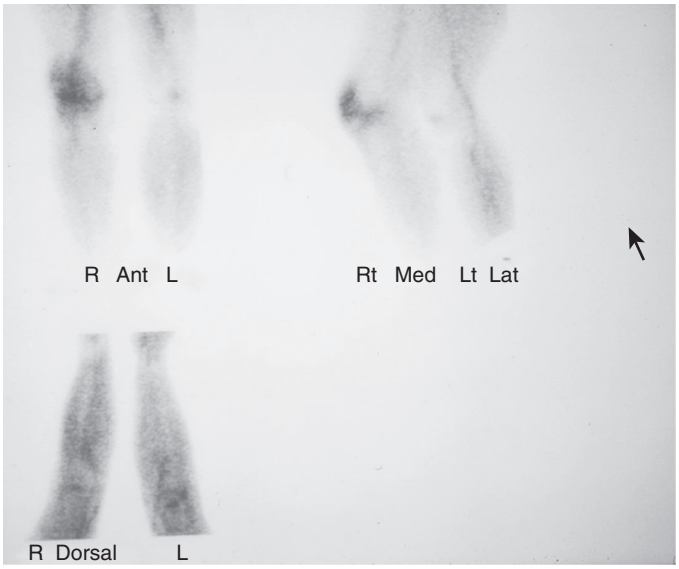


FIG 39-19 Reflex sympathetic dystrophy of the knee. A bone scan illustrates the increased uptake about the prosthesis after a total knee arthroplasty in a patient with chronic severe knee pain. This bone scan was interpreted as being consistent with reflex sympathetic dystrophy.

CRITICAL POINTS **Reflex Sympathetic Dystrophy of the Knee**

- Condition related to the combination of joint and cutaneous neuromas
- Preferred treatment is to interrupt the pain stimuli from entering the dorsal columns of the spinal cord.
- *n* = 40 upper and 30 lower extremity patients with complex regional pain syndrome followed a mean of 15 mo postoperative

Outcome

- Upper extremity patients: 55% excellent, 35% good, 10% failed
- Lower extremity patients: 66% excellent, 30% good, 4% failed

instead of attempting to treat this problem by blocking the sympathetic outflow, my preferred treatment is to interrupt the pain stimuli from entering the dorsal columns of the spinal cord using the techniques described previously. My experience with this approach was reviewed in 40 upper and 30 lower extremity patients with complex regional pain syndrome.[11] At a mean postoperative time interval of 15 months, and based on decreased pain medication usage, recovery of function, repeat history, and physical examination, outcome in the upper extremity patients was excellent in 55%, good in 35%, and failed in 10%. Outcome in the lower extremity patients was similar: excellent in 66%, good in 30%, and failed in 4%.

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Video Content

Video 1-1

28. Kim J, Dellon AL. Neuromas of the calcaneal nerves. *Foot Ankle Int*. 2001;22:890-894.
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Diagnosis and Treatment of Complex Regional Pain Syndrome

Frank R. Noyes, Sue D. Barber-Westin

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INTRODUCTION

Complex regional pain syndrome (CRPS) is the term that refers to a painful and disabling disorder that was first described during the United States Civil War.[195] Nomenclature relating to CRPS has varied over the years and has included Sudeck's atrophy, reflex sympathetic dystrophy (RSD), posttraumatic dystrophy, and causalgia. CRPS has a variable presentation, and no single test exists to confirm the diagnosis. The disorder usually follows tissue injury or surgery to a limb (although it may have a spontaneous onset[320]) that may be associated with sensory, vasomotor, sudomotor, motor, and dystrophic changes (Table 40-1).[301] The pain is distinct in that it is out of proportion to the inciting event and may be accompanied by discoloration of skin (Fig. 40-1), change in skin temperature, abnormal sweating, edema, and loss of the normal range of motion of the affected limb.

In 1994, the International Association for the Study of Pain (IASP) established a definition of CRPS to accommodate the various presentations, hypothesized pathophysiology, and anatomical structures involved.[194] The diagnostic criteria for CRPS recommended by the IASP involved four factors:

1. The presence of an initiating noxious event, or a cause of immobilization
2. Continuing pain, allodynia, or hyperalgesia in which the pain is disproportionate to any known inciting event
3. Evidence at some time of edema, changes in skin blood flow, or abnormal sudomotor activity in the region of pain (can be sign or symptom)
4. This diagnosis is excluded by the existence of other conditions that would otherwise account for the degree of pain and dysfunction.

In addition, the physician was instructed to diagnose CRPS-I if the criteria existed without "major" nerve damage and to diagnose CRPS-II if the criteria were found in the presence of major nerve damage. In this respect, the region of disproportionate pain was believed to originate initially within a dermatome.[194] As the disease progressed, it could spread beyond a single dermatome.

Although the standardized, internationally recognized terms of CRPS-I and CRPS-II were made available more than 3 decades ago, there continued to be inconsistencies in the literature that focused on this disorder. These were mainly believed to be caused by the poor specificity that existed for the IASP criteria, which lead to a high rate of false-positive diagnoses.[117] In response to this problem, an international consensus conference was held in Budapest in 2003 with the goal of improving the IASP criteria.[119] The resulting diagnostic criteria for CRPS, known as the "Budapest Criteria", were found to have excellent sensitivity and specificity (Table 40-2).[118] The Committee for Classification of Chronic Pain of the IASP approved these criteria and will use them in upcoming revisions of their formal classification and diagnostic criteria for pain states.[121]

TABLE 40-1 Terms Relevant to Complex Regional Pain Syndrome

Adrenergic: synapses in which the neurotransmitter epinephrine is used.
Abnormal sudomotor activity: excessive or spontaneous sweating.
Afferent neurons (sensory neurons): transmit sensory signals from receptors or sense organs to the central nervous system.
Allodynia: pain caused by a stimulus that normally does not produce pain (i.e., light touch, clothing, bed sheet).
Apraxia: loss of the ability to execute or perform learned skilled motor movements.
Bradykinesia: extreme slowness of movements and reflexes.
Dermatome: an area of skin that is innervated by sensory fibers from a single spinal nerve.
Dorsal root ganglions: transmits somatosensory information from afferent sensory nerve fibers (representing pain, pressure, and temperature) to the spinal cord.
Dystrophic changes: changes in the sympathetic nervous system which may include pain, sweating, edema.
Dystonia: sustained involuntary muscle contractions and spasms, cause twisting and repetitive movements or abnormal postures.
Efferent neurons (motor neurons): transmit signals from the central nervous system to effectors in the body such as muscles and glands.
Ephapses: abnormal synapses that occur between nerve fibers in the dorsal-root ganglion after a peripheral injury.
Hyperalgesia: increased sensitivity to painful stimuli.
Hyperreflexia: involuntary overactive or exaggerated reflexes.
Hyperhidrosis: excessive sweating.
Hypoalgesia: reduced sensitivity of painful stimuli.
Hypoesthesia: diminished or partial loss of sensation.
Hypohidrosis: diminished sweating.
Kinesiophobia: fear of movement.
Myoclonus: involuntary brief twitching of a muscle or group of muscles.
Neurogenic inflammation: inflammation that arises from the local release of inflammatory mediators (neuropeptides) from nociceptive C-fibers such as the substance P, calcitonin gene-related peptide, and bradykinin; evokes vasodilation in acute complex regional pain syndrome and may cause edema, sweating, elevated skin temperature, erythema, and hair growth.
Neurotransmitters, excitatory: increase the likelihood that a neuron will fire an action potential (i.e., epinephrine and norepinephrine).
Neurotransmitters, inhibitory: decrease the chance of a neuron firing an action potential (i.e., serotonin and gamma-aminobutyric acid).
Noradrenergic: synapses in which the neurotransmitter norepinephrine is used.
Paravertebral ganglia (sympathetic chain or trunk): a series of paired chains of ganglia which lie parallel to the vertebral bodies of the spinal column.
Preganglionic neurons: arise in the central nervous system and run to a ganglion in the body.
Postganglionic neurons: originate in the peripheral nervous system within a ganglion, synapse with preganglionic neurons, and then run to an effector organ.

Much debate continues regarding the etiology and pathophysiology of CRPS.[60,69,97,182,216,310] There are potential peripheral, afferent, efferent, and central mechanisms. The pain generator in CRPS has historically been described as being either sympathetically maintained pain (SMP) or sympathetically independent pain (SIP), depending on whether or not the sympathetic nervous system is involved.[296] A sympathetic nerve block has been recommended to determine how much of the patient's pain is "SMP" and how much is "SIP." The pain relieved by the block has been hypothesized to be SMP, although the remaining pain represents SIP.[294] However, recent research has questioned this explanation of pain and other signs and symptoms of CRPS, which appear to be more centrally involved, as will be discussed later.[60,138,216]



FIG 40-1 Dark discoloration of the limb upon initial presentation.

Despite the complexity of the definition of CRPS, the hallmark of this disease is pain usually starting in an arm or leg that is out of proportion to the inciting event of trauma or surgery. Recent research has shown that, despite prior beliefs, CRPS is not significantly associated with a history or presence of psychological problems.[13,14] The early diagnosis and treatment of this disorder is crucial because early management yields a more favorable outcome.[141,222,230,231] If not successfully managed, CRPS patients have a major loss of quality of life[275] and will most likely experience psychological consequences of their chronic pain.[59,315] This chapter covers basic relevant anatomy, proposed etiology and pathophysiology, clinical presentation, diagnosis, and treatment options for CRPS. It is important to note that controversy and a lack of consensus exists within the medical community regarding these issues.

ANATOMY

To understand the basis of the proposed etiology and pathophysiology of CRPS, the clinician must have an understanding of the human nervous system anatomy and function. Detailed knowledge of the innervation of the knee joint and lower limb is also required because in many instances, this disorder begins from obvious peripheral nerve injury[64] or minimal injury or degeneration of small distal nerves.[215,217]

Nervous System: Review of Basic Concepts

The human nervous system is divided into the *central nervous system* (CNS, the brain, spinal cord) and the *peripheral nervous system* (PNS, composed of cranial nerves, spinal nerves, and peripheral nerves with their motor and sensory endings). The PNS has sensory neurons that run from stimulus receptors to the CNS and motor neurons that relay information from the CNS to the muscles and glands. The PNS is subdivided into the *somatic* and *autonomic* nervous systems.

TABLE 40-2 Budapest Clinical Diagnostic Criteria for Complex Regional Pain Syndrome

General Definition:

CRPS describes an array of painful conditions that are characterized by a continuing (spontaneous and/or evoked) regional pain that is seemingly disproportionate in time or degree to the usual course of any known trauma or other lesion. The pain is regional (not in specific nerve territory or dermatome) and usually has a distal predominance of abnormal sensory, motor, sudomotor, vasomotor, and/or trophic findings. The syndrome shows variable progression over time.

To Make the Clinical Diagnosis of CRPS, the Following Criteria Must Be Met:

1. Continuing pain, which is disproportionate to any inciting event
2. Must report at least one symptom in *three of the four* following categories:
   - **Sensory:** Reports of hyperesthesia and/or allodynia
   - **Vasomotor:** Reports of temperature asymmetry and/or skin color changes and/or skin color asymmetry
   - **Sudomotor/edema:** Reports of edema and/or sweating changes and/or sweating asymmetry
   - **Motor/trophic:** Reports of decreased range of motion and/or motor dysfunction (weakness, tremor, dystonia) and/or trophic changes (hair, nail, skin)
3. Must display at least one sign at time of evaluation in *two or more* of the following categories:
   - **Sensory:** Evidence of hyperalgesia (to pinprick) and/or allodynia (to light touch and/or deep somatic pressure and/or joint movement)
   - **Vasomotor:** Evidence of temperature asymmetry (>1° C) and/or skin color changes and/or asymmetry
   - **Sudomotor/edema:** Evidence of edema and/or sweating changes and/or sweating asymmetry
   - **Motor/trophic:** Evidence of decreased range of motion and/or motor dysfunction (weakness, tremor, dystonia) and/or trophic changes (hair, nail, skin)
4. There is no other diagnosis that better explains the signs and symptoms

From Harden RN, Bruehl S, Stanton-Hicks M, et al. Proposed new diagnostic criteria for complex regional pain syndrome. *Pain Med.* 2007;8:325-331.

The somatic nervous system consists of cranial nerves (12 pairs), spinal nerves (31 pairs) (Fig. 40-2), and association nerves. It is the consciously controlled part of the PNS. Functions of this system include smell, vision, movement (stimulation of skeletal muscles), facial and mouth sensation, chewing, taste, swallowing, hearing, and balance.

The autonomic system controls the subconscious actions of cardiac muscle, smooth muscle, and glands. This system uses a two-neuron pathway from the CNS to the peripheral organ, known as the *sympathetic* and *parasympathetic nervous systems* that are described in detail later. There are two nerve fibers in this pathway termed *preganglionic* and *postganglionic*. The preganglionic neurons arise in the CNS and run to a ganglion in the body. They then synapse with postganglionic neurons, which run to the effector organ. Various neurotransmitters are frequently involved with this process, as we will describe later. For instance, postganglionic parasympathetic neurons release acetylcholine, while postganglionic sympathetic nerve fibers release norepinephrine.

CRITICAL POINTS Anatomy

- Review of nervous systems, autonomic system uses two-neuron pathway from central nervous system to peripheral organ, called sympathetic and parasympathetic nervous systems.
- Postganglionic parasympathetic neurons release acetylcholine, postganglionic sympathetic nerve fibers release norepinephrine, neurotransmitters involved with CRPS.
- Review afferent, efferent neurons, dorsal root ganglions, synapses.
- Sympathetic nervous system responsible for the fight-or-flight response, mediated by catecholamines epinephrine and norepinephrine, substance P.
- Catecholamine neurotransmitters stimulate α and β receptors. Stimulation α receptors: elevated heart rate and blood pressure, piloerection, and skin vasoconstriction. Stimulation β receptors: increased heart rate, muscle vasodilation, and bronchial dilation.
- Stellate ganglion supplies majority of sympathetic innervation to upper extremities, lumbar paravertebral ganglia supplies lower extremities.
- Nerves around knee and lower limb: femoral, obturator, common peroneal, tibial, saphenous, medial retinacular.

Neurons

Neurons process and communicate information within the body by transmitting electrical and also frequently electrochemical signals to other neurons or effector cells. A typical neuron contains a cell body, dendrites, and an axon (Fig. 40-3). Many axons are covered with a myelin sheath, which is an expanded plasma membrane of an accessory Schwann cell. There are areas where space exists between the sheath of Schwann cells, known as the node of Ranvier. These areas contain voltage-gated sodium channels, whereby depolarization sweeps along the cell. When depolarization reaches threshold, an action potential is generated. This in turn triggers the release of neurotransmitter chemicals, which will be discussed later.

Information is usually processed from the axon of one neuron to a dendrite of another, although there are exceptions to this rule. Dendrites frequently branch profusely and the axon may extend for a great distance, giving rise of hundreds of branches. There are three types of neurons:

- *Afferent neurons* (sensory neurons) transmit sensory signals from receptors or sense organs to the CNS. These neurons have an axon that extends to the periphery and another axon that extends into the CNS via the dorsal root. The cell body of these neurons is located in the dorsal root ganglion or a sensory ganglion of sensory cranial nerves (Fig. 40-4). The ventral and dorsal rootlets join together to form the root of a peripheral nerve. Specialized somatic sensory nerve endings known as nociceptors, mechanoreceptors, and thermoreceptors perceive pain stimuli, pressure stimuli, and temperature stimuli.
- *Efferent neurons* (motor neurons) transmit signals from the CNS to effectors in the body such as muscles and glands. They project their axons outside the CNS to directly or indirectly to control muscles. These include somatic and visceral motor neurons.
- *Interneurons* form complex networks within the CNS to integrate information between sensory and motor neurons.

Ganglions

Ganglions represent a group or nodule of cell bodies of sensory nerves (neurons) that are usually located outside the brain and spinal cord. There are two major types of ganglions: dorsal root (spinal) and autonomic.

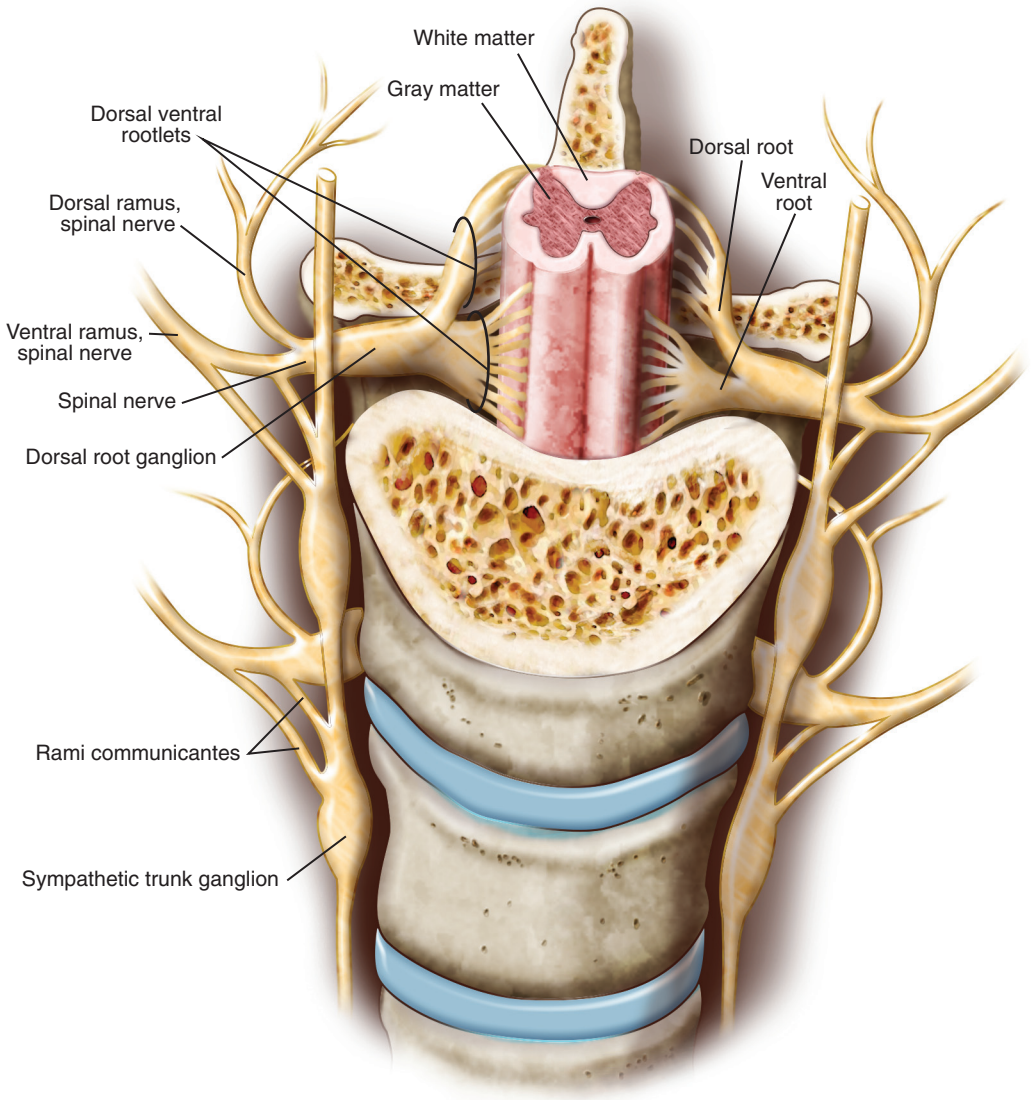


FIG 40-2 Major elements of a spinal nerve.

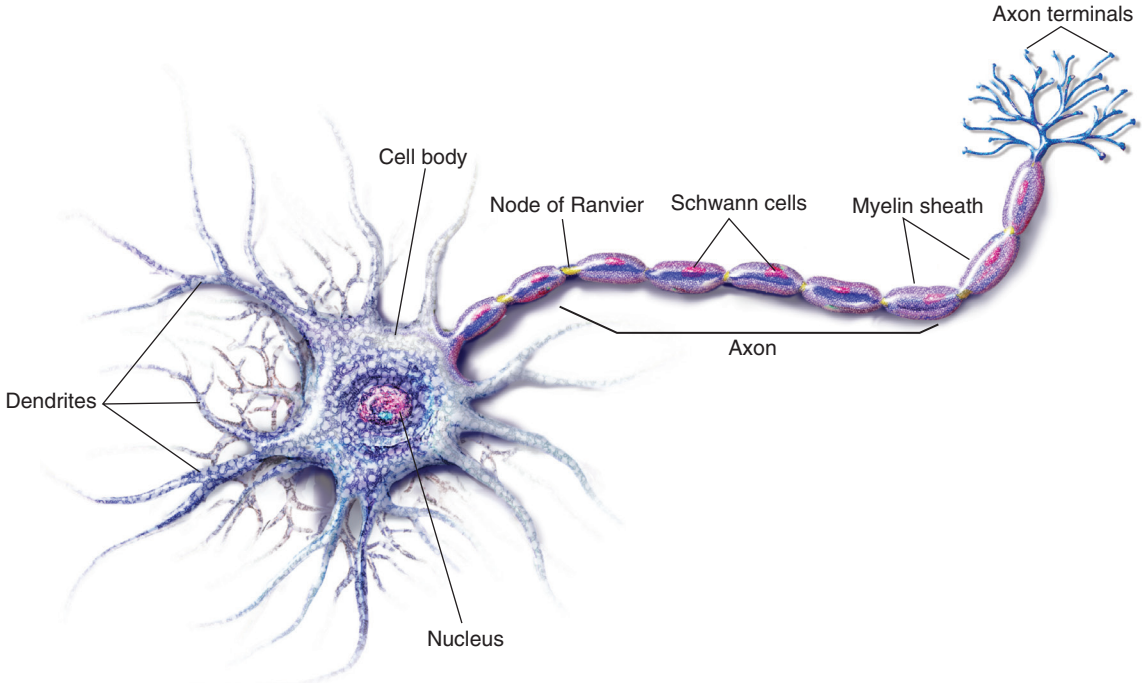


FIG 40-3 Basic components of a neuron.

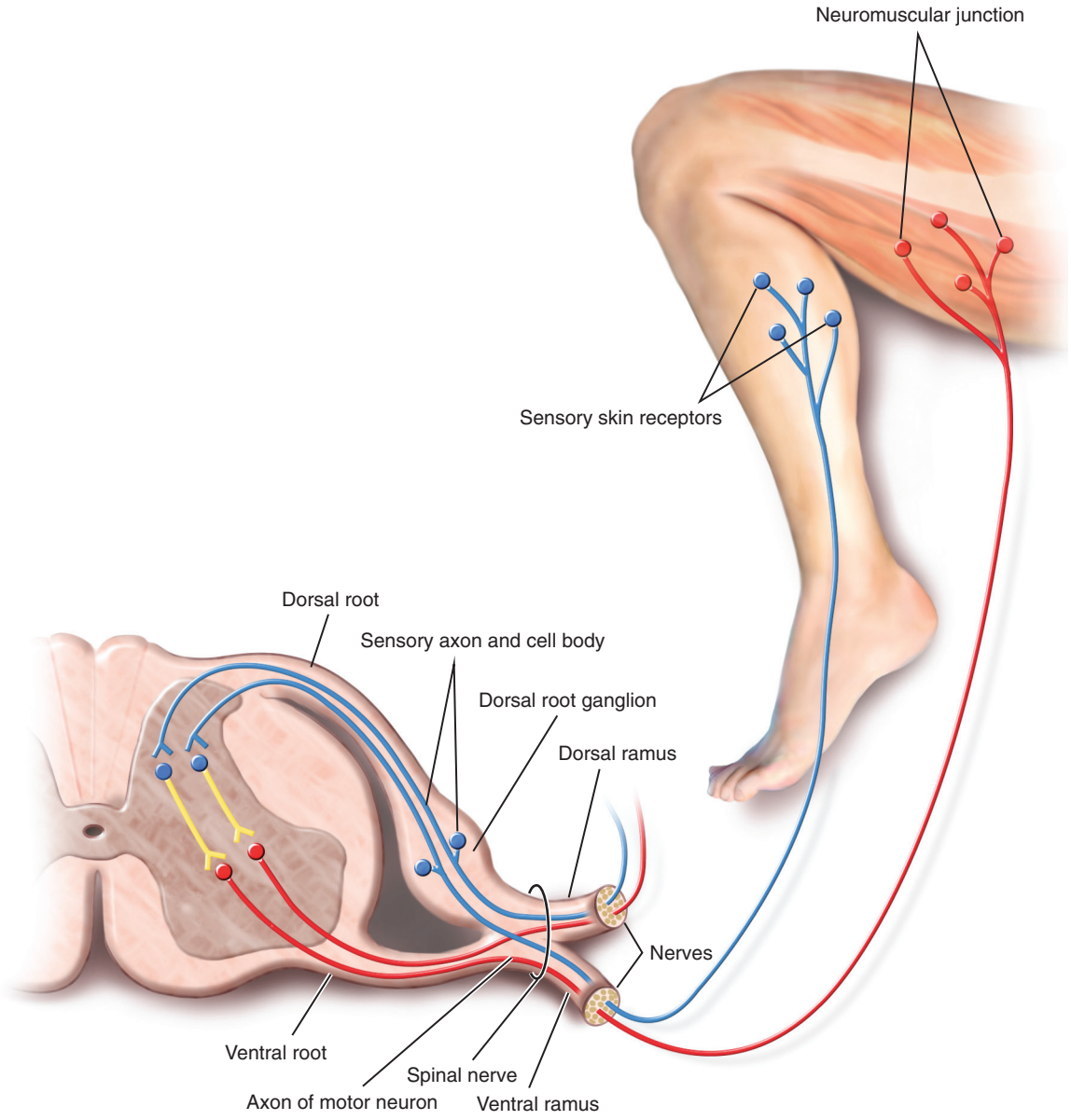


FIG 40-4 Path of afferent sensory skin receptor (blue line), which eventually causes contraction of the biceps muscle via efferent neurons (red line).

Dorsal root ganglions are located on dorsal roots along the vertebral column of the spine (Fig. 40-5).[107] It is through dorsal root ganglions that somatasesensory information from afferent sensory nerve fibers are transmitted (representing pain, pressure, and temperature) to the spinal cord.[284] Each sensory neuron in the dorsal root ganglion has a long axon which relays information to the spinal cord and ultimately to the brain in the parietal cortex.

Autonomic ganglions are part of the autonomic nervous system and are located along the sympathetic trunks, on the peripheral plexuses, and within the walls of organs.

Synapses

A synapse is the gap between a neuron and another cell (Fig. 40-6). Synapses may form between two neurons or between a neuron and an effector cell. In a typical synapse, contact occurs between the axon of one neuron and a dendrite or cell body of another.

Electrical synapses take place between two apposed neurons. The nerve transmission occurs by the passage of ions from one neuron to the other through gap junction channels. Electrical synapses occur much faster than electrochemical synapses.

An *electrochemical synapse* represents a junction that occurs between neurons or between a neuron and an effector cell via release of neurotransmitters that result in physiologic reactions.

Neurotransmitters are either *excitatory*, whereby they increase the likelihood that a neuron will fire an action potential, or *inhibitory*, in which they decrease the chance of a neuron firing an action potential. Major excitatory neurotransmitters include epinephrine and norepinephrine and some inhibitory neurotransmitters are serotonin and gamma-aminobutyric acid. Acetylocholine and dopamine may be either excitatory or inhibitory, depending upon the type of receptors that are present. Other neurotransmitters include various endorphins, enkephalins, and neuropeptides such as substance P.

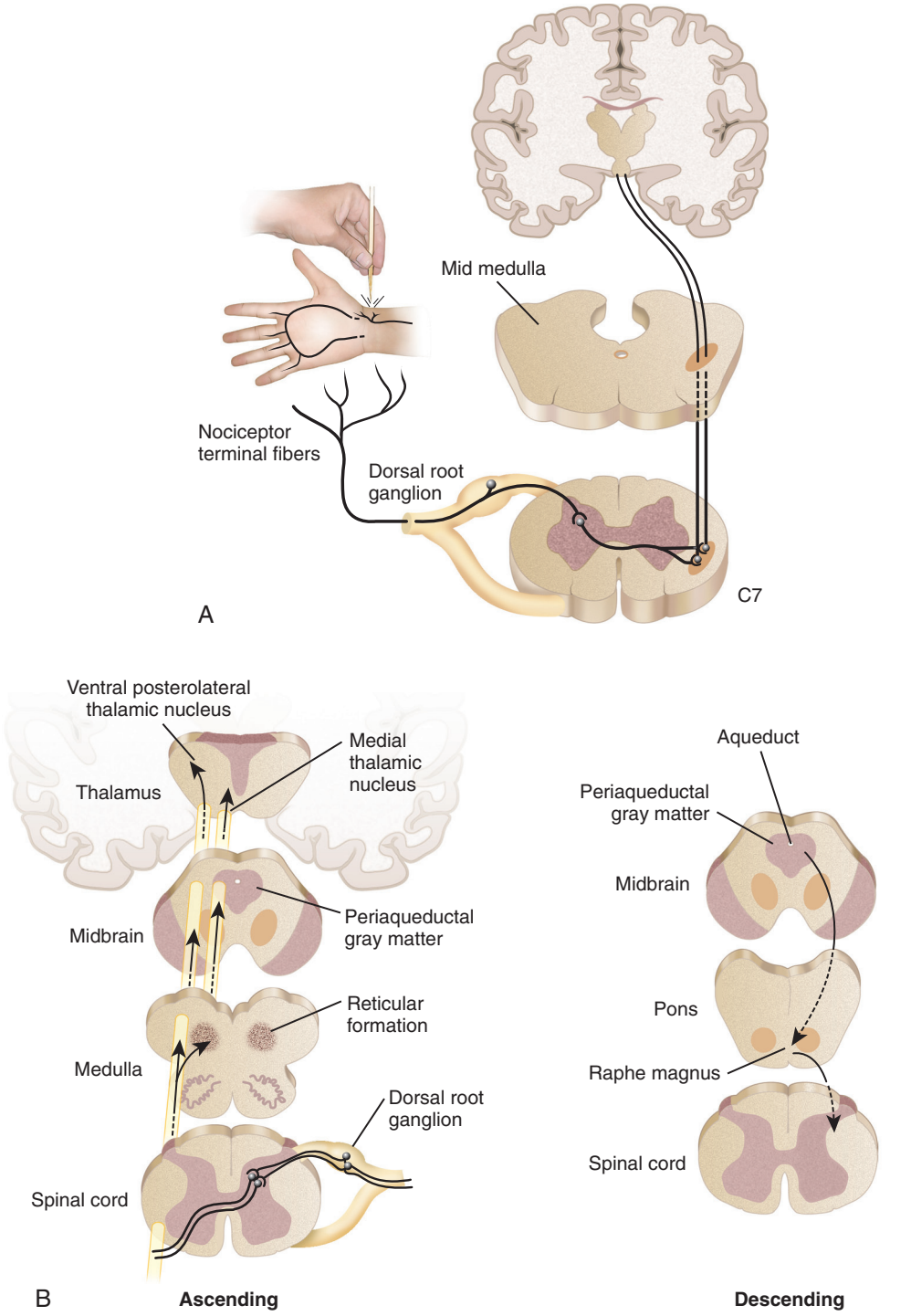


FIG 40-5 **A,** How peripheral nociceptive information is relayed by the peripheral nerve through the dorsal root ganglia to the dorsal horn of the spinal cord and then via contralateral ascending spinal tracks to the brainstem and cortex. **B,** How pain signals are modulated by descending pathways after processing in the core.

Acetylcholine is widely used at synapses in the neuromuscular junction; including motor neurons activating skeletal muscle, preganglionic neurons of the autonomic nervous system, and postganglionic neurons of the parasympathetic branch of the autonomic nervous system. Epinephrine (adrenaline) is considered a crucial component of the fight-or-flight response of the sympathetic nervous system and is released in substantial quantities when the body is under stress. Noradrenaline (norepinephrine) is released by postganglionic neurons of the parasympathetic branch of the autonomic nervous system.

At the end of a neuron's axon is an enlarged area known as the axon terminal, which is separated from the next cell by the synaptic cleft. Neurotransmitters release their contents by exocytosis into this cleft. The chemicals are received by receptor sites in the dendrites of the receiving neuron. When enough receptor sites have been filled, the

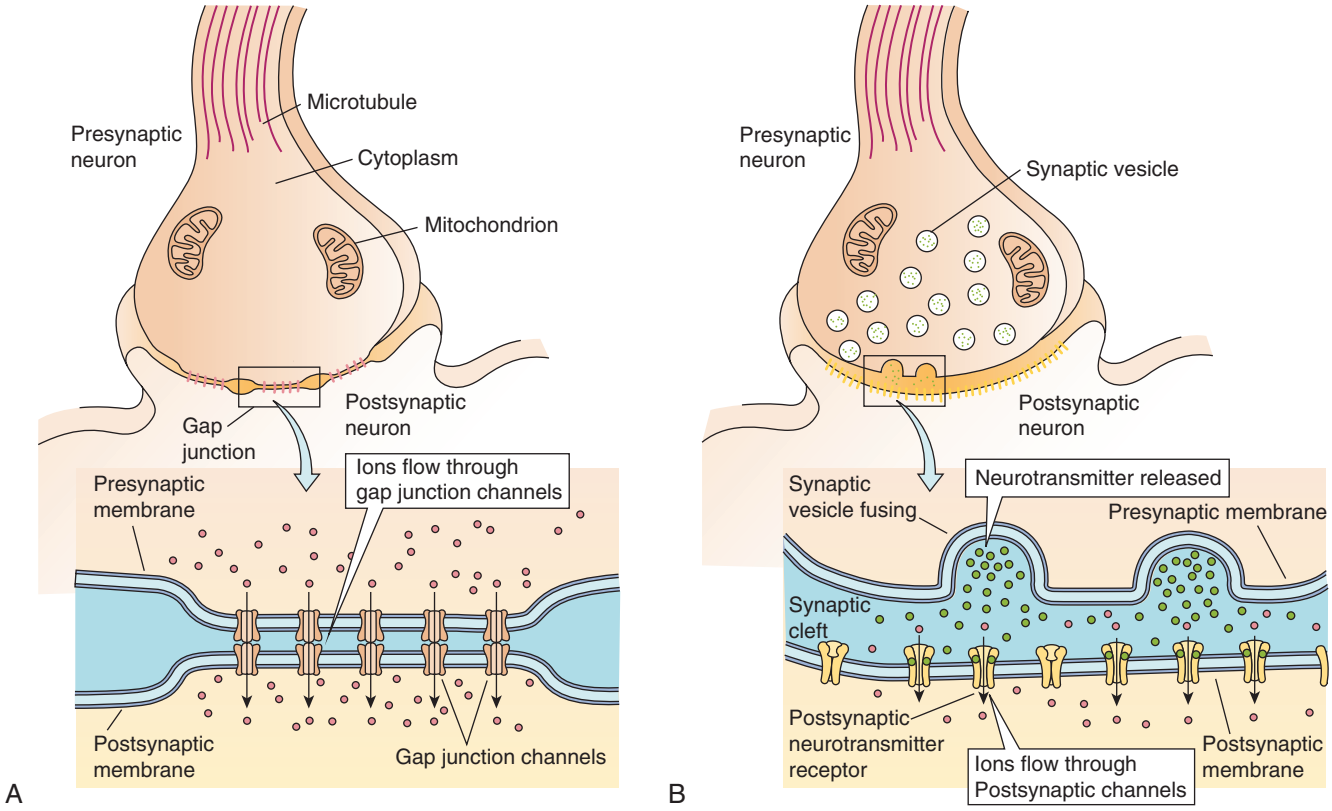


FIG 40-6 An electrical synapse **(A)** and an electrochemical synapse **(B)**. (Illustration licensed under a Creative Commons Attribution Share-Alike 3.0 License. From http://kin450-neurophysiology.wikispaces.com/file/detail/Chemical_vs_Electrical.jpg.)

receiving neuron sends the neuron impulse down its axon to its terminal fibers. The neurotransmitter is immediately inactivated by an enzyme.

In summary, before a sensory signal can be relayed to the nervous system, it must be transduced into an electrical signal in a nerve fiber. This involves a process of opening ion channels in the membrane in response to mechanical deformation; temperature; or, in the case of nociceptive fibers, signals released from damaged tissue. Many receptors become less sensitive with continued stimuli, termed adaptation. The adaptation may be rapid or slow, with rapidly adapting receptors being specialized for detecting changing signals.

There are encapsulated and nonencapsulated receptors in the skin. The nonencapsulated endings include free nerve endings, the peripheral end of the sensory axon. These mostly respond to noxious (pain) and thermal stimuli. Injuries to peripheral nerves may affect sensation and strength, resulting in severe weakness and muscle atrophy over time.

Sympathetic Nervous System

The sympathetic nervous system is responsible for the fight-or-flight response. This reaction is mediated by catecholamines, including epinephrine and norepinephrine. The term *adrenergic* refers to synapses in which epinephrine is used, although *noradrenergic* refers to synapses in which norepinephrine is used. Another neurotransmitter important for the sympathetic nervous system and CRPS is substance P, which is responsible for transmission of pain from certain sensory neurons to the CNS and aids in controlling relaxation of the vasculature and lowering blood pressure.

These catecholamine neurotransmitters stimulate α and β receptors. The stimulation of α receptors results in elevated heart rate and blood pressure, piloerection, and skin vasoconstriction. The stimulation of β receptors results in increased heart rate, muscle vasodilation, and bronchial dilation.[172]

Sympathetic nerve fibers originate inside the vertebral column at the first thoracic segment and extend to the third lumbar segment. Because the cells begin in both the thoracic and lumbar regions of the spinal cord, the sympathetic nervous system has a thoracolumbar outflow. Axons of these nerves leave the spinal cord and pass near the spinal ganglion.

The *paravertebral ganglia*, also termed the sympathetic chain or trunk, are a series of paired chains of ganglia that lie parallel to the vertebral bodies of the spinal column. The ganglia are interconnected to each other by nerve fibers and extend from the base of the skull down to the coccyx. There are three sympathetic chain ganglia located at the cervical level. The most inferior of these is the *stellate ganglion* which is believed to the supply the majority of the sympathetic innervation to the upper extremities. In the lower extremities, the sympathetic innervation is carried through *lumbar paravertebral ganglia*.[107]

All preganglionic motor neurons originate within the spinal cord and postganglionic fibers always originate in the PNS within a ganglion. There are 22 to 23 pairs of sympathetic chain ganglia. The interaction of nerve fibers begins at the spinal cord where they arise at the thoracolumbar region (T1-L2) and emerge via the ventral nerve root. They enter the sympathetic chain through the white rami communicans.

There are three options available to the preganglionic neurons in the sympathetic ganglion: (1) synapse with postganglionic neurons,

(2) pass up and down the sympathetic chain, and (3) leave the ganglion using a cord that leads to a special ganglia in the viscera. It is this ability to move superiorly and inferiorly along the chain that results in the mass response to the sympathetic nervous system. A preganglionic fiber may synapse to 15 to 20 postganglionic fibers. Sympathetic postganglionics from the chain enter the gray rami communicans and go back to the spinal nerves to be distributed to somatic tissues of the limbs and body walls.

The sympathetic nervous system innervates all vascular smooth muscle (vasomotor function for blood pressure control and distribution control), all sweat glands (sudomotor control: core temperature control), and all arrector pili smooth muscle of hair follicles (pilomotor function: temperature control). Stimulation of the sympathetic nervous system results in:

- Dilation of pupils
- Stimulation of sweat glands
- Accelerated heart rate
- Increased blood pressure
- Increased blood glucose levels
- Relaxed bronchial muscles
- Reduction of saliva and mucus
- Reduction digestive activity, urine secretion

There is a dual innervation of most organs of the body by the sympathetic and parasympathetic divisions. In these cases, one will inhibit and the other will excite, providing the opposite effect such as speeding or slowing of heart rate.

Parasympathetic Nervous System

The parasympathetic nervous system is composed mainly of the cranial and sacral spinal nerves. The preganglionic neurons, arising from either the brain or sacral spinal cord, synapse with just a few postganglionic neurons which are located in or near the effector organ (muscle or gland). The parasympathetic nervous system is responsible for the body's rest and digestion response when the body is relaxed, resting, or feeding. It basically undoes the work of sympathetic division after a stressful situation. The parasympathetic nervous system decreases respiration and heart rate and increases digestion. Stimulation of the parasympathetic nervous system results in:

- Construction of pupils
- Decreased heart rate and blood pressure
- Constriction of bronchial muscles
- Increase in digestion
- Increased production of saliva and mucus
- Increase in urine secretion

Nerves Around the Knee and Lower Limb

The major nerves around the knee and lower limb are shown in Figure 40-7. The two plexi that contribute to the innervation of the lower limb are the lumbar plexus and sacral plexus. The lumbar plexus (L2-4) gives rise to the *femoral* and *obturator nerves*. The obturator nerve innervates obturator externus, adductor brevis, adductor longus, adductor magnus, and gracilis. The femoral nerve innervates the iliacus, pectineus, all four heads of quadriceps, and sartorius. The terminal cutaneous branch of the femoral nerve is the saphenous nerve, which will be discussed in detail.

The sacral plexus (L4-5, S1-S3) forms the sciatic nerve, which passes deep to biceps femoris and divides into the *common peroneal nerve (common fibular nerve)* and the *tibial nerve* at the popliteal fossa. The tibial nerve innervates the popliteus, gastrocnemius, soleus, and plantaris. The common peroneal nerve innervates the peroneus longus, peroneus brevis, and short head of the biceps femoris muscles. The tibial nerve is the larger of the two divisions of the sciatic nerve. It runs vertically through the popliteal fossa directly underneath the fascia and is the most superficial of the neurovascular structures behind the knee. The common peroneal nerve separates from the tibial portion of the sciatic nerve at the apex of the popliteal fossa and then follows the tendon of the biceps femoris along the upper lateral margin of the popliteal fossa to the back of the head of the fibula. The nerve then winds round the neck of the fibula and passes deep to the peroneus

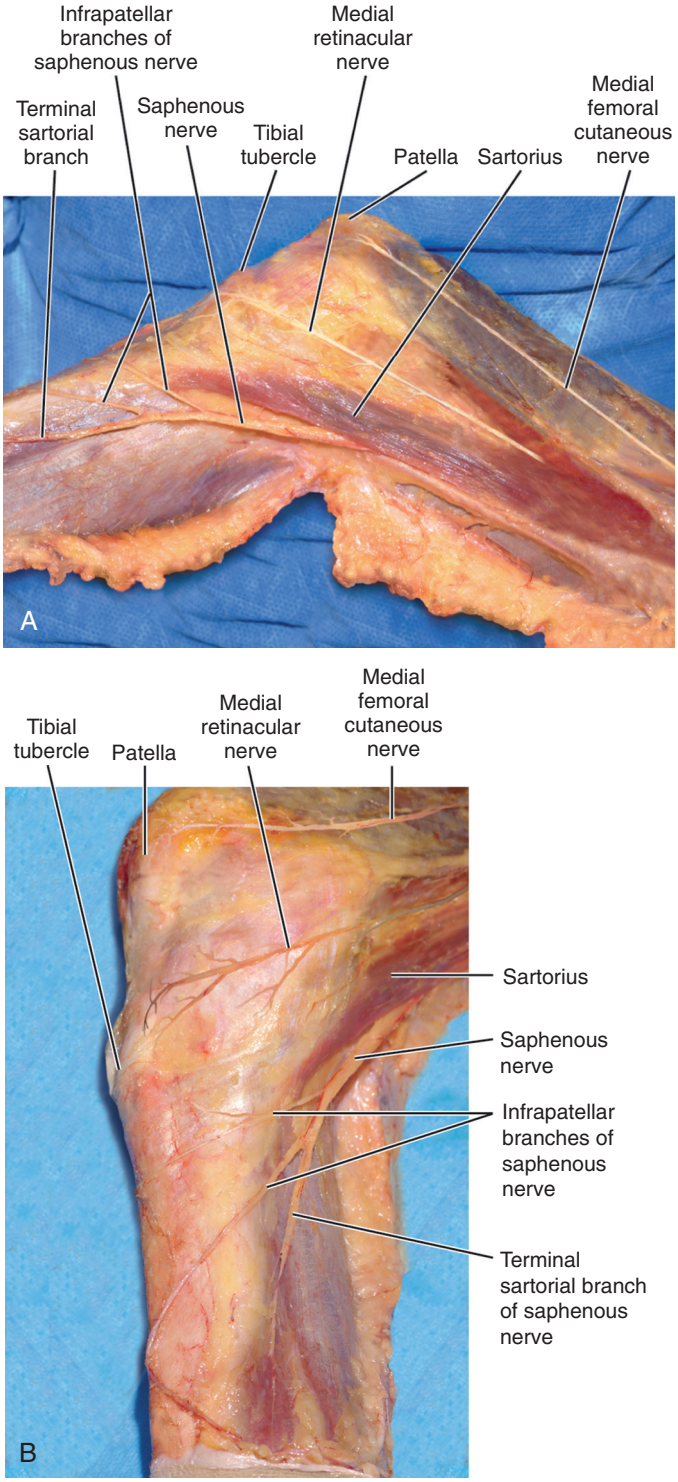


FIG 40-7 A, Anteromedial view of the superficial nerves. **B,** Medial view of the superficial nerves.

longus muscles and divides into the superficial and deep peroneal nerves.

On the medial side of the knee lies the *saphenous nerve* with its sartorial and infrapatellar branches, the medial femoral cutaneous nerve, and the medial retinacular nerve. The infrapatellar branch may follow four different courses at the medial joint line, which are described according to the nerve's relationship to the sartorius muscle. The medial femoral cutaneous nerve may travel superficially to the sartorius muscle, but is often found in Hunter's canal where it perforates the sartorius or exits deep to the sartorius. The medial retinacular nerve resides near the vastus medialis. A more detailed description of the innervation of the knee joint may be found in Chapter 39.

In the senior author's (F.R.N.) experience, many cases of knee CRPS-II are related or most likely directly caused by injury to the saphenous nerve or its branches. Injury may occur by direct trauma or contusions, or by surgical procedures on the medial side of the knee. Formation of a neuroma may result from direct injury by the scalpel during arthroscopic anteromedial portal placement. Techniques for avoiding injury to these structures include careful dissection through a 1-cm incision with identification of the nerve, transillumination with use of the arthroscope, and use of a 2-cm posteromedial incision with posterior retraction to deflect the needles anteriorly during inside-out medial meniscal repair.[252]

ETIOLOGY, PATHOPHYSIOLOGY

Several theories have been devised to explain the etiology and pathophysiology of CRPS. This chapter provides a summary of the more recent systematic reviews regarding these topics,[14,60,97,182,216,279,310] most of which discuss CRPS in general and not specifically as it relates to the knee joint.[69] Investigators typically agree that this disorder involves the central, autonomic, and somatic nervous systems; may be influenced by neurogenic inflammation and an immunologic response; creates central sensitization; and may induce cortical reorganization. In the chronic state, tissue ischemia/hypoxia may result from endothelial dysfunction and impaired circulation, and severe psychological distress and neuropsychological impairment may occur.

Etiology: Known and Speculated Risk Factors

It is known that surgery as benign as knee arthroscopy can injure nerve structures and precipitate CRPS-II, although the reported incidence has been less than 0.1%. Historically, a survey study conducted by the Arthroscopy Association of North America (AANA) of member orthopaedic surgeons in 1986 reported that 229 nerve injuries occurred during 375,069 arthroscopic knee procedures.[292] These included 97 saphenous nerve injuries, 11 peroneal nerve injuries, 7 femoral nerve injuries, 6 sciatic nerve injuries, and 108 tourniquet related or unspecified injuries. A more recent study reported 3 peripheral nerve injuries occurred in 12,271 patients who underwent knee arthroscopy.[189]

In historic outcome studies, knee surgery was frequently reported as the trigger for RSD, although whether this represented CRPS-I or CRPS-II cannot be determined with certainty. O'Brien and coworkers[214] described 60 patients referred for RSD of the knee. Of these, 40 had developed symptoms after knee surgery (24 arthroscopic and 12 arthroplasty procedures). One patient in this cohort had a neuroma identified as the potential trigger. Katz and Hungerford[144] reported the results of 36 patients treated for RSD of the knee, on whom 15 had knee surgery (6 arthroscopies, 5 total knee replacements, 1 patellectomy, 1 high tibial osteotomy, 1 medial arthrotomy, 1 Maquet tibial tubercle osteotomy). Six patients in this study had nerve injuries, two involving the peroneal nerve and four involving neuroma formation at the infrapatellar branch of the saphenous nerve. In 1988, Poehling and associates[230] described a series of 35 patients who developed RSD following injury to the infrapatellar branch of the saphenous nerve. These authors noted avoidance of trauma to this nerve during surgery was paramount, as was the early detection and initiation of treatment of RSD signs and symptoms.

In many instances, CRPS begins from obvious peripheral nerve injury,[63,64] and the diagnosis of CRPS-II is definitive; however, it may also stem from a minimal (occult) injury or degeneration of small distal nerves where the diagnosis of CRPS-I is made but may not be correct.[215,217] Knee pain may originate from direct damage to cutaneous nerves, such as the infrapatellar branch of the saphenous nerve, or from injury to a nerve far away from the knee, such as the lateral femoral cutaneous nerve.[63]

An injured or compressed peripheral nerve creates painful dorsal column input. A direct nerve injury may cause abnormal signaling, which may overstimulate sensory nerves or cause an imbalance in the normal release of transmitters resulting in an abnormal response.[69] There may also be formation of abnormal synapses (also termed *ephapses*) between nerve fibers in the dorsal-root ganglion after a peripheral injury that cause a type of short-circuit to occur. The signals being sent from the CNS to the PNS to control heart rate and other factors are short circuited to sensory fibers and misinterpreted as pain signals being sent from the PNS to the CNS.[131] The sympathetic nervous system drives the pain and, as a result, increased anxiety (which would normally increase blood pressure and heart rate) amplifies pain.

A neuroma may form as a result of a nerve injury. Within this neuroma, the transected sensory nerve endings develop a catecholamine sensitivity through the upregulation of α receptors (which respond to epinephrine from the autonomic nervous system).[236] In this manner, when the sympathetic nervous system sends signals to increase heart rate, the increased density of α receptors in the sensory nerve endings of the neuroma are stimulated and transmit the pathologic pain signal back to the CNS.[11] There is also a theory in which a similar upregulation of α receptors occurs in the dorsal root ganglion.

Whether the upregulation of α receptors occurs in the dorsal root ganglion or a peripheral nerve neuroma, it helps to explain the increased pain patients have in physical therapy or in the clinic because they anticipate the pain associated with an examination or treatment. This anxiety stimulates the fight-or-flight response. The catecholamines released from the sympathetic nervous system stimulate the intended targets of heart and blood vessels. However, because of the upregulation of α receptors, they also stimulate the sensory nervous system and produce pain.

CRITICAL POINTS Etiology, Pathophysiology

- CRPS involves central, autonomic, and somatic nervous systems.
- CRPS may be influenced by neurogenic inflammation and an immunologic response.
- CRPS may create central sensitization and induce cortical reorganization.
- Chronic CRPS may result in tissue ischemia/hypoxia from endothelial dysfunction and impaired circulation, severe psychological distress, and neuropsychological impairment.
- CRPS-II results either from obvious nerve injury/neuroma or minimal injury/compression/degeneration of small distal nerves.
- CRPS may be caused by abnormal increase in sympathetic nervous system activity after a stimulus (injury or surgery). However, role of sympathetic dysfunction questionable as the disorder progresses over time.

Small nerve fiber damage may cause edema, sweating, and vasodysregulation. In this case, CRPS represents a neuropathic pain syndrome initiated by limb trauma or its treatment. Small-fiber polyneuropathy has the same signs and symptoms as CRPS (abnormalities in limb color and temperature, sweating, and hair growth). Some neurosurgeons believe nearly all CRPS is initiated or explained by nerve injury or dysfunction and that treatment should be directed toward resolving this problem surgically.[64,215] Oaklander suggested that the terms CRPS-I and CRPS-II be abandoned and replaced with neuropathic pain syndrome.[215]

There is no association between preexisting psychological disturbances and the development of CRPS; however, studies have reported a relationship between stressful life events and the ensuing development of this disorder.[21,88,89] Immobilization of an injured limb may be a risk factor, especially following a fracture.[188] Fractures, especially those of the upper extremity, are the most common precipitating event of CRPS.[60] There is a potential genetic predisposition to this disorder, but further studies are required.

Autonomic Dysfunction

Some investigators have suggested that CRPS occurs because of an abnormal increase in sympathetic nervous system activity after a stimulus (injury or surgery).[6,130,140,172] Pain may be provoked by sympathetic outflow via sympathetic-afferent coupling in which adrenergic receptors are expressed on primary afferent nerve endings.[12,265] There may be reduced sensory input from the affected limb, an increase in peripheral catecholamine receptor sensitivity (adrenergic supersensitivity), or injury-mediated hypersensitivity at target organs to sympathetic discharge.[69]

In the early stage of the disorder, a red and warm affected extremity is frequently present, which may stem from neurogenic inflammation and/or inhibition of sympathetic vasoconstrictor neurons (from a decreased centrally mediated sympathetic outflow) and subsequent vasodilation.[182] In the chronic stage, decreased limb temperature and vasoconstriction may occur. Supersensitivity of innervated vascular structures may exist in the affected limb from decreased sympathetic activity or release of norepinephrine by the sympathetic nerve fibers.

Some investigators have questioned the role of sympathetic dysfunction because the disorder progresses over time, especially in patients who still experience pain after (apparently) successful sympathetic blocks[60,97,188] and in those with chronic CRPS. Some patients initially present with a bluish, cold affected extremity, which may be caused by reactive adrenoceptor upregulation and/or supersensitivity rather than a dysregulation of the sympathetic outflow.[70] Permanent cold temperature in chronic cases may be caused by endothelial rather than sympathetic dysfunction.[266] The percentage of pain that depends on sympathetic activity declines over the course of CRPS, as indicated by failure of sympathetic blocks in patients 24 months or more from the onset of the disorder.[144,222,299]

Sweating and trophic disturbances are not predominant features of CRPS and may be attributed to neuropeptide effects. SMP may be caused by failure of spinal inhibitory mechanisms to suppress nociceptive input by normal (instead of increased) sympathetic stimulation.[60] Inflammation or nerve injury may precipitate sprouting of new sympathetic nerves centrally in the dorsal horn or peripherally in the upper dermis.[330]

Investigations have demonstrated that the warmer affected extremity in acute CRPS is caused by inhibition of cutaneous sympathetic vasoconstrictor activity that leads to cutaneous vasodilation.[111,327,329] Several studies detected decreases in sympathetic neurotransmitters (noradrenaline, neuropeptide Y) from postganglionic sympathetic vasoconstrictor fibers on affected extremities.[71,120,325,327,329] The loss of vasoconstrictor responses and increase in skin temperature are not believed by some to be caused by a peripheral lesion of sympathetic fibers.[325] Symmetrical, normal sympathetic innervation has been measured in CRPS patients by positron emission tomography scanning[104] and histochemical evaluation of skin biopsies.[72] Conclusions have been made that a "profound central inhibition is the underlying mechanism of disturbed sympathetic vasoconstriction in the acute stage of CRPS" (Fig. 40-8).[325]

Neurogenic Inflammation

An exaggerated inflammatory response to injury or surgery in patients diagnosed with CRPS has been noted for many years.[297] Classic

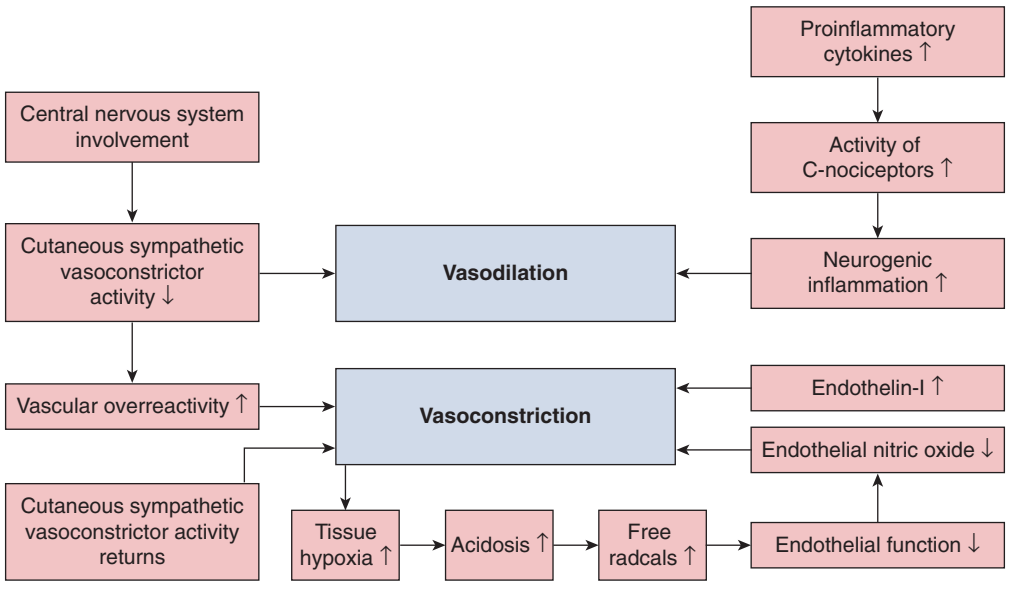


FIG 40-8 Mechanisms involved in vasomotor disturbances in complex regional pain syndrome. (From Wasner G. Vasomotor disturbances in complex regional pain syndrome—a review. *Pain Med.* 2010;11:1267-1273.)

inflammation is marked by immune cells such as lymphocytes, phagocytes, and mast cells that secrete proinflammatory cytokines. Recent studies have shown that inflammatory mediators are elevated in CRP-affected limbs, including interleukin-6 and tumor necrosis factor α (TNF α),[16,108,133,205,269] as well as activated monocytes and macrophages.[127] However, systematic parameters of classic inflammation, including white blood cell count and C-reactive protein, are normal in CRPS patients. It therefore appears that a neurogenic inflammatory process may instead occur, which may explain many of the signs and symptoms of CRPS.

Trauma causes the release of nerve growth factor and proinflammatory cytokines, both of which can activate and sensitize peripheral nociceptors. Neurogenic inflammation arises from the local release of inflammatory mediators (neuropeptides) from nociceptive C-fibers such as the substance P, calcitonin gene-related peptide (CGRP), and bradykinin.[60,182,188] These neuropeptides have been shown to be elevated in CRPS patients.[22,25,268] They evoke vasodilation in acute CRPS and may cause edema, sweating, elevated skin temperature, erythema, and hair growth. Also, aberrant neuropeptide signaling may cause decreased limb temperature and trophic changes.

Central Sensitization

Central sensitization is a process in which the excitability of neurons in the spinal cord is increased. In the *Raja model,*[235] pain receptors (nociceptors) upregulate their α receptors. Because the body is constantly sending sympathetic signals, these nociceptors are being constantly stimulated, which reduces the CNS threshold for perceiving pain.[247] Changes occur in the dorsal root ganglion.[115] The mechanoreceptors responsible for light touch sensation and thermoreceptors responsible for cold sensation instead produce an abnormal painful response when they stimulate the sensitized central pain neurons. The term central sensitization may be used to explain the clinical findings of allodynia and hyperalgesia.

In the Raja model, treatment by sympathetic blockade is effective by the production of a temporary inhibition of norepinephrine release. By temporarily blocking the release of catacholamines, the sympathetic block relieves pain. By allowing the CNS to experience relief from pain, the central pain neurons may be desensitized (downregulation of α receptors), resulting in a long-term improvement in the painful response to light touch.[11]

The change in regulation of α receptors also explains the change in appearance of the limb over time. Initially, an increase in α receptors causes excess stimulation, which presents as a red, warm, and swollen limb (increased sympathetic function). Later, as the body adjusts and downregulates the expression of α receptors, the same limb will take on a blue, cool, and contracted appearance.[11] Secondary psychological problems such as pain-related fear and movement anxiety have been associated with central sensitization.[310] Changes in somatosensory processing have been shown to occur at the cortical level in CRPS-I[319] of the upper extremity.

Central Nervous System Alterations, Cortical Reorganization

Many studies have stressed the important role of the CNS in the disease process of CRPS.[9,90,140,178,182,191,276,312] The question of whether the changes that occur in the CNS do so as a direct response to the initiating event or subsequently over time remains unanswered. There are changes in central sympathetic, somatosensory, and motor systems that many believe imply alterations occur in the CNS. Many patients develop muscle paresis in the affected limb, which results in restrictions in active range of motion.[276] Studies have reported that 9% to 49% of patients with CRPS develop movement disorders such as loss of voluntary control, bradykinesia, myoclonus, dystonia, and tremor.[312] Central sensitization occurs as a result of functional and structural changes in the CNS. The pattern of sensory disturbances is usually not limited to the area of a single peripheral nerve but are rather in a wider area detected as brush-evoked allodynia.[70,182] Hemisensory deficits have been reported, with sensory disturbances detected in the contralateral normal limb.[253,254] Thermoregulatory reflexes are disturbed in the distal areas of the affected limbs, which investigators attributed to alterations in cutaneous vasoconstrictor neurons.[329] In addition, up to 50% of patients with chronic CRPS-I develop hypoesthesia on the affected side of the body, which is believed to be caused by changes in central processing of tactile stimuli at the thalamic or cortical level.[253,254]

Alterations in the CNS are manifest in CRPS studies that have demonstrated impaired perceptual learning,[177] global cognitive impairment,[171] altered brain activation patterns,[66,85,162,176,279] changes in cerebral blood flow, and body perception disturbances (Fig. 40-9).[60] *Cortical reorganization* is a potential consequence of this disorder, with functional magnetic resonance imaging (MRI) studies providing evidence of alterations in the primary somatosensory cortex (S1) contralateral to the CRPS affected side.[179,180] Changes have also been detected in the motor cortex during finger tapping tests.[176] Altered central opioidergic neurotransmission was reported in one study from ligand positron emission tomography studies.[155] Abnormal thalamocortical activity (spontaneous abnormal low frequency rhythmic magnetoencephalographic activity) was detected in another study of CRPS patients.[324] Patients may abnormally activate the dorsolateral and ventromedial prefrontal cortex, regions important for perceptual learning and emotional decision making.[171]

The sensory representation of the CRPS-affected limb is frequently altered in that the limb feels disfigured and out of place.[97] From a psychophysical standpoint, studies have reported that high percentages of patients (54%-84%) have cognitive and/or motor neglect–like symptoms in which the affected limb may feel foreign, and directed mental and visual attention are required to move the limb.[84,86,87] Patients may perceive the affected limb to be larger than it actually is[201] or that the limb is altered in shape and appearance.[170] In one study, patients with long-standing CRPS expressed strong negative feelings about the affected limb, and many wanted it amputated.[170] Libon and associates[171] noted that significant neuropsychological deficits were present in 65% of 137 patients with chronic CRPS. These included reduced performance on tests that assessed working memory/mental search and problems on tests of naming and memory. These impairments were not associated with spread of CRPS to other limbs, duration of symptoms, or medication use. These authors concluded that the data was consistent with recent MRI studies suggesting the disorder involves the CNS and involves a large amount of cortical and subcortical areas.

Limb Ischemia/Hypoxia

The concept that limb ischemia or hypoxia occurs in CRPS-affected limbs is associated with the inflammatory hypothesis.[97] There is the possibility that the abnormal inflammation leads to a compartment-syndrome scenario that results in oxygen–free radical–induced microvascular damage. This in turn leads to further tissue ischemia and nociceptor excitation. The presence of ischemia, with decreased capillary oxygenation, has been shown in superficial skin layers in CRPS-affected limbs and may also be present in deeper tissues.[157,306] In muscle, nuclear magnetic resonance spectroscopy showed signs of acidosis and impaired high-energy phosphate metabolism in amputated specimens from patients with chronic CRPS.[306] Hypoxia and its associated acidosis and free radical formation can trigger primary afferents to cause severe pain. It has been proposed to be caused by extreme

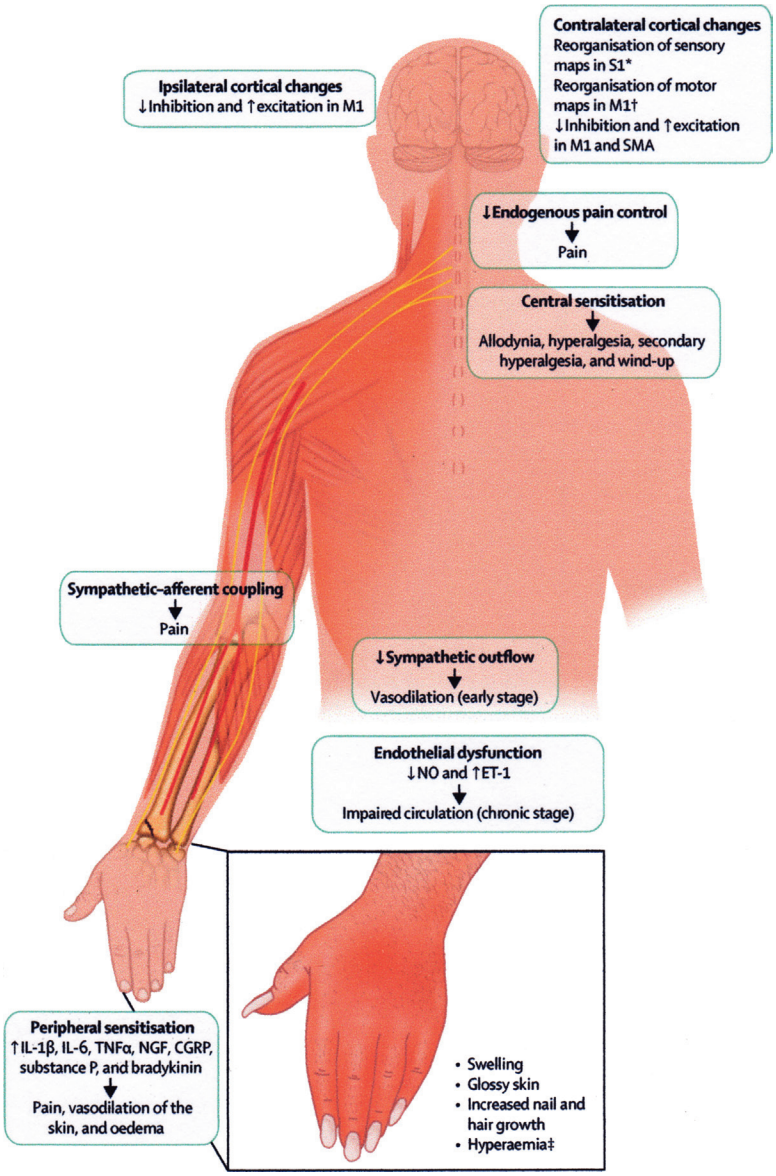


FIG 40-9 Clinical features and proposed pathophysiologic mechanisms of complex regional pain syndrome (CRPS). Although these pathophysiologic mechanisms have all been identified in CRPS, they might occur independently of each other. The absence of such fixed relations explains the clinical heterogeneity that is often encountered in this condition. *Reorganization of contralateral S1 is associated with spontaneous CRPS pain and mechanical hyperalgesia. This reorganization might also explain altered sensations (e.g., perceptual disturbances and referred sensations). †Reorganization of contralateral M1 is associated with motor dysfunction (i.e., tapping). However, these changes might be secondary to the symptoms rather than being a cause of the symptoms. ‡Decreased sympathetic outflow might also be responsible. *CGRP*, Calcitonin-gene-related peptide; *ET*, endothelin; *IL*, interleukin; *M1*, primary motor cortex; *NGF*, nerve growth factor; *NO*, nitric oxide; *S1*, primary somatosensory cortex; *SMA*, supplementary motor cortex; *SP*, substance P; *TNF*, tumor necrosis factor. (From Marinus J, Moseley GL, Birklein F, et al. Clinical features and pathophysiology of complex regional pain syndrome. *Lancet Neurol.* 2011;7:637-648.)

vasoconstriction or from a local imbalance between endothelial factors.[108, 266]

Psychological Factors

The association between psychological factors and CRPS-I is controversial because of the lack of high quality studies.[14] Historically, many believed that preexisting psychological disorders played a role in the development of this disorder.[4,313] However, a recent systematic review encompassing 31 studies conducted by Beerthuizen and associates[14] refuted this bias. This investigation found no evidence for a relationship between CRPS-I and depression, anxiety, neuroticism, anger, obsessive-compulsive behavior, comatization, hostility/anger, interpersonal sensitivity, extraversion/introversion, or paranoia. There did appear to be a relationship between stressful life events that were soon followed by the development of this disorder.[21,88,89] This association has been hypothesized to be caused by a repeatedly triggered sympathetic

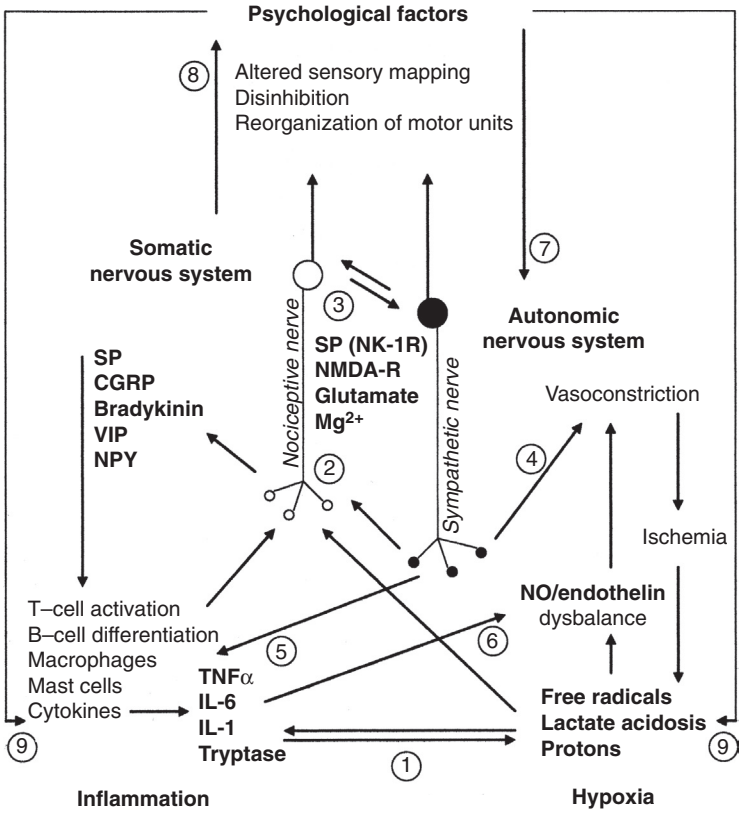


FIG 40-10 Possible paths for interaction among proposed pathogenic mechanisms of complex regional pain syndrome. 1. Hypoxia may trigger inflammatory response *(Interaction: hypoxia inflammation [classic and neurogenic])*. 2. Continuous nociceptive input by hypoxia, inflammation, or sympathetic stimulation may lead to sensitization and alterations in cortical organization of sensory and motor units. *(Interaction: hypoxia, inflammation, and autonomic dysfunction somatic neuronal dysfunction [sensitization and cortical reorganization])*. 3. Neuropeptides (substance P [SP]) released in dorsal horn may facilitate sensitization through interaction with NK-1 and NMDA) receptors. *(Interaction: inflammation [neurogenic] somatic neuronal dysfunction [sensitization])*. 4. Sympathetic dysfunction (either central sympathetic hyperactivity or increased peripheral adrenergic receptor hypersensitivity) may cause hypoxia because of impaired nutritive blood flow. *(Interaction: autonomic dysfunction hypoxia)*. 5. Adrenergic receptors can be expressed on immune cells, and catecholamines can modulate cellular immunity, and it also has been speculated that inflammation may change sensitivity or expression of α-adrenergic receptors on nociceptive fibers. *(Interaction: autonomic dysfunction inflammation [classic])*. 6. Cytokines influence the balance of nitric oxide (NO) to endothelin (ET). *(Interaction: [classic] inflammation hypoxia)*. 7. Psychological distress may influence sympathetic outflow and levels of catecholamines. *(Interaction: psychopathology autonomic dysfunction)*. 8. Severe chronic pain and disability may cause psychological distress. *(Interaction: somatic neuronal dysfunction [sensitization] psychopathology)*. 9. Fear of movement may result in the accumulation of inflammatory mediators and free radicals and prevent desensitization. *(Interaction: psychopathology inflammation and hypoxia and somatic neuronal dysfunction)*. *CGRP*, Calcitonin gene-related protein; *IL*, interleukin; *Mg^2*, magnesium ions; *NK-1R*, neurokinin-1 receptor; *NMDA-R*, N-methyl-D-aspartate receptor; *NPY*, neuropeptide Y; *SP*, substance P; *TNF α,* tumor necrosis factor α; *VIP*, vasoactive intestinal pain. (From de Mos M, Sturkenboom MD, Huygen FJ. Current understandings on complex regional pain syndrome. *Pain Practice* 2009;9:86-99.)

system (from the stressful event), which develops an altered local catecholamine responsiveness, resulting in prolonged increased autonomic arousal.[14] A recent prospective study found a positive association between the development of CRPS-I after a distal radius fracture and patients with an "anxious personality," or a high level of general anxiety.[67] However, there was no significant relationship between a history of psychiatric disorder and the development of CRPS-I.

There is a relevant question of the contribution of longstanding CRPS to the development of psychological disturbances. There are psychophysiological mechanisms that we previously discussed that may lead to changes in personality and management of anger. In chronic cases, extreme fear of pain may lead to disuse of the affected extremity resulting in prolonged immobilization that leads to decreased active range of motion, diminished nutritive blood flow, and trophic alterations (Fig. 40-10).[60]

Autoimmune Disorder

Studies have shown evidence of antineuronal autoantibodies in 30% to 90% of CRPS patients.[23,100,159] A randomized controlled trial reported that low-dose intravenous immunoglobulin reduced pain in chronic CRPS, considered circumstantial evidence for an autoimmune etiology.[97] Several case reports have been published that report the onset of CRPS in patients with an autoimmune disease.[60] A recent investigation suggested that antigens for the autoantibodies found in CRPS patients

might be α adrenoceptors and muscarinergic acetylcholine receptors.[188] The question of autoimmune mechanism involvement in the pathophysiology of CRPS requires further study.

DIAGNOSIS

Differential Diagnosis

The diagnosis of CRPS-I and CRPS-II is based mostly on clinical findings. Other diseases and disorders such as infection, inflammatory disorder, metabolic disorders, vascular insufficiency, neoplasms, stress fractures, and missed intraarticular disorders should be ruled out. Pelvic disorders and occult hip osteoarthritis should also be excluded in patients with knee symptoms. Neuropathy (such as diabetic polyneuropathy) and unilateral arterial or venous occlusive diseases may present with similar symptoms and must be ruled out.

The full blood count, erythrocyte sedimentation rate, fasting blood sugar, and serum calcium levels should be determined along with thyroid function to exclude systemic causes of pain. There is no laboratory marker for CRPS. Increased white blood count, erythrocyte sedimentation rate, and C-reactive protein can indicate a generalized inflammatory process, but these findings are nonspecific. However, these tests along with others such as rheumatoid factor and antinuclear antibody tests assist in identifying other possible diagnoses (Table 40-3).

The diagnosis for CRPS is based on criteria obtained from the patient's medical history, clinical presentation, and comprehensive diagnostic tests to be described. The Budapest clinical diagnostic criteria should be used as described in Table 40-2.[119] The presence of at least three of the symptoms and two of the signs shown in Table 40-2 has a diagnostic sensitivity of 0.85 and specificity of 0.69.[119] The inclusion of all four of the symptom and sign components increases the diagnostic sensitivity to 0.95 and specificity to 0.81.[118]

CRPS-II indicates nerve injury, entrapment, or compression or the formation of a neuroma. In the knee, this frequently involves the saphenous nerve and/or its branches and, therefore, the detection of this problem is paramount. Electromyography (EMG) and nerve conduction studies are helpful to determine the presence of a nerve injury, nerve root avulsion, entrapment, or a painful neuropathy attributed to diabetes. Documentation of a pain source with a successful diagnostic nerve block is indicative of CRPS-II.[64] However, it is important to realize that sympathetic hypersensitivity and denervation do not account for all the abnormalities in CRPS-II because the symptoms often spread beyond the dermatome of the damaged nerve.

CRITICAL POINTS Diagnosis

- Diagnosis CRPS-I and CRPS-II based mostly on clinical findings, Budapest clinical diagnostic criteria. No laboratory marker available. Early diagnosis highly important.
- Women have a higher incidence.
- Usual trigger is trauma, surgery, immobilization.
- Rule out all other possible diseases and disorders.
- EGM studies, diagnostic nerve blocks indicate CRPS-II.
- Most common finding is pain disproportionate to the inciting event: burning and shooting, or as deep, constant, and aching.
- Changes in skin temperature and color, extraarticular and painful swelling, frequent findings.
- Hyperalgesia and/or allodynia usually present, hypoalgesia may also exist.
- Motor abnormalities: decreased active range of motion, action tremors, myoclonus, hyperreflexia, muscle spasm, voluntary guarding.
- Tests: x-rays, MRI, bone scan, diagnostic nerve block, skin surface temperature.

Clinical Presentation

The clinical presentation of CRPS has diverse signs and symptoms, but one of the most common findings is pain disproportionate to the inciting event. Women have a higher incidence of developing this disorder, with reported female/male ratios varying from 2:1 to 4:1.[21,58,261,275] The average age of onset ranged from 41.8 years to 50.4 years in three investigations,[3,21,261] and in a more recent investigation of 656 patients, 37.8 ± 12.3 years for males and 36.7 ± 12.1 years for females.[275] The usual trigger is trauma to an extremity from an injury that is frequently treated with immobilization. Surgery is another initiating event. Approximately 3% to 11% of cases are of spontaneous onset.[62]

The percent of CRPS-I patients in one investigation who experienced specific symptoms and signs of the disorder according to the Budapest criteria is shown in Table 40-4.[121] The most commonly self-reported symptoms were asymmetry in skin color, hyperesthesia (allodynia, hyperpathia), asymmetric edema, and motor changes. The most frequent signs observed on physical examination were skin color

TABLE 40-3 Differential Diagnoses for Complex Regional Pain Syndrome

Problem	Potential Diagnoses
Bone or soft tissue injury	Stress reaction, stress fracture, ligament damage, meniscus tear
Neuropathic pain	Peripheral (poly) neuropathy, nerve entrapment, neuroma, radiculopathy, postherpetic neuralgia, deafferentation pain after cerebrovascular accident (stroke), plexopathy, motor neuron disease, metabolic (diabetes), neoplastic
Infection	Bone, joint, soft tissue, skin
Inflammation	Erysipelas, inflammation nitric oxide synthase, bursitis, seronegative arthritis, rheumatologic diseases, Lyme disease
Compartment syndrome	
Arterial insufficiency, vascular disease	Thrombosis, acrocyanosis, atherosclerosis, thromboangitis obliterans (Burger's disease), Raynaud's disease, erythromelalgia, phlebothrombosis
Movement disorders	
Lymphatic or venous obstruction	
Central nervous system	Stroke, neoplasm, encephalitis, spinal cord trauma or transverse myelitis, multiple sclerosis, poliomyelitis
Myofascial pain	Overuse, disuse, tennis elbow, repetitive strain injury, fibromyalgia
Thoracic outlet syndrome	Nerve compression or vascular compression
Gardner-Diamond syndrome	
Psychiatric problems	Self-harm, somatoform pain disorders (malingering), Munchhausen syndrome

TABLE 40-4 Statistically Significant Differences in Diagnostic Signs and Symptoms of CRPS-I Patients vs. Non-CRPS Patients with Neuropathic Pain

Variable	CRPS-I (n = 113)	Non-CRPS (n = 47)	P Value
Self-reported symptoms (% yes):			
Skin color asymmetry	91.1	27.7	<.01
Hyperesthesia (allodynia, hyperpathia)	90.2	63.8	<.01
Asymmetric edema	89.2	40.4	<.01
Motor changes	88.3	46.7	<.01
Temperature asymmetry	86.6	38.3	<.01
Trophic changes	75.0	38.3	<.01
Sweating asymmetry	62.5	15.2	<.01
Hypoesthesia (localized numbness)	38.5	65.0	<.01
Signs observed on physical examination (% yes):			
Skin color asymmetry	83.9	36.2	<.01
Hyperalgesia to pinprick	81.5	43.5	<.01
Decreased active range of motion	80.0	37.8	<.01
Motor changes (any)	79.3	40.0	<.01
Allodynia (any stimulus)	70.5	29.8	<.01
Temperature asymmetry by palpation	69.4	14.9	<.01
Trophic changes (any)	68.5	29.8	<.01
Allodynia to cold	63.5	10.5	<.01
Asymmetric edema	63.5	24.2	<.01
Allodynia to deep joint pressure	67.6	26.7	<.01
Hypoesthesia to light touch	57.7	77.5	<.05
Altered reflexes in affected area	50.8	86.7	<.05
Sweating asymmetry	43.8	10.6	<.05
Allodynia to vibration	40.0	10.5	<.05
Tremor	30.1	5.6	<.05
Dystonia	26.5	5.6	<.05
Mean asymmetry by infrared thermometry (°C)	–0.62 ± 1.97	0.11 ± 1.04	<.01

From Harden RN, Bruehl S, Perez RS, et al. Validation of proposed diagnostic criteria (the "Budapest Criteria") for complex regional pain syndrome. *Pain.* 2010;150:268-274.
Factors not statistically different not shown. The negative thermometric asymmetry value for the complex regional pain syndrome (CRPS) group indicates that on average, the affected side was colder.

TABLE 40-5 Self-Reported Symptoms According to Years After Onset of CRPS

Variable	First 5 yr (n = 485) %	>10-15 yr (n = 171) %	Correlation With Progression of CRPS (P Value)
Loss of strength	93	94	NS
Dynamic mechanoallodynia	91	>96	NS
Continuous pain	87	98	NS
Touch allodynia	84	>90	NS
Muscle spasms	84	93	NS
Skin temperature changes	83	95	<.05
Swelling	75	90	<.05
Skin color changes	71	81	<.05
Abnormal limb posture	57	80	<.05
Visceral (internal organ) pain	47	62	<.01
Increased sweating	33	44	NS

From Schwartzman RJ, Erwin KL, Alexander GM. The natural history of complex regional pain syndrome. *Clin J Pain.* 2009;25:273-280.
CRPS, Complex regional pain syndrome; *NS,* not significant.

asymmetry, hyperalgesia to pinprick, decreased active range of motion, and any motor changes. A natural history study of 656 patients treated between 1 and 46 years following the onset of CRPS-I and CRPS-II had similar findings in terms of self-reported symptoms (Table 40-5) but also reported a vast array of "other" problems that occurred over the course of the disease (Table 40-6).[275]

Disproportionate Pain to Inciting Event

The hallmark finding of CRPS is pain disproportionate to the inciting event. The disproportionate response includes pain more intense than expected, lasting longer than expected, and expanding beyond the dermatomal region of the extremity. Pain is the body's response to impending or ongoing cell death. With CRPS, the pain may be generated in the absence of cellular insult.[160] Within hours to days after the inciting event, the pain becomes diffuse and expands beyond the site of the injury and dermatomal area in a stocking or glove pattern, with a preference for distal limb involvement. Patients describe the pain as burning and shooting or as deep, constant, and aching. A classic finding is allodynia, which is found during the physical exam and described by the patient as the inability to tolerate pressure from bed sheets at night, clothing, and even air currents. The pain may fluctuate in intensity in response to many influencing factors. Pain may worsen with aggressive physical therapy, weather changes (becoming colder), physical activity, and fear or agitation.

Vasomotor Abnormalities

Changes in skin temperature and color are frequent findings. In most patients, the limb will initially appear red, warm, and dry and progress over time to a mottled, bluish, cool and moist condition. However, some affected limbs will be blue and cooler than the opposite extremity after the initial onset of the disorder.

Sudomotor/Edema Abnormalities

Patients frequently report extraarticular and painful swelling. This is a prominent finding early in the course of the disease that decreases over time. Initially, the skin is edematous but gradually is replaced by skin that is tight, shiny, and lacking in normal skin creases.[75] Excessive or diminished sweating or sweating asymmetry is also frequently noted. The sudomotor function may be opposite of what is normally expected. A red and swollen limb will normally be moist, and a bluish and cool limb will normally be dry.

Sensory Abnormalities

There is usually evidence of hyperalgesia and/or allodynia, but there may also exist hypoalgesia. Of particular interest is an unusual

TABLE 40-6 Other Symptoms and Problems in 656 Patients with CRPS Followed From 1 to >20 Years After Onset

Symptom	% Affected	Correlation With Progression of CRPS (*P* Value)
Pain interfered with quality of life	>97	NS
Pain interfered with personal relationships	93	NS
Pain spread	92	NS
Pain caused work disability	81	NS
Difficulty sleeping	71.9	NS
Tiredness	68.5	<.05
Weakness	64.7	NS
Headache	61.5	NS
Memory problems	54.5	NS
Difficulty thinking	52.6	NS
Sweating	48.5	NS
Cold weather aggravated pain	48	NS
Feeling drowsy	38.9	NS
Constipation	38.9	<.01
Physical activity aggravated pain	37	NS
Dizziness	35.1	NS
Nausea	33.4	NS
Indigestion	26.6	NS
Lack of appetite	26.6	NS
Urinary problems	24.9	<.01
Blurred vision	24.5	NS
Itching	25.5	<.05
Weight changes	23.0	NS
Rash	19.5	NS
Diarrhea	17.8	.01
Swallowing difficulties	16.9	NS
Difficulty breathing	15.7	<.01

From Schwartzman RJ, Erwin KL, Alexander GM. The natural history of complex regional pain syndrome. *Clin J Pain.* 2009;25:273-280.
CRPS, complex regional pain syndrome; *NS*, not significant.



FIG 40-11 A and **B**, Ice test.

intolerance to cold, which is often first encountered in physical therapy when cryotherapy is used to control swelling and elicits a significant painful response.[172] In the office, the clinician may conduct an ice cube test (Fig. 40-11) in which ice is applied to the sensitive region and the patient's evoked sensations are determined. The abnormal response the clinician seeks is a description of intolerable, burning pain. Early after the onset of CRPS, the patient may describe the sensation evoked from the ice cube test as decreased cold sensation compared with the contralateral limb. In a similar manner, cold weather can precipitate a painful flare.[172]

Motor Abnormalities

Some form of motor impairment is usually present. The abnormalities range from decreased active range of motion to hyperfunction, manifested as action tremors, myoclonus, hyperreflexia, muscle spasm, and voluntary guarding.[270] Even when motor abnormalities are grossly evident, EMG test results may be normal. This finding suggests that the motor response of CRPS is centrally mediated, most likely at the spinal cord level.[326] Initially, weakness may be attributed to disuse and expected muscle atrophy. Some patients develop pseudoparalysis, which may extend to limb neglect. In long-standing illness, dystonia, apraxia, lack of coordination, and impaired proprioception may be present.[9,10,92,326]

Trophic Changes

Common trophic changes are abnormal nail growth, increased or decreased skin hair growth, fibrosis, thin and glossy skin, and osteoporosis.

Psychological Issues

Historically, a bias toward patients with CRPS and their disproportionate pain existed in terms of belief of fictitious disorders or other psychiatric overtones. However, as with other chronic pain syndromes, comorbid psychiatric disease either develops as a result of the pain syndrome or it promotes the pain syndrome.[36,218] It is uncertain whether or not this is a cause or effect of CRPS, but in daily diaries kept by patients with chronic pain, investigators found that a depressed mood one day contributed to increased pain the next day.[80] In addition, pain one day contributed to depression, anxiety, and anger the next day. It is likely that the emotional and behavioral disturbances are the

result of chronic pain and loss of function. These psychological disturbances have been shown to resolve when the pain resolves.[187,198]

Stages and Natural History of Complex Regional Pain Syndrome

Historically, three progressive stages of CRPS have been cited, but their existence has since been disproven.[33,121,199] A patient with CRPS may present with some or all of the well-known signs and symptoms but may also present only with disproportionate pain. In addition, the natural history of CRPS does not appear to have progressive stages.[275] The largest natural history study published to date encompassed 656 patients, 485 of whom were followed from 1 to 9 years and 171 of whom were followed 10 to 46 years after the onset of the disorder.[275] The authors noted that after 1 year, most of the signs and symptoms were well developed and did not change greatly thereafter (see Table 40-5). None of the patients demonstrated a spontaneous remission of symptoms. The data were collected via a patient questionnaire between 1995 and 2006, so many patients did not have access to the latest treatment options which could have affected the course of the disorder.

Objective Tests

CRPS is primarily a clinical diagnosis. There are no laboratory tests or imaging studies that can absolutely confirm this diagnosis; however, many are useful for lending additional credibility to clinical suspicions and ruling out other possible diagnoses.[199,272]

Radiographs

Radiographs of the affected knee should be taken to rule out concomitant pathology. In the acute phase of CRPS, no change in radiographic appearance will be found. As the disorder progresses, films will reveal decreased cortical density of the affected extremity when compared with the contralateral limb. The classic radiographic finding for CRPS is a patchy periarticular osteoporosis, with osteopenia of the patella and medial femoral condyle.[130,291] In late stages, profound bone demineralization occurs.[49]

Magnetic Resonance Imaging

MRI should be performed to exclude other possible causes of pain and allow the clinician to narrow the differential diagnosis. MRI may identify a possible focus for the pathology that triggered the disease, such as a meniscus tear. It may also detect bone marrow edema, stress reaction, stress fractures, soft tissue changes, and occult fractures. MRI findings of CRPS include thickening of the skin, intraarticular effusions, soft tissue and muscle edema, interstitial edema, and vascular hyperpermeability.[212,278] Chronic changes are muscle atrophy, fibrosis or fatty infiltration of the affected muscle, and thinning of the skin.[212,278]

Triple-Phase Bone Scintigraphy

The diagnosis of CRPS based on results of triple-phase bone scintigraphy (TPBS) is controversial.[129,156,199,340] The TPBS has three phases: arterial, soft tissue and bone. Historically, wide ranges of sensitivity (19%-97%) and specificity (56%-97%) have been reported in the ability of this test to diagnose CRPS.[272] Note that many studies did not use the current standardized criteria for the diagnosis of CRPS, and most focused on upper extremity disease involvement. Fluctuations in sensitivity and specificity have been hypothesized to be attributed to the use of phases I and II of the bone scan, qualitative or quantitative image analysis, and the time that elapsed between the onset of CRPS symptoms and when the scan was performed.[335] Some studies reported increased uptake in CRPS in the second and third phase of the scan.[225,270] A recent investigation found that the TPBS was highly specific in diagnosing CRPS of the upper limb when only phase 3 of the test was considered and when the test was done within 5 months of the onset of the disorder.[335]

A recent investigation of 69 patients diagnosed using the Budapest criteria with either upper or lower extremity involvement reported sensitivity of TPBS for the diagnosis of CRPS of 40.6% and specificity of 76.6%.[199] The odds ratio of TPBS for diagnosing CRPS was 2.24 (95% CI, 0.98-5.12). Although a positive TPBS result was related to skin color changes and edema, the diagnostic performance of the test was low. The authors reported no differences in findings based on the chronicity of the disorder and believed their findings support the absence of pure clinical stages of CRPS.

Few studies have evaluated the diagnostic ability of TPBS for lower extremity CRPS. Wuppenhorst and associates[335] empirically noted several technical limitations of this test that occur at the feet. For example, the tracer uptake in phase 3 is smaller than that noted in the hands, leading to a weaker demarcation of the joints. In addition, regions of interest can currently only be localized over the metatarsophalangeal joints.

Successful treatment of CRPS may result in a paradoxical increase in tracer uptake as the blood flow improves to the affected limb.[129,183] Thus increased uptake to a limb can indicate CRPS in the initial phase or successful treatment of the disorder (Fig. 40-12). This tendency for change in bone scan results over time is also why this test should not be used to track the course of the disease or the success of treatment.[129,341]

Diagnostic Blocks

In patients with suspected nerve injuries or neuromas, a diagnostic nerve block is indicated. In the knee, this usually involves the infrapatellar branch of the saphenous nerve and may also involve the medial retinacular nerve, the medial cutaneous nerve, and the lateral retinacular nerve. Dellon[64] recommends a 50:50 mixture of 1% xylocaine and 0.5% bupivacaine, each without epinephrine. Each nerve block contains 5 cc of this mixture that is injected into the region of the known joint afferent and not into the nerve itself or suspected cutaneous neuroma. Ten minutes after the block, the patient is asked to walk on level ground, climb and descend stairs, and kneel on a padded chair. A reduction of 5 points on a visual analogue scale confirms sufficient relief and a diagnosis of CRPS-II.

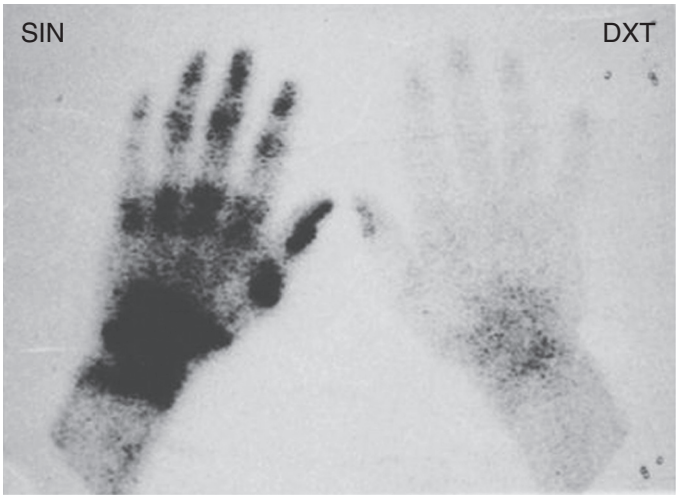


FIG 40-12 The left hand represents either an acute-phase complex regional pain syndrome (CRPS) or successful treatment of CRPS. The right hand represents either a normal examination or a dystrophic/atrophic-phase CRPS.

A lumbar sympathetic ganglion block is one tool used for both diagnosing and treating CRPS-I, although its use is controversial.[125,172,233] The patient is injected with a local anesthetic under fluoroscopic control. Successful block of the ganglion is monitored by documenting vasomotor and sudomotor changes in the extremity. van Eijs and associates[308] recently defined a successful block as one in which there is radioscopic confirmation of adequate craniocaudal contrast dye outline over the prevertebral sympathetic chain at the L3-L4-L5 level for the lower limb and at the C6-C7-T1 level for the upper limb.

The patient may be examined while the block provides relief to determine if a specific focus for the pain exists. Before the procedure, the patient may complain of diffuse pain about the knee. Following a successful block, the patient may be able to localize the pain (for instance, to the medial aspect of the knee), and the clinician may be able to localize clinical findings to a specific disorder (such as saphenous neuritis). We recommend that a MRI be done before a lumbar block to detect other possible triggers for pain such as a meniscus tear to avoid the necessity of this test. It is important to note that there are many potential side effects of a sympathetic block. A recent study[308] found that 79% of 27 patients with lower extremity (Table 40-7) and 90% of 22 patients with upper extremity CRPS-I had side effects following the procedure. In addition, a potential placebo effect may ensue following sympathetic blocks.[218,271,293] Horner's syndrome (partial ptosis, miosis, and anhidrosis) may occur after a stellate block.

Spinal or epidural blocks may be used for diagnosis of CRPS because the nerve fibers respond to varying concentrations of local anesthetic differently. The lowest concentrations of local anesthetic penetrate the least myelinated sympathetic nerve fibers. At increasing concentrations, the sensory nervous system is blocked, and even higher concentrations block the motor system. When used to test for CRPS, the initial injection is often saline to detect a placebo response. Unfortunately, even at low concentrations, some sensory blockade that may lead to false-positive results occurs.[172]

Vasomotor Measurement

Skin surface temperature measurements may be done by the clinician using a variety of commercially available devices. Handheld infrared thermometers measure skin temperature in the periphery of the hands and feet.[34,118,145,199,211,219,221,224,328,332] There is also a noninvasive clinical thermal test that assesses the function of small nerve fibers and their central connections. An investigation of 37 hands and 48 feet in patients with tonic dystonia showed cold and warmth hypesthesia without increased heat pain sensitivity with this device.[207] Thermography is another technique available for detecting temperature differences.[43,211] However, this test requires extensive setup and monitoring and is not useful clinically if only for cost reasons. One problem with all of the available skin surface temperature devices is that there is no agreement on the amount of temperature difference which constitutes a positive test for CRPS.

Sudomotor Measurement

The quantitative sudomotor axon reflex test (QSART) is one method of measuring sweat output. In this test, acetylcholine is administered to the extremities, and the sweat output of each extremity is measured and compared.[20,174,262] One criticism of this test is based on the theory that sudomotor dysfunction is centrally mediated and this test has its mechanism of action at the postganglionic sympathetic neuron. Therefore, the results of this test may not reflect CRPS sympathetic hyperactivity.[20]

TABLE 40-7 Side Effects After Lumbar Sympathetic Ganglion Blockade in 28 Patients

Side Effect	*n* (%) Patients	Median Time (Range) (Days)
Back pain	17 (60.7)	2 (0-7)
Increased pain	10 (35.7)	3 (0-11)
Headache	8 (28.6)	2 (0-3)
Groin pain	5 (17.9)	2.5 (0-3)
Nausea/vomiting	5 (17.9)	2 (1-3)
Hoarseness	2 (7.1)	3 (2-4)
Hematoma	2 (7.1)	3 (2-4)
Dysphagia	1 (3.6)	1 (0-1)
None	6 (21.4)	

From van Eijs F, Geurts J, van Kleef M, et al. Predictors of pain relieving response to sympathetic blockade in complex regional pain syndrome type 1. *Anesthesiology.* 2012;116:113-121.

TREATMENT

Many treatment options have been proposed for CRPS, but few are supported by high-level clinical trials. This is especially true for CRPS related to the knee or lower extremity. Even so, agreement exists in the literature that multiple disciplines should be involved in providing patient care, including orthopedists, neurologists, pain specialists, anesthesiologists, physical therapists, occupational therapists, psychologists, and primary care physicians.[121,172,182,295]

The treatment options presented in this section should begin as soon as possible following a definitive diagnosis. Identification and appropriate management of nerve injuries in CRPS-II patients should be performed without delay. In CRPS-I patients, all attempts should be made to identify any triggers responsible for the abnormal

CRITICAL POINTS Treatment

- Multiple disciplines should be involved, including orthopedists, neurologists, pain specialists, anesthesiologists, physical therapists, occupational therapists, psychologists, and primary care physicians.
- Few treatment options are supported by high-level studies for lower extremity CRPS.
- Educate patient; ensure he or she is actively involved in treatment options.
- Identify, treat nerve injuries immediately.
- Look for hidden triggers in CRPS-I.
- Begin physical therapy, occupational therapy immediately. Include graded exposure to activities/movements/light touch, desensitization activities, active range of motion and flexibility, water therapy, graded motor imagery and mirror visual feedback, coping/relaxation techniques, tissue massage. Work hardening, vocational rehabilitation required to return to normal function.
- Use psychotherapy as required in patients with chronic CRPS.
- Medications: few tested in high-level studies. Treat comorbidities as required. Options include corticosteroids, nonsteroidal anti-inflammatories, free radical scavengers, bisphosphonates, anticonvulsants, calcium channel blockers.
- Stronger interventions: IV ketamine, sympathetic block, epidural infusion, surgical sympathectomy, neurostimulation, surgery.
- Authors disagree with amputation, high percentage recurrence symptoms, phantom pain.

pain response (such as a meniscus tear). Although surgery may be poorly tolerated in some patients, it may be done in a manner that minimizes the chance of exacerbating the condition.[172] In most cases, it is worth the risk of worsening the condition to eliminate the primary cause of the pain symptoms. There is a general consensus that physical and occupational therapy is paramount in the treatment of CRPS, although high level data regarding the specific components and modalities (along with other medical and psychological intervention) that successfully restore normal function are currently not available.[68,121]

Regardless of the lack of high-level investigations, protocols and practical guidelines for the treatment of CRPS have emerged from consensus conferences, metaanalyses, systematic literature reviews, and extensive clinical experience. In 2013, Harden and associates[121,310] described the necessity for specific treatments that included physical therapy, occupational therapy, vocational rehabilitation, medications, psychotherapy, and if required, interventions (nerve blocks, drug infusions, implantable pain treatment devices) to regain *functional restoration*. Functional restoration is based on the principle of gradual and steady progression from activation of presensorimotor cortices (graded motor imagery) to gentle active movements to weight-bearing activities. An increase in function corresponds with desensitization to increasing sensory stimuli. A gradual increase in normalized sensation is believed to reset some of the complex, higher central changes previously described, such as central sensitization. These investigators introduce pharmaceutical and other interventions if the patient fails to progress in a reasonable time frame, to be discussed later.

Occupational and Physical Therapy

Occupational and physical therapy are considered essential in the treatment of CRPS.[21,53,68,202,220,244] In fact, many drug regimens are intended to relieve symptoms so patients can tolerate effective therapy measures. Several guiding principles[53] have been developed for therapy of CRPS patients (Fig. 40-13), including:

- Patient education
- Graded exposure to activities, movements, light touch
- Sensorimotor treatment: desensitization activities
- Exercises: flexibility, active range of motion, water therapy, stress loading
- Graded motor imagery and mirror visual feedback
- Pain management: coping/relaxation techniques, tissue massage

A successful patient-therapist alliance with strong communication is paramount. The therapist must be an advocate for the patient, gaining trust and lending credibility to the treatment regimen. Slow response to treatment and frequent setbacks may occur, but confrontations between the patient and therapist are always counterproductive.[295] The rehabilitation program should not be overly aggressive because this may trigger more pain, edema, distress, and fatigue that only exacerbate the inflammation and sympathetic symptoms of CRPS. Cryotherapy should be avoided.

In patients with a recent onset of CRPS, when pain is experienced at rest, therapy should consist of careful and gentle active and active-assisted mobilization. Exercises on the contralateral extremity may be performed. In patients with long-standing CRPS, therapy should initially focus on correcting the "mismatch between the motor and sensory systems and the sustained attention to the painful limb."[190] A program that combines graded motor imagery and mirror visual feedback[30,79,168,190,263] is becoming popular.[121] *Graded motor imagery* (Table 40-8) attempts to sequentially activate the premotor and primary motor cortices through limb laterality recognition, motor imagery (imagination), and mirror therapy (small movements performed by the opposite extremity that are watched in a mirror while the affected extremity is hidden from view). Moseley in 2004[200] described a three-stage program that was found to effectively alleviate pain in chronic CRPS-I patients with upper extremity involvement.[200] A recent metaanalysis found that this program had large (beneficial) effects compared with standard physical therapy alone in patients with chronic pain syndromes.[30] Although the mechanisms of the effect of this program remain unclear, the hypothesis is that this type of training forces attention to the affected extremity, decreases kinesiophobia, and provides corrective sensory feedback into a system when a discrepancy exists between motor output and sensory feedback.[190]

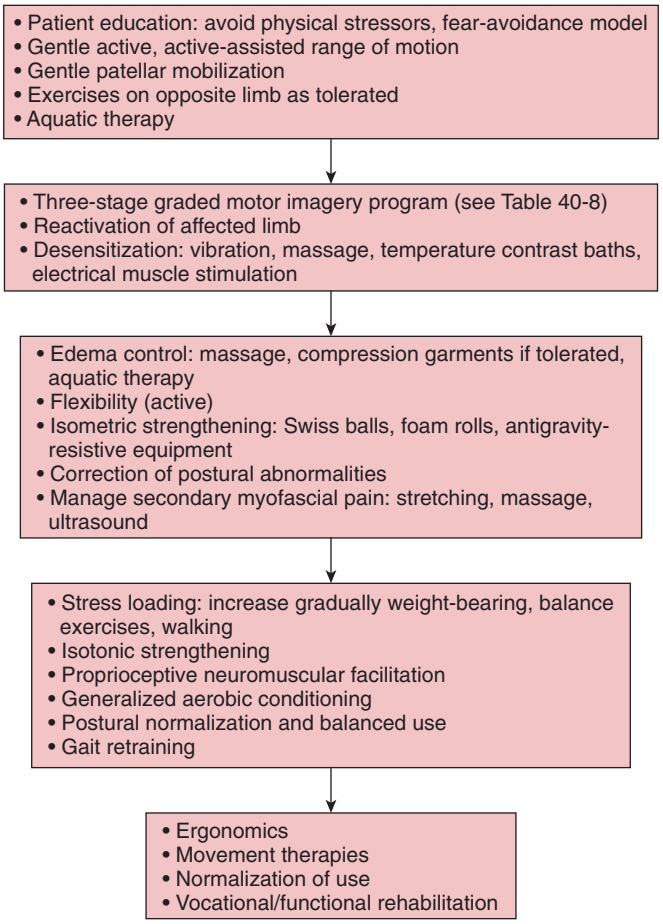


FIG 40-13 Physical therapy algorithm to regain functional restoration for complex regional pain syndrome (CRPS). Conduct the program within bounds of patient tolerance. Do not use when the patient is insensate (after a block) or a patient with pronounced hypoesthesia. Aggressive therapy, range of motion devices, cryotherapy, and inactivity may aggravate CRPS. (From Harden RN, Oaklander AL, Buron AW, et al. Complex regional pain syndrome: practical diagnostic and treatment guidelines, ed 4. *Pain Med.* 2013;14:180-229.)

Patients with chronic CPRS have pain with any movement of the affected limb and will guard by voluntarily restricting its range of motion. These movement phobias must be overcome before long-term sequelae develop. Active and active-assisted range of motion exercises are preferred over passive motion. Forced passive motion is too aggressive, painful, and counterproductive to treatment.[122] Gentle patellar mobilization should also be performed. Minimizing edema may be done using active motion, elevation, massage, and compression with special garments if tolerated. Myofascial pain, which is a common finding in patients with longstanding CRPS, should be treated with stretching, massage, and ultrasound on the trigger points. Normalizing

TABLE 40-8 Graded Motor Imagery Program for Chronic Knee-Related Complex Regional Pain Syndrome

Stage 1: Recognition of Laterality (2 Weeks)

Using web-accessible software (Recognise, Noigroup*), the patient is shown photographs of normal right and left knees in a variety of positions in random order. The patient is asked to identify as quickly as possible which knee (right or left) he or she sees. Emphasis is on speed and accuracy. Normal guidelines: ≥80% accuracy, similar results for left and right knees, response time 2 ± 0.5 sec, consistent for ≥1 week.

Stage 2: Imagined Movement (2 Weeks)

Pictures of a knee are shown in random order to the patient, who is asked to imagine moving his or her own knee to adopt the posture shown in the picture. Emphasis is on accuracy, not speed. The patient does not actually move the knee during this phase.

Stage 3: Mirror Therapy (2 Weeks)

With the patient sitting on an examination table, a high vertical mirror is positioned so that the affected knee is concealed from the patient. The patient begins by watching the unaffected knee (which is in a comfortable position) in the mirror. Then the patient is shown pictures of a knee doing simple movements or asked to do simple movements by the therapist. The patient slowly tries to perform the movements simultaneously with both knees. The affected knee is kept concealed at all times, and emphasis is on watching the reflection of their unaffected knee in the mirror. Movements should be very easy initially and gradually increase in difficulty as tolerated. The therapist should check behind the mirror to ensure the limbs are moving together and that the affected limb does not stop. Emphasis is on full concentration; sequence should not be done for more than 5 min at a time.

*www.noigroup.com/recognise and www.gradedmotorimagery.com/.

sensation is accomplished through vibration, massage, temperature contrast baths, and electrical muscle stimulation. Initially, light touch will be painful, but as treatment progresses, patients will gradually be able to tolerate greater amounts of stimulation.

Aquatic therapy is an excellent approach for lower extremity CRPS, especially in patients in whom weight bearing cannot be tolerated because any land-based exercise may be initially done in the water. Walking is begun when the patient is able to tolerate weight on the leg. Loads are increased with verbal cues or by having the patient carry a weighted object on the affected side. Activities that promote weight shifting and balance (e.g., ball toss) are encouraged.

When the patient is ready, strengthening exercises are performed isometrically to minimize painful motion with devices such as Swiss balls, foam rolls, and antigravity-resistive equipment.[121] Over time, the patient is advanced to isotonic strengthening. Loads are gradually increased from water exercises to full weight-bearing activities. Gait retraining may be required as patients progress to full weight bearing.[295] Proprioceptive neuromuscular facilitation patterns are useful to facilitate strength and balance.

Another approach that has been briefly described for chronic CPRS patients in whom previous treatments have failed is *graded pain exposure therapy*.[57,77,304] This program consists initially of patient education regarding the fear-avoidance model and development of the willingness to engage in activities previously avoided. It is based on the assumption that behavioral and psychological factors can exacerbate pain and dysfunction, which may in turn maintain CRPS in some patients. An individualized program is designed by the therapist that includes active and active-assisted joint motion, passive stretching, and friction massage. Use of the affected extremity is encouraged, with gradual progression of exercises and loading. Unlike most other therapeutic programs, pain severity is not used as a guideline to increase or reduce activities. Patients are encouraged to perceive pain as a false warning sign of the nervous system that should be ignored. Family members and partners are involved and educated to provide the correct support as the patient initially goes through an increase in pain.

Returning the patient to normal function is accomplished through work-hardening and vocational-rehabilitation programs. Future rehabilitation studies are required that use the Budapest diagnostic criteria and appropriate outcome measures for pain and function. Randomized controlled trials should be performed on some of the measures described here that appear promising, such as graded motor imagery and graded pain exposure therapy.

Psychotherapy

A recent systematic review of 31 articles found that despite prior beliefs, the onset and maintenance of CRPS is not significantly associated with a history or presence of psychological problems.[13,14] However, as this chronic pain condition persists, patients may develop some degree of emotional distress, increased anxiety, and depression. Investigators agree that all CRPS patients and their families, regardless of the duration of the disorder, should be educated about the negative effects of disuse, the pathophysiology of the syndrome, the possible interactions with psychological/behavioral factors, the importance of reactivation, and the need for an active self-management approach to treatment.[32,121] Chronic CRPS patients should undergo a thorough psychological evaluation, followed by appropriate treatment that might include relaxation training and cognitive-behavioral interventions. Relaxation training with biofeedback can help increase the patient's ability to control his or her pain and decrease emotional arousal. This includes breathing-focused relaxation, progressive muscle relaxation, relaxing imagery, and autogenic training. Cognitive-behavioral intervention aims to reframe the patient's role as that of an active participant in the treatment process rather than a passive recipient. Correcting misconceptions that the patient may have regarding the disorder and treatment options is essential. Changing the patient's focus from completely negative thoughts to more positive, constructive ones is stressed. The combination of psychotherapy and physical therapy is advocated when techniques such as graded exposure therapy, autogenic relaxation techniques, mirror therapy, and hypnotic imagery are available.[121]

Medications

Many medications have been tested for efficacy in chronic pain conditions such as peripheral neuropathy, but few have been tested in high-level studies (double-blind, randomized, placebo-controlled studies) to treat CRPS (Table 40-9).[121,175,182,255] Because CRPS may involve central sensitization, motor abnormalities, and sympathetic efferent features that differ among patients, no one medication can be expected to treat this disorder.[121] In addition, there may be the need to treat comorbidities such as depression and insomnia; therefore the decision on prescribed medication must take into account the entire patient presentation.

Corticosteroids and Nonsteroidal Antiinflammatories

Corticosteroids are potentially effective if begun early in the course of CRPS.[18,45,109,142,161,206] In a small randomized controlled trial,

TABLE 40-9 Pharmacology Treatment Options for Complex Regional Pain Syndrome

Study, Country	Level	Subjects (*n*)	Type and Location Pain	Drug	Results/Complications
Kozin et al[161] (1981), U.S.	Open label	17 "definite," 9 "probable," 5 "possible"	RSD, upper and lower extremities	**Corticosteroid**: oral prednisone, tapered	Good/excellent pain relief in 82% of "definite" group, 66% of "probable" group, 0% of "possible" group.
Christensen et al[45] (1982), Denmark	RCT	23	RSD, upper extremity	**Corticosteroid**: oral prednisone, 30 mg daily vs. placebo for 12 wk	All 13 patients in prednisone group had >75% clinical improvement compared with 2/10 patients in placebo group. No side effects.
Grundberg[109] (1996), U.S.	Open label	69	RSD, upper extremity	**Corticosteroid**: IM long-acting methylprednisolone	At 1 year, 47 patients significantly improved pain and ROM. Mild side effects in 8 patients, all resolved.
Kalita et al[142] (2006), India	RCT	60	CRPS-I upper extremity after stroke	**Corticosteroid**: oral prednisone 40 mg or piroxicam 20 mg daily for 1 mo	25 (83%) patients in prednisone group improved compared with 5 (17%) in piroxicam group. Five patients had mild gastritis, 2 had upper respiratory tract infection; all resolved.
Bianchi et al[18] (2006), Italy	Open label	31	CRPS hand (25), foot (4), knee (2)	**Corticosteroid**: oral prednisone, tapered + therapy; 4 patients required 2 cycles of Rx, 2 patients also had ganglion blocks	Significant improvement short term and at 1-yr follow-up in clinical CRPS severity score. No side effects.
Munts et al[206] (2010), The Netherlands	DB RCT	21	CRPS-I, upper and lower extremities (chronic)	**Corticosteroid**: single intrathecal dose 60 mg methylprednisolone vs. placebo	No improvement at 6 wk, trial stopped prematurely. Minor side effects in 10 Rx patients and 11 placebo patients.
Rico et al[245] (1987), Belgium	Nonrandomized	26	RSD, lower extremity	**NSAID**: oral naproxen 1000 mg daily vs. IM calcitonin	At 3 mo, calcitonin group had significant decrease in bone/soft tissue uptake index on bone scan; naproxen group had increase in index. No side effects.
Goris et al[105] (1987), The Netherlands	Crossover	20	RSD, upper and lower extremities	**Free radical scavenger**: all patients 50% DMSO cream 1 wk, placebo 1 wk	DMSO more effective for improving ROM and symptoms. No side effects.
Geertzen et al[88] (1994), The Netherlands	RCT	26	RSD, 3-mo duration, upper extremity	**Free radical scavenger**: DMSO vs. regional IV Ismelin block	At 9 weeks: better result in DMSO group. DMSO had onion-garlic–like taste and smell but no side effects.
Zuurmond et al[339] (1996), The Netherlands	DB RCT	32	RSD, acute, upper and lower extremity	**Free radical scavenger**: 50% DMSO cream vs. placebo + therapy	At 2 mo, DMSO had group significantly better results; 13 DMSO patients and 3 placebo patients had mild scaling of skin.
Perez et al[229] (2003) The Netherlands	DB RCT	145	CRPS-I, 105 upper extremity, 41 lower extremity	**Free radical scavenger**: 50% DMSO cream vs. oral N-acetylcysteine (NAC) 1800 mg	Both interventions equally effective at 1 yr; 3 patients on DMSO and 5 patients on NAC had severe stomach complaints and dropped out of study.
Perez et al[227] (2008), The Netherlands	DB RCT	41	CRPS-I	**Free radical scavenger**: IV mannitol vs. placebo 4 hr, 5 consecutive days + therapy	At 9 wk, no difference between groups. Mild side effects in 16 patients on Rx, 13 patients on placebo; all resolved.
Gobelet et al[95] (1986), Switzerland	RCT	24	RSD, stage I	**Calcitonin:** 100 IU injection daily 3 wk + therapy vs therapy only	Significant pain improvement in calcitonin group after 1 wk.
Bickerstaff & Kanis[19] (1991), United Kingdom	DB RCT	40	Algodystrophy, posttraumatic	**Calcitonin:** 400 IU nasal daily 4 wk vs. placebo	No improvement in clinical or skeletal progression of disorder.

TABLE 40-9 Pharmacology Treatment Options for Complex Regional Pain Syndrome—cont'd

Study, Country	Level	Subjects (*n*)	Type and Location Pain	Drug	Results/Complications
Gobelet et al[96] (1992), Switzerland	DB RCT	66	RSD	**Calcitonin:** 300 IU nasal daily 3 wk + therapy vs. placebo + therapy	At 8 wk, significant improvement in pain and range of motion in calcitonin group. Effect not equally observed for other parameters. Two patients in each group had nasal pruritus, 3 patients on Rx had headache, 6 patients on placebo had nausea and fatigue; all resolved.
Maillefert et al[184] (1995), France	Open label	11	RSD, chronic; 5 feet, 2 hand, 2 upper limb, 1 knee, 1 lower limb	**Bisphosphonate/IV pamidronate:** 30 mg 3 consecutive days	At 3 mo, significant reduction in pain, physician-noted improvement in 7 patients. Two patients had transient fever, 2 had asymptomatic hypocalcaemia, 1 had symptomatic hypocalcaemia; all resolved.
Adami et al[1] (1997), Italy	DB RCT	20	RSD; 8 feet, 12 hands	**Bisphosphonate/IV alendronate:** 7.5 mg 3 consecutive days vs. placebo; then 14 days later, all received open IV alendronate 7.5 mg/day for 3 days	At 2 wk, Rx group had significantly better results in pain, tenderness, swelling, and motion than placebo. All patients responded to open alendronate therapy. Three Rx patients had fever after first injection that resolved.
Cortet et al[52] (1997), France	Open label	26	RSD; 17 foot/ankle, 3 hand, 2 hip, 2 knee, 1 shoulder	**Bisphosphonate/IV pamidronate:** 1 mg/kg/day for 3 consecutive days (14), 2 days (7 because of adverse events), 1 day (2 because of adverse events)	At 30, 60, 90 days, significant decrease in pain. Six patients had transient fever, 3 hypocalcaemia, 2 venous irritation, 1 patients each nausea, transient hypertension, and leucopenia with neutropenia. All resolved.
Varenna et al[317] (2000), Italy	DB RCT	32	RSD	**Bisphosphonate/IV clodronate:** 300 mg daily for 10 consecutive days or placebo, then 40 days later, placebo group received clodronate	After 40 days, Rx group had significantly better results in pain, clinical global assessment scores. At 180 days, significant improvement seen in entire group for pain.
Kubalek et al[163] (2001), France	Open label	29	RSD, upper and lower limb	**Bisphosphonate/IV pamidronate:** 60 mg/day for 3 days	At day 45, pain resolved in 86%, functional improvement seen in 70%. Six patients had fever, 5 shivers, 3 diarrhea.
Manicourt et al[187] (2004), Belgium	DB RCT	40	CRPS-I, lower extremity (30 foot/ankle, 10 knee)	**Bisphosphonate/oral alendronate:** 40 mg/day for 8 wk vs. placebo; then 4 wk no therapy, then 8 wk voluntary (open) use of alendronate	Rx group had "marked and sustained" improvement in levels of spontaneous pain, pressure tolerance, joint mobility at weeks 4, 8, 12; 24 patients volunteered for 8-week open trial, all had positive response. One Rx patient dropped out because of upper gastrointestinal intolerance. One placebo patient had nausea for 1 hr, resolved.
Robinson et al[249] (2004), New Zealand	DB RCT	27	CRPS-I, upper and lower limb	**Bisphosphonate/IV pamidronate:** 60 mg/day 1 dose vs. placebo	At 3 months, pain, global assessment, SF-36 scores significantly better for Rx group. Five patients in Rx group and 2 in control group had minor influenza-type symptoms, 2 in Rx group had mild infusion site reactions; all resolved.

Continued

TABLE 40-9 Pharmacology Treatment Options for Complex Regional Pain Syndrome—cont'd

Study, Country	Level	Subjects (*n*)	Type and Location Pain	Drug	Results/Complications
Breuer et al[31] (2008), U.S.	Open label	10	CRPS	**Bisphosphonate/IV ibandronate:** 6 mg for 3 days	At 4 wk, improvements observed in average and "worst" pain ratings; 8 patients had transitory flulike symptoms.
Varenna et al[316] (2013), Italy	DB RCT	82	CRPS-I hand, foot, <4 mo onset symptoms	**Bisphosphonate/IV neridronate:** 100 mg 4 times over 10 days vs. placebo; after 50 days, placebo group open trial neridronate available	At 20 days, Rx group had significantly better results in pain that continued for next 20 days. Significant improvements in Rx group for several SF-36 indexes vs. placebo; 21 patients in Rx group, 12 in placebo group had minor adverse events. 14 patients had open trial phase (39%) minor adverse events.
Prough et al[234] (1985), U.S.	Open label	13	RSD, 10 upper extremity, 3 lower extremity, acute and chronic	**Calcium channel blocker/oral nifedipine:** 10-30 mg tid	7 patients' pain resolved, 2 patients' pain partially resolved, 3 withdrew for side effects (severe headache); 1 failed.
Muizelaar et al[204] (1997), U.S.	Retrospective chart review	59	CRPS-I (41), CRPS-II (18), 80% upper extremity, 20% lower extremity, 12 early stage, 47 chronic	**Calcium channel blocker/oral nifedipine** or **α-sympathetic blocker/oral phenoxybenzamine:** dosages varied, 8-12 wk	92% early-stage symptoms resolved, majority treated with phenoxybenzamine. 40% chronic stage symptoms resolved, majority treated with nifedipine. One third of patients on nifedipine had mild headaches. Phenoxybenzamine dizziness, orthostatic hypotension symptoms, impotence in men in majority; 7 patients dropped out because of these side effects.
Mellick and Mellick[193] (1997), U.S.	Open label	6	RSD, 4 upper extremity, 2 lower extremity	**Calcium channel blocker/oral gabapentin:** 300-800 mg tid	Verbal pain scale, reduction of pain, 85%-100% in 5 patients, 60% in 1.
van de Vusse et al[305] (2004), The Netherlands	DB RCT	58	CRPS-I, chronic, upper and lower extremity	**Calcium channel blocker/oral gabapentin:** 600 mg days 1-2, 1200 mg days 3-4, 1800 mg days 5-21 vs placebo; two 3-wk Rx periods; gabapentin or placebo, then washout	Pain relief found in favor of gabapentin in first study period. Sensory deficits reversed compared with placebo. Therapy less effective in second period, no effect when both periods combined. Mild side effects (dizziness, somnolence, lethargy) in 95% of gabapentin group and 58% placebo in first Rx period.
Tan et al[298] (2007), Turkey	Open label	22	RSD, acute (<6 mo onset); 15 hand, 5 foot, 1 elbow, 1 knee	**Calcium channel blocker/oral gabapentin:** 600 mg/day, increased every 3 days by 300 mg until satisfactory pain relief obtained; done for 3 wk, then 6 wk at maintenance dosages	At 6 wk, significant improvements in pain, motion; 5 patients had complete resolution of pain. Mild dizziness in 3 patients, headache in 2, turning in tongue in 1; all resolved.

CRPS, Complex regional pain syndrome; *DB*, double-blind; *DMSO*, dimethyl sulfoxide; *IM*, intramuscular; *IV*, intravenous; *RCT*, randomized controlled trial; *Rx*, treatment; *RSD*, reflex sympathetic dystrophy.

Christensen and associates[45] found that 30 mg per day of prednisone was significantly better in terms of clinical improvement than a placebo. A second study compared the use of 40 mg prednisolone per day combined with piroxicam in CRPS-I following stroke and reported improvements in symptoms and signs after 1 month of treatment.[142]

A course of cortisone may be indicated in the initial period after onset of CRPS. Maihofner and colleagues[182] empirically recommended methylprednisolone 100 mg/day, which is reduced to 25 mg every 4 days. The senior author has found a Medrol Dosepak, or other equivalent steroid dosage, is also useful early in the course of the disease process. If the patient has a positive but incomplete response to an initial course of oral steroids, a second course may be beneficial.

Although very little clinical data exist,[245] NSAIDS are commonly used to treat CRPS especially early after the onset of the disorder if the limb has an inflamed appearance.[175,264,295] The mechanism of action of these agents is inhibition of cyclooxygenase which decreases the production of prostaglandins. However, the problem is that inflammation in CRPS is now regarded to be neurogenic in nature and no drugs have been studied for this type of inflammation.[121] In addition, there is a real danger of overdose from prescription combination products containing acetaminophen.

Free Radical Scavengers

The use of free radical scavengers to combat CRPS is based on the proposed inflammatory response theory in which an excessive production of inflammatory mediators and oxygen radicals harms healthy tissue. A randomized controlled trial in 32 patients with acute RSD reported that topically applied 50% dimethyl sulfoxide (DMSO) was superior to placebo and led to improved pain and inflammatory signs.[339] Two other studies reported positive effects of DMSO in CRPS-1 patients.[88,105] Oral N-acetylcysteine was found to be equally effective as DMSO in a high-level trial involving 146 CRPS-I patients.[229] It appeared from this study that 50% DMSO cream was more effective in primary "warm" CRPS-1 patients, although N-acetylcysteine was more effective in primary "cold" CRPS-I patients.

Zollinger and associates[337] found vitamin C, taken at 500 mg per day for 50 days, to be effective in reducing the prevalence of CRPS in wrist fractures. This is the only CRPS medication prevention trial conducted to date.

Calcitonin, Bisphosphonates

One problem in select CRPS patients is rapid and painful bone reabsorption (identified with MRI or a three-phase bone scan). Inhibiting osteoclast activity and bone reabsorption is important not only for pain reduction but also for preservation of bone mass in the affected extremity. Calcitonin, used commonly for osteoporosis in women, has been studied in just three randomized controlled trials for "posttraumatic algodystrophy" and RSD with conflicting results in terms of pain relief.[19,95,96]

More extensive work has been conducted with various oral and intravenous (IV) bisphosphonates in CRPS patients.[1,31,52,163,184,187,249,316,317] However, most of the trials are older and used first- and second-generation drugs. One such study revealed that IV alendronate was successful in improving function and increasing the bone density in the affected limb.[1] The bone density in the unaffected limb remained unchanged. A double-blind placebo controlled trial of oral alendronate[187] in 40 patients reported improvement 4 weeks after alendronate was initiated which continued after the medication was stopped. All patients exhibited improved pain levels, pressure tolerance, and joint mobility.

A small, open-label trial of a third-generation bisphosphonate, ibandronate (6 mg infusion, 3 consecutive days) showed encouraging results 4 weeks posttreatment.[31] Eight of 10 participants had flulike symptoms, which resolved. The investigators concluded that a future randomized, double-blind, placebo-controlled trial was justified.

In 2013, Varenna and associates[316] published the results of IV-infused neridronate compared with placebo in 82 patients with acute (<4 months' duration) CRPS-I in the upper and lower extremities. The placebo patients were offered open-label neridronate treatment after 50 days. Significant improvements were found between the treatment and placebo group for pain and a number of quality of life indices. The improvements were also found in the patients who participated in the open-label phase of the trial. One year later, none of the patients complained of CRPS-related symptoms. The authors concluded their results "provide conclusive evidence that the use of bisphosphonates, at appropriate doses, is the treatment of choice for CRPS-I" in patients diagnosed after recent onset of the disorder.

Anticonvulsants and Calcium Channel Blockers

Drugs that block entry of sodium or calcium into neurons, used as anticonvulsants and antiepileptics, may play a role in CRPS, although high-level study evidence remains lacking.[121,175] The mechanisms of action are not well understood for these medications in regard to neuropathic pain. The main hypothesis is that peripheral nerve injury alters the distribution and expression of subtypes of sodium channels on axonal membrances.[255] This in turn induces upregulation of primary nociceptive afferent fibers and small dorsal root ganglia pain transmission neurons. Blocking sodium channels should reduce the action potentials of these neurons.[121]

Nifedipine (Procardia) decreased pain and improved signs of sympathetic dysfunction in two small studies[204,234] but has not been investigated for CRPS for many years. Gabapentin (Neurontin) has received considerable attention in both neuropathic pain[93,281] and CRPS trials.[193,298,305] Gabapentin has been reported to be effective in decreasing both allodynia and hyperalgesia.[44,305] Start with smaller doses such as 300 mg three times a day and gradually increase the dosage, observing for side effects. A newer antiepileptic drug, pregabalin (Lyrica), may also be considered because it has a similar mechanism of action as gabapentin. To date, pregabalin has not been studied in CRPS patients.[121]

Antidotal recommendations have been made for usage of carbamazepine[124] (or preferably oxcarbazepine) in CRPS-II.[175,255] Oxcarbazepine may be a better alternative because it has fewer side effects and drug-drug interactions,[121] but this medication has not been studied in CRPS patients.

Alpha-Adrenergic Antagonists

Alpha-adrenergic antagonists, or α-sympathetic blockers, have been used clinically for CRPS, but they have significant side effects, and no high-level evidence exists to support their efficacy.[154,175,204,255] Typical adverse effects include sedation, dizziness, headache, nausea, and hypotension. Clonidine was used several years ago in two small series of patients topically ($n = 6$)[55] and epidurally ($n = 19$)[242] to treat CRPS. Phenoxybenzamine (Dibenzyline) was tested in four small studies for causalgia (orally, $n = 40$)[91], RSD (orally, $n = 35$[204] and intravenously, $n = 5$[185]), and CRPS (orally, $n = 4$).[137] Inchiosa and coworkers[137] recommended oral phenoxybenzamine for refractory cases of CRPS before consideration of more invasive treatment, but this advice was based on the results of treatment in just four patients.

Topical Lidocaine and Capsaicin

Topical medications that remain local and do not cause systematic side effects offer an alternative medication option for CRPS patients,

although high-level study evidence of their efficacy for this disorder does not currently exist. Investigators have empirically recommended consideration for use of the 5% lidocaine patch (Lidoderm).[121] This patch is approved in the United States for treating postherpetic neuralgia.[54,256] One open-label study that included six CRPS patients (5 CRPS-I and 1 CRPS-II) reported that all patients experienced pain relief after wearing the patch an average of 6.2 weeks.[65]

Many years ago, a preliminary study was performed on high-dose topical capsaicin delivered with regional anesthesia in 10 patients with refractory CRPS.[246] All but one patient experienced some pain relief that lasted from 1 to 18 weeks. This medication is approved in the United States (8% capsaicin patch, Qutenza) for postherpetic neuralgia and has been found to be effective in peripheral neuropathic pain.[285,286] The problem is that capsaicin causes a painful burning sensation at the site of application, which Harden and associations found to be "intolerably painful, messy, and unacceptable to most patients."[121]

Antidepressants

To date, no high-level evidence exists regarding the use of various antidepressant medications for CRPS.[121,228] In neuropathic pain, tricyclic and heterocyclic drugs have been found to be advantageous for both pain relief and antidepressant effects.[48,192,289] These medications include peripheral sodium-channel blockade, which may also add to their efficacy.[334] For example, amitriptyline (Elavil) has been shown to provide relief from burning pain. In addition, this medication treats mood and anxiety disorders that may develop in patients with a chronic pain condition. Amitriptyline has sedating properties, which can relieve insomnia. The problem with tricyclic antidepressants is their toxicity in an intentional overdose situation.

Selective serotonin reuptake inhibitors have been ineffective in providing analgesic effects.[121] However, combined serotonin-norepinephrine reuptake inhibitors, such as duloxetine (Cymbalta) and venlafaxine (Effexor), are approved in the United States for several chronic pain diagnoses and have been found to be effective for neuropathic pain.[226,240,241,288] There is a tremendous need for high-level studies on the potential effectiveness and safety of antidepressants for CRPS.

Opioids

The use of opioids such as morphine, oxycodone, and tramadol for the treatment of CRPS (or any chronic pain condition not related to cancer) is controversial. Many studies have demonstrated the effectiveness of these medications in controlling pain and improving the quality of life in patients with chronic peripheral neuropathic pain[7,73,94,257,331] and knee osteoarthritis.[213] Combining an opioid with another drug (e.g., a tricyclic antidepressant or gabapentin) may have an even greater effect on neuropathic pain.[41] Side effects with opioids are common and, with high doses, include nausea, vomiting, constipation, cognitive impairment, respiratory depression, and addiction. Long-term use may lead to tolerance, hyperalgesia, decreased libido, suppression of the immune system, and overdose leading to death.[74,175] As a matter of course, orthopedists in most cases should avoid using opioids in chronic pain conditions and explain the disadvantages to patients. However, there are times when it may be necessary to use these drugs, especially for patients in pain crisis,[116] and in those instances it is best to provide a pain management referral and have only one physician dispensing the opioid. Tramadol is an option because it blocks serotonin/norepinephrine reuptake and has been proven clinically useful in randomized controlled trials to decrease pain associated with peripheral neuropathy[73,113] and osteoarthritis.[39] Methadone has a theoretical usefulness because it also acts as an N-methyl-D-aspartate (NMDA) antagonistic (see "Interventions" below) and is low in cost.[121]

Pharmacotherapy for Movement Disorders

A common movement disorder in patients with chronic CRPS is dystonia, which may be limited to small areas or may encompass larger regions such as the fingers, wrist, and feet where a fixed flexion posture occurs.[312] There is also a tendency for dystonia to spread to other extremities. Intramuscular botulinum toxin injections have been suggested for pain relief in chronic neuropathic pain[38,239,336] and treatment of pain and dystonia in chronic CRPS.[5,148,259,260] The most widely known action of botulinum toxin is its relaxing effect on skeletal muscles; however, recent studies indicate that it appears to have an early antinociceptive action that may be beneficial in CRPS.[38] Harden and associates[121] suggested these injections are most useful for focal dystonia limited to small areas.

Baclofen has been suggested for dystonia in CRPS because of its stimulation of presynaptic and postsynaptic gamma-aminobutyric acid B receptors that enhance central inhibitory activity.[307] Investigators reported mixed results in terms of partial or complete resolution of focal dystonia from oral[276] and intrathecal pump[307,311,338] administration of baclofen. Intrathecal administration has a high complication rate, including infections, catheter and pump system failures, postdural puncture headache, and the formation of intrathecal granulomas, which have the potential to produce spinal cord compression.[310] High-level studies on the efficacy of botulinum toxin injections and baclofen on the treatment of dystonia in CRPS patients are lacking.

Interventions

N-Methyl-D-Aspartate Receptor Antagonists: Intravenous Ketamine

NMDA receptor antagonists are a class of anesthetics that work to inhibit the action of the N-methyl-D-aspartate receptor. This receptor allows for the transfer of electric signals between neurons in the brain and in the spinal column. The receptor must be open for the signals to pass and, therefore, chemicals that deactivate the NMDA receptor are termed antagonists. Common antagonists include ketamine, amantadine, dextromethorphan, and memantine. Only memantine,[110] magnesium,[47] and ketamine have been studied in CRPS patients, with recent extensive attention given to ketamine (Table 40-10).[51,101-103,158,258] However, high-level trials (double-blinded, randomized, placebo-controlled) with adequate numbers of patients receiving this treatment for CRPS are lacking.[15,46]

Initial case reports appeared in 2002 on the topical application (0.25%-1.5%) of ketamine in CRPS-I and CRPS-II patients with allodynia or hyperalgesia.[302] Pain relief and reduction in swelling were observed 1 to 2 weeks later in CRPS-I subjects. A more recent study found that a single-dose topical application of ketamine did not lead to pain reduction, but did reduce allodynia in a group of 20 patients with CRPS-I.[81]

Most case reports[78,114,149,152,153,208,282] and studies[51,101,102,150,151,158,267,273,283] have involved IV infusion of ketamine of varying dosage levels. Koffler and associates[158] used a high dosage (anesthetic) of ketamine in nine refractory CRPS patients, producing a medically induced coma for 4.5 days, and reported no problems with cognitive function 6 weeks later. Lower, subanesthetic doses were reported effective in reducing pain in other studies.[102,273,283] Schilder and colleagues[267] recently studied the effects of continuous, low-dose IV infused ketamine and placebo (for 4 days) on motor function in 29 CRPS-I patients. Motor function was determined by measuring a finger tapping task. Over a period of 12 weeks following treatment, a direct correlation was found between pain intensity and motor function, irrespective of receipt of ketamine or placebo. This study leads credence to the belief that achieving pain relief is an important goal in the management of motor problems and in rehabilitating patients with CRPS.

TABLE 40-10 Investigations on N-Methyl-D-Aspartate Receptor Antagonist Ketamine

Study, Country	Level	Subjects (*n*)	Type and Location of CRPS	Drug	Results/Complications
Correll et al[51] (2004), Australia	Open-label, retrospective review	33	CRPS-I in 31, CRPS-II in 2, upper and lower extremities	Continuous IV infusion of 10 mg/hr, increased as tolerated Cycles stopped after 12-24 hr complete pain relief, 24 hr after partial pain relief with no further improvement, after 48 hr of no pain relief. 12 patients had 2 courses of therapy, 2 patients had 3 courses of therapy.	After one course, complete pain relief in 25 (65%), partial relief in 6 (18%), and no relief in 2 (6%). After repeat therapy, all had complete relief. Duration of pain relief: 9 mo after one course, 25 mo after 2-3 courses. Side effects: inebriation, dizziness, blurred vision, nausea. Hallucinations in 6 patients.
Goldberg et al[101] (2005), U.S.	Open label	40	CRPS-I, CRPS-II, chronic	IV infusion, outpatient, 40 mg and increased over 10-day period to 80 mg	Day 10: significant reductions in pain intensity, percentage of overall pain relief, improvements in motion, some reduction in skin color changes. Side effects minimal: 4 patients had headaches, 5 restlessness.
Koffler et al[158] (2007), Germany	Open label	9	CRPS-I, chronic	Continuous IV infusion high dose (anesthetic), medically induced coma 4.5 days	At 6 weeks, significant reduction in acute and overall pain. Brief attention and processing speed improved, all other cognitive domains remained stable, slight decline in motor strength. Side effects: muscle weakness, dizziness, fatigue, hyperhidrosis, anxiety; 2 patients had flashbacks.
Kiefer et al[151] (2008), Germany	Open label pilot	4	CRPS, chronic	Continuous IV, gradually titrated from 50 mg/day to 500 mg/day (subanesthetic) over 10-day period	No improvement in pain, no relevant side effects. Lack of therapeutic response led to termination of study.
Kiefer et al[150] (2008), Germany	Open label phase II	20	CRPS, chronic, severe	Continuous IV infusion high dose (anesthetic), patients intubated, mechanically ventilated 5 days	Significant reduction in pain intensity at 1 wk and 1, 3, and 6 mo. Complete remission at 1 mo in all patients, 3 mo in 17, 6 mo in 16.
Finch et al[81] (2009), Australia	DB RCT	20	CRPS-I in 18, CRPS-II in 2, 12 upper extremity, 8 lower extremity	Topical, 10%, 0.5 mL vs. placebo cream; one-time application, both extremities	At 7 days, allodynia and punctate hyperalgesia significantly reduced affected side, slightly reduced opposite side. No change in pain.
Schwartzman et al[273] (2009), U.S.	DB RCT	19	CRPS, chronic, upper and lower extremity	IV infusion, outpatient, over 10-day period, ketamine vs. placebo. Max rate 100 mg over 4-hr period. First day 50% of max dosage, second day, 75% of max, 3-10 days max.	At 1 mo, ketamine group had significant reduction in pain; placebo group had no treatment effect. Side effects: nausea, headache, tiredness, or hysphoria (4 with ketamine, 2 with placebo).

Continued

TABLE 40-10 Investigations on N-Methyl-D-Aspartate Receptor Antagonist Ketamine—cont'd

Study, Country	Level	Subjects (*n*)	Type and Location of CRPS	Drug	Results/Complications
Sigtermans et al[283] (2009), The Netherlands	DB RCT	60	CRPS-I, chronic, upper and lower extremity	Continuous IV infusion 4 days, low-dose ketamine vs. placebo. Dosage individualized based on effect, side effects.	For 11 wk, pain score in ketamine group significantly lower, but treatment effect lost at week 12. No effect on function. Most ketamine patients had side effects: 92% inebriation, 63% nausea, 93% psychometric, 37% headache.
Goldberg et al[102] (2010), U.S.	Open label	16	CRPS-I and CRPS-II	Continuous IV infusion 5 days, begun at 10 mg/hr and titrated to 40 mg/hr (subanesthetic)	Significant reduction in pain scores by days 3, 4, 5 compared with baseline and day 1.
Schilder et al[267] (2013), The Netherlands	DB RCT	29	CRPS-I, chronic, upper extremity	Continuous IV infusion 4 days, low-dose ketamine vs. placebo. Dosage individualized based on effect, side effects.	Over 12 wk, direct correlation of pain intensity and motor function, irrespective of ketamine or placebo. Ketamine had no direct effect on motor function.

CRPS, Complex regional pain syndrome; *DB RCT*, double-blind randomized controlled trial; *IV*, intravenous; *NMDA*, N-methyl-D-aspartate.

Intravenous Immunoglobulin and Tumor Necrosis Factor-α Inhibitors

The use of IV immunoglobulin (IVIG) or anti-TNF antibodies has generated some interest as evidence of immune system involvement in CRPS has become available.[24,133,181,303] Only two small studies have appeared to date in which IVIG was used in CRPS patients. Goebel and associates[99] demonstrated some pain relief in a group of 12 patients 28 days after receiving 9 to 18 g of IVIG. More recently, Goebel and coworkers[98] assessed the effectiveness of low-dose IVIG (0.5 g/kg) in 12 CRPS patients. Pain intensity was reduced in eight patients; however, the patients were only followed for 19 days after treatment.

A few case reports have observed reduced cytokine levels and pain after the use of IV regional block with low-dose administration of infliximab, a TNF-α inhibitor.[17,134] Thalidomide, a TNF-α and interleukins 1 and 6 inhibitor, has also shown promise in case reports and small trials.[42,237,274]

Sympathetic Block

Blockade of the sympathetic nervous system is typically performed with a local anesthetic at the stellate ganglion for upper extremity involvement and at the lumbar L2-L4 levels for lower extremity involvement. There are other sympatholytic procedures available such as IV phentolamine, IV regional anesthesia, and epidural infusion. The literature regarding sympathetic blocks for CRPS has been reviewed extensively and recently by others.[40,56,121,293,310] The common conclusion is that high-level study evidence demonstrating the efficacy of these blocks in reducing pain and improving function is not available. There are problems identifying a clinically successful block, and the potential exists for a high rate of partial or incomplete sympathetic blockade.[186] Even so, many investigators include these blocks in their treatment algorithms (Fig. 40-14) because of their clinical importance in terms of decreasing pain and increasing function in some patients, thereby allowing participation in physical therapy.[121] The senior author has empirically found that, when it is necessary to operate on a limb with CRPS, a perioperative sympathetic ganglion block can reduce the recurrence rate of CRPS.

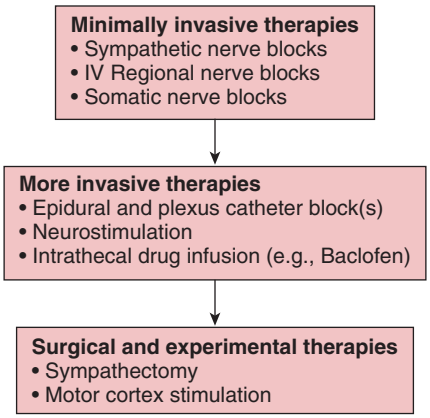


FIG 40-14 Interventional pain treatment algorithm for complex regional pain syndrome. (From Harden RN, Oaklander AL, Buron AW, et al. Complex regional pain syndrome: practical diagnostic and treatment guidelines, ed 4. *Pain Med.* 2013;14:180-229.)

Many studies have investigated the effect of IV regional blockade with a variety of sympatholytic, anesthetic, or antiinflammatory medications for CRPS.* These blocks are performed mostly with guanethidine, and to a lesser extent, lidocaine, clonidine, reserpine, methylprednisolone, and phentolamine. Unfortunately, several good quality investigations failed to find a beneficial effect from this therapy.[121,154,227,228,300] IV regional blockade offers placement of medication directly into the affected extremity, which is potentially

*References 26, 28, 76, 88, 128, 132, 139, 143, 173, 209, 210, 238, 243, 251, 318, 323.

advantageous if a suitable agent or combination of agents is eventually found.

Phentolamine and lidocaine have been intravenously infused in patients with CRPS in just a few studies with disappointing results. Verdugo and Ochoa[322] failed to find any differences with respect to pain, sensory testing, regional blood flow, or hyperalgesia between placebo, phentolamine, and phenylephrine infusions in 100 patients with RSD or causalgia. Wallace and associates[323] found that IV infused lidocaine had no effect on cool, warm, or cold pain thresholds, spontaneous pain scores, and mechanical allodynia in 16 patients with CRPS-I and CRPS-II. The treatment did decrease pain response to cold stimuli. Lack of efficacy precludes recommendation of these treatment options.[121]

Epidural Infusion

Continuous epidural infusion may be used to treat CRPS,[50,203,242] and some authors believe this is the anesthesia of choice when operating on a CRPS limb (discussed later).[167] The drug concentration may be titrated to allow motor function to remain intact although still blocking sympathetic and sensory input. This treatment option may be combined with other medications such as clonidine with or without bupivacaine.[50,242] The use of tunneled epidural catheters for extended periods of time is discussed in detail in Chapter 38. There is a risk of infection that does increase with long-term use.[242]

Surgical Sympathectomy

Surgical sympathectomy involves removal of the sympathetic chain and ganglia from the lower third of the stellate ganglia to T3 or removal of the sympathetic chain and ganglia from L2 to L4. The procedure is done endoscopically when feasible and has been successfully used to treat CRPS-I and CRPS-II.[29,197,248,277,290] Singh and associates[290] found better results in patients with upper extremity CRPS-II who were treated with thoracoscopic sympathectomy compared with an open procedure and in patients treated within 3 months of the onset of symptoms compared with those treated more than 3 months from onset of symptoms. Schwartzman and coworkers[277] reported better outcomes in CRPS-I patients treated within 12 months of onset of symptoms (100% permanent symptom relief) than those treated within 24 months (69% symptom relief) and those treated more than 24 months (44% symptom relief). This series included 8 patients with knee-related CRPS.

Initial pain relief may be significant, but symptoms may recur 6 months to 24 months later, requiring additional treatment.[8,223] This is believed to happen because of incomplete surgical removal of all sympathetic innervation to the extremity. Reinnervation and contralateral innervation may also occur. Harden and associates[121] recommended against surgical ablative sympathectomy because of the potential of long-term postoperative problems.

Neurostimulation

Neurostimulation refers to spinal cord stimulation (SCS) and peripheral nerve stimulation. The treatment methods are believed to be effective by blocking the transmission of pain nerve fibers or causing the release of endogenous opioids.[270] SCS (also called dorsal column stimulation) has been used in chronic pain conditions since 1967.[250] Electrodes are implanted in the epidural space in either the cervical or lumbar region. Several studies and reviews have shown favorable results in patients with CRPS in both regions.[83,106,123,135,146,164,165,232,280,287,294] However, even if SCS is entirely successful, the patient will require repeat surgery for battery or electrode replacement.[166] There is also the possibility of infection or electrode displacement/breakage. The effect of a permanent SCS on pain may gradually decrease over time.[147] Kemler and associates[147] reported no difference in outcome in a randomized study between CRPS-I patients who received a SCS and physical therapy and those who underwent 6 months of physical therapy alone when assessed 5 years later. van Eijs and colleagues[309] reported that brush-evoked allodynia predicted poor outcomes of a permanent implant in a study of 36 CRPS-I patients. Patient age, duration of symptoms, localization of the disorder, pain intensity, and the presence of mechanical hypoesthesia did not predict success of SCS.

It is possible to disrupt the sympathetic chain ganglion with caustic chemicals (such as alcohol) or peripheral nerve stimulation, but few reports exist to support these treatment options.[35,37,126,196,250,333] Pulsed radiofrequency for ablation of the saphenous nerve is another option; however, to date, there are few data available and future high-level studies are necessary to evaluate this treatment option.[2,112,136]

Surgery

Operating on a limb with active or quiescent CRPS should normally be avoided. Patellofemoral surgery is associated with a high rate of painful CRPS flares.[82] Lankford and Thompson[169] recommended that sympathetic blocks be performed and the CRPS process be allowed to "cool down" for 1 year before considering other surgical procedures. Katz and Hungerford[144] recommended in postarthroplasty patients with CRPS that surgery to correct mechanical dysfunction (aseptic loosening, ligament imbalance, component malalignment) be delayed until the CRPS symptoms are under control. These authors also recommended that patients undergo a series of sympathetic blocks before the anticipated surgery.

However, if the painful focus can be identified, appropriate surgical intervention to eliminate this focus is advocated.[49] Without this intervention, resolution of the CRPS is unlikely to occur. Tourniquets should be avoided because they can cause a painful flare.[321] Exacerbation of CRPS symptoms has been reported to occur in patients when appropriate perioperative pain management has not been accomplished.[144,321] The likelihood of a painful flare response may be decreased with a sympathetic block during and after the procedure.

A continuous epidural infusion for 2 to 5 days after surgery can help minimize the chance of CRPS recurrence.[167] Regional anesthesia has proven to be more effective in our experience in blocking painful flares than general anesthesia. The block is gradually reduced until it is discontinued. If the patient begins to experience pain during this weaning period, the dosage is increased until the pain is relieved and weaning begins again the following day. During this treatment phase, it is critical to protect the patient from decubitus ulcers. The patient should log roll every 2 hours, use heel cushions, be placed on an air mattress, and be helped out of bed frequently during the day. Sequential compression devices and antiembolism stockings are required to prevent deep vein thrombosis. Anticoagulant medications are contraindicated in patients with indwelling epidural catheters. A Foley catheter may be required if the patient is unable to void. A history of peripheral venous disease, blood clots, or high-risk factors (diabetes, obesity) contraindicate this form of treatment. Lower extremity ultrasound for venous clots is used as indicated, and the patient is examined every day for signs of a lower extremity venous clot condition (tibial edema, calf or inner thigh compression pain, Homan's test). In our experience, no exacerbation of CRPS symptoms has occurred as long as a sympathetic blockade and other appropriate pain management is used in the perioperative period.

Patients with chronic, unremitting pain may demand an amputation, which, in our opinion, should not be performed. Bodde and associates[27] systematically assessed the results of 111 amputations in 107 CRPS-I patients. Recurrence of CRPS symptoms in the stump occurred in 48%, and phantom pain occurred in 41% of the patients.

Conclusions

Many treatment options have been proposed for CRPS, but few are supported by high level clinical trials. This is especially true for CRPS related to the knee or lower extremity. Even so, agreement exists in the literature that multiple disciplines should be involved in providing patient care, including orthopedists, neurologists, pain specialists, anesthesiologists, physical therapists, occupational therapists, psychologists, and primary care physicians.

It is important to take all complaints seriously in a patient with suspected CRPS before discounting his or her comments as indicative of a personality disorder or drug-seeking behavior. By maintaining a high degree of clinical suspicion, the likelihood of early diagnosis of CRPS is greatest. A careful examination and use of other tests (MRI, TPBS) may be necessary to assist in identifying any triggers responsible for the abnormal pain response (such as a meniscus tear).

At the time of the initial CRPS diagnosis, it is important for the patient to be educated and become a participant in their recovery. In regard to the appropriate medications to prescribe, several have been tested for efficacy in other chronic pain conditions, but few have been investigated in high-level studies in CRPS patients. As such, there does not exist a consensus on which medications to use during the initial onset and subsequent course of the disease. The senior author empirically initiates a Medrol Dosepak or a short course of prednisone and prescribes physical therapy for desensitization and active and active assisted range of motion exercises. Neurotin (Gabepentin) is considered. The patient is referred early in the course of symptoms to an anesthesiologist skilled with administering paravertebral ganglion blocks. It is important to begin the treatment protocol within the first weeks of the onset of CRPS and not delay progressive treatment strategies if relief is not obtained.

The senior author does not refer CRPS patients to general pain management centers because they do not perform paravertebral sympathetic blocks. Patients are referred only to physicians skilled and experienced in treating CRPS who are able to perform the paravertebral blocks necessary (along with the use of other medications) to help resolve the condition. Multiple blocks may be required over several weeks. If the condition is refractory to treatment at this point, other medications are required (Table 40-11) and should be provided by a pain management specialist knowledgeable in the treatment of CRPS at either a local center or a major national treatment center. A comprehensive review of available treatment strategies, physical therapy options, and indications for various medications and blocks was recently published by Harden and associates.[121]

TABLE 40-11 Pharmacotherapy Guide

Problem	Intervention
Mild to moderate pain	Simple analgesics and/or blocks
Excruciating, intractable pain	Opioids (short-term) and/or blocks or later, more experimental interventions
Inflammation/swelling and edema	Steroids, systemic or targeted (acutely) or NSAIDs (chronically); immune modulators
Depression, anxiety, insomnia	Sedatives, analgesic antidepressant/anxiolytics and/or psychotherapy
Significant allodynia/hyperalgesia	Anticonvulsants and/or other sodium channel blockers and/or NMDA receptor antagonists
Significant osteopenia, immobility, trophic changes*	Calcitonin or bisphosphonates
Profound vasomotor disturbance	Calcium channel blockers, sympatholytics, and/or blocks

From Harden RN, Oaklander AL, Burton AW, et al. Complex regional pain syndrome: practical diagnostic and treatment guidelines, ed 4. *Pain Med.* 2013;14:180-229.

The following strategies are suggested for patients who have been diagnosed with complex regional pain syndrome who cannot begin or progress in the functional restoration algorithm (see Fig. 40-13). Remember that these suggestions are overruled by individual patient presentation.

*Certain drugs, such as calcitonin, may be associated with analgesia as well as the more primary action.

NMDA, N-methyl-D-aspartate; *NSAID*, nonsteroidal anti-inflammatory drug.

ILLUSTRATIVE CASE REPORTS

Case 1. A 25-year-old female U.S. Army sergeant injured her left knee during combat training. She sustained a complete PCL rupture from an anterior blow to the anteromedial tibia. Her chief complaint was a feeling of instability going down stairs. She had unexplained aching pain along the anteromedial aspect of her leg, which was especially noticeable at night and which interfered with her sleep for more than 2 years. She did not have normal sensation along this aspect of her leg. She had been seen by multiple physicians, who were unable to provide a diagnosis of her severe pain.

Upon examination, a careful palpation of the tissues about the knee joint was performed to find the exact areas producing this patient's pain. In Figure 40-15, the patient points to the two areas that were exquisitely sensitive, in which any pressure produced marked pain. The first area is in the infrapatellar nerve region, and the second is along the saphenous nerve. This represented a classical presentation of CRPS type II in which the anterior blow produced a nerve contusion and injury. A PCL reconstruction could not be performed until the infrapatellar nerve branch was ablated and her symptoms resolved. Any surgery would carry the risk of exacerbating the CRPS II symptoms.

Case 2. A 47-year-old woman presented 2 years after a total knee arthroplasty that was performed for degenerative joint disease of the left knee. Her postoperative course was complicated by a failure to achieve a normal range of knee motion owing to aching pain to the medial and anterior aspect of knee that was present during the day and even more so at night. She also had hypersensitivity of the skin to touch and a burning sensation along the anteromedial aspect of her knee (Fig. 40-16). For two years, her pain symptoms were treated with standard medication, with the burning sensation and severe aching not appreciated to represent symptoms of CRPS. She had no color changes or coolness to her skin.

Unfortunately, as a result of the pain, this patient developed arthrofibrosis with complete entrapment of the patella, no medial or lateral patellar mobility, a patellar infera, and knee flexion limited to 80 degrees. As a result, she had a limping gait and a feeling of stiffness in

the knee and was incapacitated for daily activities. Other physicians were consulted and the diagnosis of arthrofibrosis was made but not the underlying CRPS. She presented to us with multiple questions regarding what had occurred with her knee, believing her pain symptoms were psychological, and was in a depressed state.



FIG 40-15 Patient described in Case 1 pointing to the painful areas along the regions of the infrapatellar nerve and the saphenous nerve.

Treatment immediately initiated by a pain management specialist involved multiple sympathetic nerve blocks and medications. The extensive release of soft tissues required to regain knee motion must unfortunately await control of the CRPS symptoms.

Our comments: This case emphasizes that CRPS symptoms may only present as aching and burning, with a hypersensitivity component that may not be recognized without careful questioning.

Case 3. A 47-year-old woman underwent arthroscopy for persistent medial knee pain, locking, and clicking in her knee after MRI had suggested a medial meniscal tear. The patient had a history of saphenous neuritis; however, her symptoms were quiescent at the time of surgery. At arthroscopy, an intact medial meniscus was found along with scaring of the anteromedial infrapatellar fat pad, which was debrided. One month later, the patient had a recurrence of mild saphenous nerve tenderness, which was treated with oral prednisone with no relief. Five weeks postoperatively, she had temperature sensitivity and light touch sensitivity (hyperesthesia and allodynia) and was referred to a pain management specialist for a sympathetic nerve block. The block produced complete relief of the hypersensitivity and a significant improvement in pain. Based on this response, the patient was scheduled for a series of epidural sympathetic blocks and medications. After a series of seven blocks performed over 2 months, the hypersensitivity to light touch was resolved, but the patient remained exquisitely tender to palpation about the knee.

The duration of relief became shorter and shorter between blocks, and the patient was admitted for an inpatient 7-day epidural blockade. Her pain was relieved initially but only partially resolved at follow-up. A repeat series of six epidural blocks was ineffective, and referral was made for a surgical sympathectomy which was performed 9 months after the index arthroscopic procedure. This entirely relieved her symptoms for 4 months, but the recurrence of pain after this treatment was more severe than that experienced before surgical sympathectomy.



FIG 40-16 **A** and **B**, Patient described in Case 2 indicating site of skin hypersensitivity to touch and a burning sensation on the anteromedial aspect of her knee.

At approximately 1 year from the index operation, the patient began to manifest CRPS symptoms in the contralateral leg. She ultimately underwent paravertebral ganglion blocks and had a nerve stimulator implanted, which was later removed for hardware failure. For this patient, all treatments provided initial relief, only to be followed with later relapses. At the time of writing, she still had pain and was seeking another pain management specialist.

Our comments: This patient demonstrates the long-term treatment aspects that some patients with CRPS will undergo. Often, these treatment aspects are only partially successful, and, unfortunately, these patients must live with a painful debilitating condition.

Case 4. A 28-year-old woman presented for evaluation of left lower extremity pain. She had an acute onset of left-sided weakness, numbness, tingling, and blurred vision of the left eye, which were attributed to transverse myelitis. She had previously been seen by neurologists and pain-management specialists. On evaluation, there were dark discoloration of the limb (see Fig. 40-1) and increased sensitivity to light touch from the knee to the foot. A 30-degree flexion contracture of the knee and ankle equinus was noted. The patient was unable to sleep under sheets owing to the inability to tolerate the pain from foot contact with the sheets. Additionally, pulses could not be palpated owing to her inability to tolerate the pressure required. The patient had been previously diagnosed with reflex sympathetic dystrophy and underwent three sympathetic blocks and implantation of a spinal cord stimulator. She was taking Neurontin, Lyrica, Morphine, and Vicodin.

The patient was advised to stop smoking. Paroxetine (Paxil) was prescribed, and although consideration was given for the addition of alendronate, its benefit was believed to be limited because the patient had a normal dual-energy x-ray absorptiometry (DEXA) scan. Physical therapy was continued but was ineffective, and referral was made to an outside facility specializing in CRPS. Eight weeks of treatment included elimination of narcotics and desensitization training with a device that swirled cornhusks around the leg at levels of intensity controlled by the patient. On her return, the patient had an erythematous appearance (improved from the dark discoloration previously) and had made great improvement in her ability to tolerate light touch. The patient continued physical therapy and her medications and was able to ambulate without pain.

Case 5. An 18-year-old female student was diagnosed with bilateral patellofemoral pain and medial patellofemoral ligament insufficiency. She was sent to physical therapy for quadriceps strengthening and stretching. Celebrex 200 mg daily was initiated and the patient advised to restrain from aggravating activities. Eight weeks later, the right knee pain had improved, but the left knee pain persisted. MRI detected no operative lesions, but the patient exhibited pain with light touch medially and laterally from the knee to midtibia. The pain was described as burning, and an ice cube test showed decreased temperature sensation in the affected region. There was no discoloration, but her skin felt cooler to touch. The diagnosis was made of early CRPS, and the patient was referred to physical therapy for desensitization training and provided a Medrol Dosepak. Her symptoms improved but were not eliminated, and a second Medrol Dosepak was prescribed. The patient's CRPS symptoms entirely resolved and she resumed her treatment for patellofemoral pain.

Our comments: In our experience, many patients with anterior knee pain are diagnosed with patellofemoral chondrosis without the appreciation of an associated CRPS that requires treatment first.

Case 6. This series of three cases is presented because it is the only familial representation of CRPS we have encountered. A possible genetic association between CRPS and the human leukocyte antigen (HLA) system has been previously described.[61,314] However, when the following patients were tested for HLA-specific antigens, none related to CRPS were detected. The following cases represent a mother and her two daughters, each of whom developed CRPS.

The primary case, a 43-year-old mother, was diagnosed with bilateral patellofemoral malalignment and severe trochlear dysplasia at the age of 13 years. The patient had repeated injuries (bilateral meniscal tears, bilateral patellar subluxations, and right patellar chondral injury) while playing tennis and softball. These injuries resulted in multiple surgical procedures (seven on the left knee, four on the right knee) to address her patellofemoral malalignment, meniscal injuries, and patellofemoral arthritis. At the age of 26 years, bilateral, staged patellectomies were performed for severe patellofemoral arthritis. She had brief relief of pain; however, 2 months after the right patellectomy, she experienced increasing pain that was generalized around the knee and along the leg. The pain was described as "severe and burning," even with the light touch of her clothing. The skin over the leg was shiny and edematous. Her family history was not significant except for a brother with diabetes mellitus and a sister with rheumatoid arthritis. There was no history of smoking. There were no lawsuit or workers' compensation claims involved. She was initially treated with multiple medications, physical therapy, and transcutaneous electrical nerve stimulation (TENS). The medications included combinations of anti-inflammatories, analgesics, anxiolytics, oral steroids, and gabapentin. Later that year, four sympathetic lumbar blocks were performed that provided only temporary relief. A surgical sympathectomy was performed. One month later, most of her symptoms had resolved, though she continued to have occasional episodes of hyperesthesia over the medial aspect of her knee. This patient was treated before the development of modern spinal stimulators that would not likely be offered today.

This patient's 13-year-old daughter was diagnosed with idiopathic toe walking at the age of 8 years. She developed tendoachilles contracture on the left side, which was treated using sequential below-knee casts in maximal dorsiflexion. After removal of the second cast, she refused to bear weight on the involved side and complained of burning pain around her ankle and foot. The skin over the foot was shiny, edematous, and cooler compared with the contralateral side. Prompt treatment was instituted in the form of multiple medications, physical therapy, and TENS. Six months later, there was no improvement in her symptoms, and she was admitted for continuous epidural sympathetic blockade for 5 days. The patient had complete relief of symptoms with the epidural blockade, only to have a recurrence of all her symptoms 1 month later, after a great toe injury on the same side. Again, treatment was instituted with medications, physical therapy, and hydrotherapy. The symptoms gradually diminished over a period of 3 months. She developed a normal heel-toe gait pattern during this time frame.

The mother's 15-year old daughter sustained an ankle sprain at the age of 11 years. She was treated with a soft ankle support brace, crutches, and partial weight bearing. Three weeks later, she developed hyperesthesia, burning sensation, and temperature changes along her ankle and foot. She had increased swelling and shiny skin over the involved area. The pain was not resolved with antiinflammatories, rest, and elevation and was worse with ice application. The family members promptly recognized the symptoms consistent with CRPS owing to their prior experiences and sought immediate medical attention. Treatment consisted of multiple medications, TENS, physical therapy, and hydrotherapy. The symptoms gradually resolved over a period of 6 months.

Case 7. A 38-year-old woman sustained a fall at work and dislocated her left patella. She underwent initial conservative treatment. Within 3 months, the patient was diagnosed with CRPS owing to a burning sensation and had developed arthrofibrosis. Ice to the affected area created burning pain. She had no recurrent instability episodes. The range of motion was 5 to 110 degrees, and severe quadriceps atrophy was noted. She was referred to pain management and placed on venlafaxine hydrochloride (Effexor) and Baclofen. As well, she continued physical therapy for knee motion and strengthening exercises. Over several months, she consistently improved but had a gradual return of her hypersensitivity 1.5 years later. She was placed on Neurontin and Depakote, and her symptoms abated within 1 month.

Case 8. A 26-year-old woman diagnosed with a medial meniscus tear by MRI was referred for extreme pain. The patient was taking oxycodone and acetaminophen (Percocet) and celecoxib (Celebrex). Her medial knee and tibia were exquisitely tender to palpation. She held her leg flexed 30 degrees and would not allow physical examination secondary to extreme pain with light touch. She had a mild effusion with no color changes, but her limb was cool to the touch. She reported being unable to tolerate the pressure of her bed sheets on her knee. She was prescribed Neurontin and referred for paraspinal ganglion blocks. Although the Neurontin helped her pain, the patient was prescribed tramadol because she could not tolerate the sedating effects. She underwent 10 blocks, which relieved her pain. She is currently in remission and being treated conservatively for patellar malalignment syndrome. She never underwent arthroscopy at our institution. This case demonstrates the importance of an immediate diagnosis because the pain could have been mistakenly attributed to the medial meniscus tear.

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41

Cincinnati Knee Rating System

Frank R. Noyes, Sue D. Barber-Westin

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INTRODUCTION

The assessment of outcome following the treatment of knee injuries and disorders has received tremendous attention in the orthopaedic literature. In regard to rating the outcome of anterior cruciate ligament (ACL) reconstructions, early scoring scales and systems were introduced into the medical community without undergoing an assessment of the psychometric properties of reliability, validity, and responsiveness.[25,31,52,55,63,90,98,107] There was a lack of consensus regarding which variables to include in the measurement of patient outcome. As a result, studies conducted in the 1990s comparing the results of ACL reconstruction using different rating systems showed distinct differences in results and conclusions.[11,35,83,91]

However, many knee-specific scales and rating systems have been published in the past decade with acceptable psychometric properties for a variety of diagnoses (Table 41-1).[102] It is important to understand the difference between *scales* that rate specific activities and *rating systems* that are more encompassing in terms of assessing the entire knee condition. For instance, scales have been designed to quantitate athletic activity levels,[5,19,59,90,98] problems with activities of daily living (ADLs),[9,40,52] or both,[62,84] all from the patient's perspective. We agree with Zarins[106] that although the subjective assessment of symptoms and functional limitations is important, the final outcome of a specific treatment must also take into account objective measures that are appropriate for the diagnosis or injury under study. The determination of patient outcome according to subjective questionnaire-based data only[93] does not provide a complete understanding of the ability of the treatment protocol to restore normal knee function. For instance, knee rating scales exist in which a patient may be rated as "excellent" even though an ACL reconstruction failed to restore normal or nearly normal knee stability, which is a major goal of the operation.[98] It is well known for this injury that in the short term, patients may do well without a functional ACL, but over time, the knee joint deteriorates, and problems increase to eventually affect daily activities.[3,7,15,77]

In contrast to scales, rating systems provide a comprehensive analysis of the knee condition and its impact on activity and function. Clinical investigators have suggested that such systems should measure a variety of symptoms, sports and daily activity functions, patient satisfaction, and objective physical findings.[2,91,106] Only three knee rating systems are currently available that have established reliability, validity, and responsiveness: the Cincinnati Knee Rating System (CKRS),[6,67] the International Knee Documentation Committee (IKDC) Knee Evaluation system,[37-39,89] and the new Knee Society Scoring System.[66,88] The CKRS and IKDC Knee Evaluation measure pain, swelling, giving way, functions of sports and daily activities, sports activity levels, patient perception of the knee condition, range of knee motion, joint effusion, tibiofemoral and patellofemoral crepitus, knee ligament subluxations, compartment narrowing on radiographs, and lower limb symmetry during single-leg hop tests. The CKRS has been validated for a variety of knee problems[6,58] and the IKDC has been validated for ACL reconstruction,[89] patellar dislocation,[80] and meniscus procedures.[18] The IKDC system is discussed in detail in Chapter 42. The new Knee Society Scoring system is discussed in detail in Chapter 45.

General health outcome instruments are also available that determine general health and other indicators such as the psychological and social aspects of the patient's life (Table 41-2).[56] The most widely used of these types of scales for knee research appears to the be Short Form 36 (SF-36) Health Survey,[99] although a recent study[100] indicated the Short Form 12 Health Survey may also be appropriate for ACL reconstruction studies. Generic health questionnaires have limited usefulness in studies comprised of patients with a specific diagnosis and therefore should be used in addition to disease-specific rating

TABLE 41-1 Psychometric Properties Measured in Knee-Specific Outcome Instruments

Targeted Diagnosis	Study	Outcome Instruments	Reliability Measured?	Validity Measured?	Responsiveness Measured?
ACL deficiency, ACL reconstruction	Lysholm[52] (1982)	Lysholm	No	No	No
	Tegner & Lysholm[98] (1985)	Lysholm, Tegner	No	No	No
	Hanley & Warren[31] (1987)	HSS	No	No	No
	Straub & Hunter[108] (1988)	Sports Performance Index	No	No	No
	Seto[90] (1988)	Sports Participation Survey	No	No	No
	Mohtadi[62] (1998)	ACL-QOL	Yes	Yes	No
	Irrgang[39] 1998	IKDC Knee Evaluation Form	No	Yes	No
	Roos[85] (1998)	KOOS	Yes	Yes	Yes
	Barber-Westin[6] (1999)	Cincinnati Knee Rating	Yes	Yes	Yes
	Briggs[13] (2006)	Lysholm & Tegner	Yes	Yes	Yes
	Briggs[14] (2009)	Lysholm & Tegner	Yes	Yes	Yes
	Salavati[86] (2011)	KOOS	Yes	Yes	No
"Nonoperative"	Leigh Brown[48] (1999)	Edinburgh Knee Function	Yes	Yes	No
Chondral lesion	Kocher[45] (2004)	Lysholm	Yes	Yes	Yes
	Bekkers[8] (2009)	KOOS	Yes	Yes	No
Osteoarthritis	Bellamy[9] (1988)	WOMAC	Yes	Yes	Yes
	Rejeski[82] (1995)	Knee Pain	Yes	Yes	No
	Williams[104] (2012)	WOMAC, Pittsburgh ADL, LEFS	Yes	No	Yes
Knee arthroplasty	Amstutz[109] (1984)	UCLA	No	No	No
	Insall[36] (1989)	Knee Society	No	No	No
	Finch[27] (1995)	LEAP	Yes	Yes	Yes
	Zahiri[105] (1998)	UCLA	No	Yes	No
	Dawson[20] (1998)	Oxford	Yes	Yes	Yes
	Liow[51] (2000)	Knee Society	Yes	No	No
	Lingard[50] (2001)	Knee Society, WOMAC	No	Yes	Yes
	Roos[85] (2003)	KOOS	Yes	Yes	Yes
	Whitehouse[103] (2003)	Reduced WOMAC	Yes	Yes	Yes
	Naal[64] (2009)	UCLA, Marx Activity Rating, Tegner	Yes	Yes	No
	Talbot[97] (2010)	High-Activity Arthroplasty Score	No	Yes	No
	Scuderi[88] (2012), Noble[66] (2012)	New Knee Society Scoring System	Yes	Yes	Yes
Revision knee arthroplasty	Saleh[87] (2005)	Lower Extremity Activity Scale	Yes	Yes	Yes
Meniscus procedure	Briggs[13] (2006)	Lysholm & Tegner	Yes	Yes	Yes
	Crawford[18] (2007)	IKDC Knee Evaluation Form	Yes	Yes	Yes
Patellofemoral pain	Chesworth[16] (1989)	Functional Index	Yes	Yes	No
	Kujala[46] (1993)	Kujala	No	No	No
	MacIntyre[53] (1995)	Functional Index	Yes	Yes	No
	Harrison[32] (1995)	Functional Index	Yes	Yes	Yes
	Piva[81] (2009)	Pittsburgh ADL	No	No	Yes
	Lee[47] (2013)	Samsung Medical Center	Yes	Yes	Yes
Articular cartilage procedure	Ebert[23] (2013)	KOOS, Lysholm, Tegner	No	No	Yes
	Greco[29] (2010)	IKDC Subjective, WOMAC, Cincinnati	Yes	No	Yes
Patellar dislocation	Paxton[80] (2003)	IKDC, Kujala, Fulkerson, Lysholm, Tegner	Yes	Yes	No
Variety of knee problems combined	Irrgang[40] (1998)	Pittsburgh ADL, Lysholm	Yes	Yes	Yes
	Binkley[10] (1999)	LEFS	Yes	Yes	No
	Marx[59] (2001)	Marx Activity Rating	Yes	Yes	No
	Marx[59] (2001)	Cincinnati, Lysholm, ADL, AAOS Sports/Knee	Yes for all	Yes for all	Yes for all
	Irrgang[37] (2001)	IKDC Subjective	Yes	Yes	No
	Johanson[41] (2004)	AAOS Lower Limb Core Scale	Yes	Yes	Yes
	Irrgang[38] (2006)	IKDC Subjective	NA	NA	Yes

ACL, Anterior cruciate ligament; *ACL-QOL*, Anterior Cruciate Ligament-Quality of Life; *ADL*, activities of daily living; *HSS*, Hospital for Special Surgery; *AAOS*, American Academy of Orthopaedic Surgeons; *IKDC*, International Knee Documentation Committee; *KOOS*, Knee Injury & Osteoarthritis Outcome; *LEAP*, Lower Extremity Activity Profile; *LEFS*, Lower Extremity Functional Scale; *UCLA*, University of California at Los Angeles; *WOMAC*, Western Ontario and McMaster Universities Osteoarthritis Index.

TABLE 41-2 Psychometric Properties Measured in General Health Outcome Instruments Used in Knee Studies

Targeted Diagnosis	Study	Outcome Instrument	Reliability Measured?	Validity Measured?	Responsiveness Measured?
ACL deficiency, ACL reconstruction	Salavati[86] (2011)	SF-36	Yes	Yes	No
Knee arthroplasty	Lingard[50] (2001)	SF-36	No	No	Yes
Articular cartilage procedure	Greco[29] (2010)	SF-36	Yes	No	Yes
	Ebert[23] (2013)	SF-36	No	No	Yes
Patellar dislocation	Paxton[80] (2003)	SF-36, MFA	Yes	Yes	No
Various knee problems	Martin[57] (1997)	SF-36, MFA	Yes	Yes	Yes

ACL, Anterior cruciate ligament; *SF-36*, Short Form 36; *MFA*, Musculoskeletal Function Assessment.

CRITICAL POINTS Introduction

- Many knee-specific scales and rating systems have been published in the last decade with acceptable psychometric properties for a variety of diagnoses.
- Scales rate specific activities, such as sports or daily functions.
- Rating systems provide a comprehensive analysis of the knee condition and its impact on activity and function after the treatment protocol under study.
- Only three knee rating systems are currently available that have established reliability, validity, and responsiveness: Cincinnati Knee Rating System, International Knee Documentation Committee Knee Evaluation system, and Knee Society Scoring System.
- The Cincinnati Knee Rating System is one of the most commonly used instruments in the orthopaedic literature to measure the results of ACL reconstruction, and has been considered a gold standard in the development and content and criterion validity analyses of other knee rating scales.

systems.[29,80] Finally, global outcome instruments that are extremity specific (upper or lower) or disease specific (e.g., osteoarthritis) are widely used to determine the outcome of a many types of knee injuries and disorders. The most commonly used assessments are discussed in Chapter 43.

The CKRS was first published in concert with the largest ACL natural history study conducted during that time period.[77] In the early 1980s, the dilemma of the appropriate treatment for complete ACL ruptures stemmed in part from limited knowledge of the functional limitations caused by the injury and the lack of a rigorous rating system which graded symptoms and limitations according to the specific type of activity during which they occurred. Over the next decade, additional scales and modifications were developed for the CKRS to provide a comprehensive assessment of the knee condition.[6,67,69,76] An overall rating scheme was devised to provide a final rating, which is available in either in a numeric or categorical manner, as is discussed later. The major components of the CKRS are shown in Table 41-3. This system is one of the most commonly used instruments in the orthopedic literature to measure the results of ACL reconstruction and has been considered a gold standard in the development and content and criterion validity analyses of other knee rating scales.[29,34,37,39,59] The CKRS was initially designed and validated in athletically active populations; however, it is also useful for patients who have undergone other operative procedures such as articular cartilage restorative procedures,[29] meniscus repairs or transplants, osteotomies, or patellofemoral procedures. This chapter describes the rationale and methodology for the major components of the CKRS.

TABLE 41-3 Components of the Cincinnati Knee Rating System

I: Subjective Assessment
- Symptom Rating Scale
- Patient Perception of the Overall Knee Condition Scale
- Sports Activity Scale
- Rating of Individual Sports and Daily Activity Functions
- Occupational Rating Scale

II: Patient History
III: Knee Examination
IV: Objective Testing
V: Operative Procedures and Articular Cartilage Rating
VI: Postoperative Complications
VII: Overall Rating

MEASUREMENT OF PSYCHOMETRIC PROPERTIES OF OUTCOME INSTRUMENTS

Outcome instruments and scales must have strong psychometric properties to be useful in evaluating the results of treatment. These properties—(reliability, validity, and responsiveness)—are determined in a variety of methods.

Reliability is the extent to which scores on an instrument are reproducible and is measured either between subjects (test-retest) or between observers (interobserver). Patients complete questionnaires at separate time periods; a minimum 1-week interval was recommended by Deyo and coworkers[21] to elapse between questionnaire administration. Reliability is measured with product-moment correlations and intraclass correlation coefficients (ICCs). ICC is the most commonly used statistic in modern studies and is calculated by

$$(A^2 + B^2 - C^2)/A^2 + B^2 + D^2 - C^2/n$$

where A is the standard deviation (SD) from all values in trial number 1, B is the SD from all values in trial number 2, C is the SD of the difference in all values between trials number 1 and number 2, D is the mean of the difference between trials number 1 and number 2, and n is the total number of patients.

Correlations among test-retest data should be greater than 0.70, which is considered the standard for adequate reliability for questionnaires.[79] The use of ICC rather than the more common Pearson correlation coefficient was suggested by Deyo and coworkers[21] and Lin[49] to provide a more sensitive assessment of variability within data. The problem that can occur with the Pearson correlation coefficient is that duplicate measurements may be systematically different yet correlate

CRITICAL POINTS Review of Analyses Used to Measure Psychometric Properties of Outcome Instruments

- Reliability is the extent to which scores on an instrument are reproducible and is measured either between subjects (test-retest) or among observers (interobserver).
- Internal consistency represents the concept that the consistency with which a patient answers from one question to the next can be used to provide an estimate of reliability for the total test score.
- Construct validity is the extent to which a measure corresponds to expected theoretical concepts or hypotheses regarding the diagnosis.
- Item-discriminant (or -divergent) validity is present when variables which are hypothesized to be dissimilar are proven so.
- Criterion (or concurrent) validity is assessed by correlating scores on the instrument under study with other criteria known or believed to adequately measure the function or symptom.
- Responsiveness is the ability of an instrument to detect clinically important change.

highly and, as a result, be falsely interpreted. For example, if every patient scored exactly 5 points lower on a scale on the second administration, the test-retest correlation would be a perfect 1.0, despite the fact that every patient had a lower score. The ICC handles this problem because it not only assesses the strength of the correlation but also determines whether or not the slope and intercept in the regression line of test-retest data vary from those expected with duplicate results. In our example, the ICC would correspondingly be reduced to demonstrate the systematic difference among the test-retest data.

Internal consistency is determined by a coefficient α greater than 0.60.[42] The underlying concept of this measure is that the consistency with which a patient answers from one question to the next can be used to provide an estimate of reliability for the total test score.[65] A high coefficient α indicates that the items in a questionnaire are consistently measured or are homogeneous with regard to the measurement of the underlying diagnosis or attribute.[44]

Several measures have been described to determine the validity of an instrument, including content, construct, item discriminant, convergent, and criterion. In general, *validity* is the psychometric criterion in which an instrument is tested to determine its ability to actually measure what it claims to measure.[41] *Content validity* is the extent to which a question or instrument represents the area of interest and has been described in various manners. Face validity, one example of content validity, is determined by consulting both patients and experienced medical professionals regarding the development of a scale's questions and their relevance to the diagnosis under study.[26] For instance, for ACL reconstruction investigations, a questionnaire with good face validity would be believed by patients, surgeons, and therapists to measure the common problems caused by this injury, such as pain and instability. This represents a subjective analysis that is not statistically analyzed. Another method to determine content validity is to calculate floor (worst result) and ceiling (best result) effects.[60,96] Scales in which the majority of patients score either the highest level or the lowest level do not allow for an assessment of deterioration or improvement over time. Floor and ceiling effects are present when greater than 30% of the population marks either the best possible or worst possible scores on a scale.[42]

Construct validity is the extent to which a measure corresponds to expected theoretical concepts or hypotheses regarding the diagnosis. An instrument will accurately differentiate patients whose outcome is expected to vary with regard to certain characteristics known to the disease process.[24,95] Researchers develop hypotheses based on prior research and clinical experience in which the questionnaire scores are expected to be significantly different among selected patient groups. The hypotheses are confirmed using the F and T-test at the level of $P < .01$. In addition, construct validity is determined by conducting Pearson product-moment correlation coefficients between scale items and either previously validated instruments or physician and patient assessments. A moderately strong coefficient is proven at $R > .60$.

Item-discriminant (or *item-divergent*) *validity* is present when variables which are hypothesized to be dissimilar (such as patient age and anteroposterior [AP] knee displacements) are indeed found to be statistically unrelated.[24,61] Pearson correlations are performed to detect statistical dissimilarities, proven at $R = 0.28$ or less. In the opposite manner, convergent validity is present when variables which are believed to be similar within the questionnaire are indeed found to be statistically similar.

Criterion (or *concurrent*) *validity* is assessed by correlating scores on the instrument under study with other criteria known or believed to adequately measure the function or symptom. This determines how a new instrument compares with an accepted gold standard instrument. The Pearson product-moment correlation coefficient is used to determine this property, with moderately strong findings indicated by $R > 0.60$.

Responsiveness, or the ability of an instrument to detect clinically important change, is determined by calculating standardized response means (SRM) and effect sizes (ES) of the selected instrument categories. The magnitude of the SRM (mean change in score from preoperative to follow up/SD of change in score)[30] and the ES (mean change in score from preoperative to follow up/SD of preoperative score)[43] are interpreted using the Cohen standard of greater than 0.20 for small effects, greater than 0.50 for moderate effects, and greater than 0.80 for large effects.[17] This analysis provides a more precise indication of the change in results over time from those obtained by the standard Student t-test. An instrument's sensitivity simply denotes its ability to measure any change, which by definition does not necessarily indicate one that is clinically meaningful.[41]

COMPONENTS OF THE CKRS

Rating of Symptoms

Pain, swelling, partial giving way, and full giving way are the major knee symptoms assessed in ACL investigations. Pain and swelling are also symptoms that may occur in all other types of knee injuries and disorders, and instability is a problem with other knee ligament ruptures and certain patellofemoral disorders. Authors have proposed a variety of methods for measuring symptoms, from a binary system ("yes" or "no"[31,55]), to visual analogue scales,[28,34,62] to a severity rating (such as mild, moderate, severe), which can be done either alone[52] or in combination with activities (such as "slight after strenuous sports").[25,52,84,107]

In 1983, Noyes and associates[77] proposed that knee symptoms should be rated according to the activity during which they occurred: strenuous sports, recreational sports, or walking. This rationale provided an understanding of the impact of a chronic ACL-deficient knee because 30% of 103 patients reported pain with walking alone, 47% with recreational sports, and 69% with strenuous sports in the authors' natural history study.

The assessment of symptoms was later refined and the scale increased to a six-level gradient shown in Figure 41-1.[67,69,75] Points are awarded for the highest activity level in which the patient is able to participate without incurring the symptom (Appendix A). If the

DIRECTIONS: Using the key below, circle the appropriate boxes on the four scales which indicates the highest level you can reach WITHOUT having symptoms.

Scale	Description
10	Normal knee, able to do strenuous work/sports with jumping, hard pivoting
8	Able to do moderate work/sports with running, turning, twisting; symptoms with strenuous work/sports.
6	Able to do light work/sports with no running, twisting, jumping; symptoms with moderate work/sports
4	Able to do activities of daily living alone; symptoms with light work/sports
2	Moderate symptoms (frequent, limiting) with activities of daily living
0	Severe symptoms (constant, not relieved) with activities of daily living.

1. PAIN

10 — 8 — 6 — 4 — 2 — 0

2. SWELLING (actual fluid in the knee, obvious puffiness)

10 — 8 — 6 — 4 — 2 — 0

3. PARTIAL GIVING WAY (partial knee collapse, no fall to the ground

10 — 8 — 6 — 4 — 2 — 0

4. FULL GIVING WAY (knee collapse occurs with actual falling to the ground)

10 — 8 — 6 — 4 — 2 — 0

FIG 41-1 Symptom Rating Scale.

CRITICAL POINTS Rating of Symptoms and Patient Satisfaction

Rating of Symptoms

- Pain, swelling, partial giving way and full giving way are major symptoms assessed in knee injuries and disorders.
- Symptoms are rated according to the highest activity level possible without incurring the symptoms.
- Six-level scale

Rating of Patient Perception of the Knee Condition

- Patients rate the overall condition of the knee by circling a number on a scale from 1 to 10.
- Descriptors are provided to assist the patient in understanding the meaning of the numerical scale.
- Most subjective of all factors, not correlated with other outcome measures

symptom is present with ADL, it is rated as either moderate (frequent, limiting) or severe (constant, not relieved). Definitions are provided for terms that might otherwise be ambiguous to patients, such as "moderate" sports (running, turning twisting) and "strenuous" sports (jumping, hard pivoting).

When reporting symptoms before and after surgery, a distribution of the percent of patients in each of the six levels should be shown (along with a mean and SD) for both time periods. An example is shown in Figure 41-2 for a group of patients who received a meniscus transplant.[73] The data were also expressed in the body of the text as "the mean preoperative Cincinnati Knee Rating Scale pain score of 2.5 points (range, 0-6 points) improved to a mean of 5.8 points (range, 0-10 points) at follow up (P <.0001). Before the meniscus allograft, thirty patients (79%) had moderate to severe pain with daily activities but at follow up, only four patients (11%) had pain with daily activities."[73]

One problem may occur in the rating of symptoms when patients have not attempted to return to strenuous sports activities. In these situations, a potential bias may occur if the patient or clinician attempts to project the correct symptom level based on a hypothetical answer. For instance, if a patient returned to bicycling or swimming and had no pain with those activities, then the pain score awarded would be a level 6 (see Fig. 41-1). However, if the patient is asked whether she or he believes pain would occur with level 8 activities (running, twisting, turning) and she or he responds that it probably would not occur, a bias would occur if this score was assigned without further verification that this was indeed true. This is often the case with the symptom of giving way, because patients frequently return asymptomatically to level 6 or 8 activities postoperatively but state that they participated a few times at level 10 activities (jumping, hard pivoting) without problems. Points are awarded only with a reasonable basis for the assessment and not speculated by the patient as to the level that may be possible.

This potential bias is a particular problem with populations of chronic knee injuries with compounding problems of advanced articular cartilage deterioration, multiple ligament reconstructive procedures, or varus osseous malalignment, which is corrected with a high tibial osteotomy (HTO) in addition to ACL reconstruction. This problem has two solutions. First, the clinician may ask the patient to

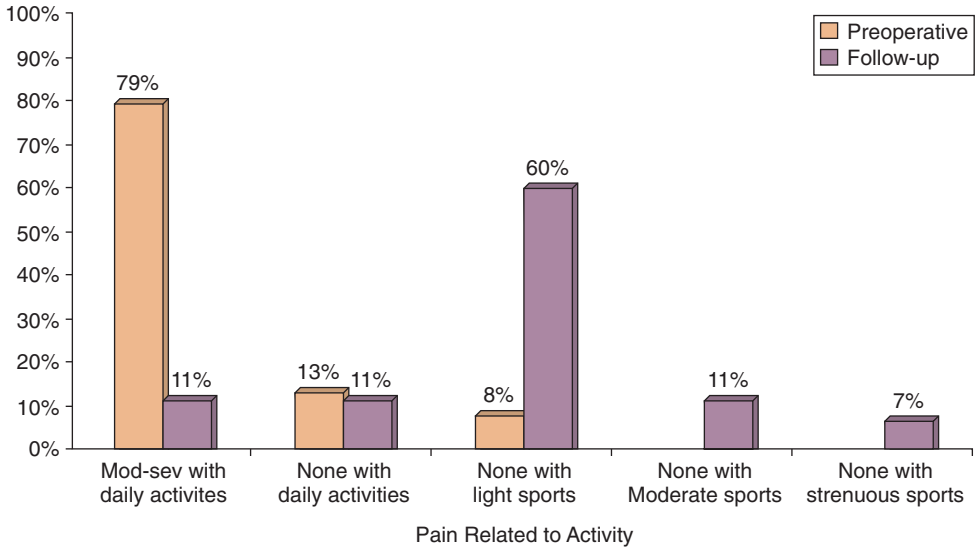


FIG 41-2 The pain scale shows the highest level of activity possible without the patient experiencing knee pain. This example was taken from a clinical study on meniscus transplantation. The difference between the preoperative and follow-up visit was statistically significant ($P < .0001$). *Mod-sev,* Moderate to severe. (From Noyes FR, Barber-Westin SD, Rankin M. Meniscal transplantation in symptomatic patients less than fifty years old. *J Bone Joint Surg Am.* 2004;86A:1392-1404.)

DIRECTIONS: Using the key below, circle the appropriate boxes on the four scales which indicates the highest level you can reach WITHOUT having symptoms.

Scale	Description
6	Able to do light /moderate/strenuous work/sports without symptoms
4	Able to do activities of daily living alone; symptoms with light work/sports
2	Moderate symptoms (frequent, limiting) with activities of daily living
0	Severe symptoms (constant, not relieved) with activities of daily living

1. PAIN

6 — 4 — 2 — 0

2. SWELLING (actual fluid in the knee, obvious puffiness)

6 — 4 — 2 — 0

3. PARTIAL GIVING WAY (partial knee collapse, no fall to the ground)

6 — 4 — 2 — 0

4. FULL GIVING WAY (knee collapse occurs with actual falling to the ground)

6 — 4 — 2 — 0

FIG 41-3 Modified Symptom Rating Scale.

test the knee at higher levels of activities if both patient and physician believe this is a reasonable request. Then, the patient can be contacted later for a symptom rating after he or she has participated in strenuous activities several times.

Second, the clinician may use the modified symptom rating scale (Fig. 41-3) that was first introduced in an investigation of patients with varus osseous malalignment and ACL deficiency who were treated with multiple operative procedures.[70] This modified scale consists of a four-level gradient. The levels of 0, 2, and 4 are the same as the original scale shown in Figure 41-1. The fourth and highest level (level 6) indicates that some type of sports participation is possible without the symptom. This modified scale is intended for studies in which the majority of patients do not return to moderate or strenuous athletics indicated in levels 8 and 10. The reliability of this modified scale was previously

shown to be adequate for patients and normal subjects.[6] However, clinicians should be aware that the modified scales may have reduced sensitivity, especially if the results of a study that used the modified scale are compared with another study that used the original scale. This pertains only to the individual symptom results. The effect of the modified scale on the overall rating score, described later in this chapter, is small and only has a negligible impact when comparing the data of the overall scores among different populations.

Even though there is always the potential for a bias to exist regarding the scoring of subjective symptoms, the CKRS format allows for an accurate assessment of the activity levels patients return to on a routine basis. The scale was designed to not award points if a patient participates at a high activity level but has symptoms, thereby fulfilling the criteria of the "knee abuser."[77]

Rating of Patient Perception of the Knee Condition

Modern knee rating systems incorporate some form of patient satisfaction, or rating of the patient's perception of the knee condition, into the assessment of clinical outcome.[6,37] In the CKRS, patients are asked to rate the overall condition of the knee by circling a number on a scale from 1 to 10 (Fig. 41-4). Four descriptors are provided to assist the patient in understanding the meaning of the numerical scale. Under the number 2 is the term "poor," defined as "I have significant limitations that affect activities of daily living," whereas under the number 10 are the terms "normal/excellent," defined as "I am able to do whatever I wish (any sport) with no problems" (see Appendix A). For data reporting purposes, a distribution of responses is shown in a five-level gradient. Responses under numbers 1 and 2 are termed "poor," those under numbers 3 and 4, "fair"; those under numbers 5 and 6, "good"; those under numbers 7 and 8, "very good"; and those under numbers 9 and 10, "normal."

An example is shown in Figure 41-5 for a group of patients who received a meniscus transplant.[73] The data were also expressed in the body of the text as "the mean preoperative patient perception score of 3.2 points (range, 1-6 points) improved to a mean of 6.2 points (range, 1-9 points) at follow up ($P = .0001$). Two patients rated the knee condition as the same, and two as worse."

Clinicians and researchers should realize that inconsistencies may arise from the responses to the patient perception scale and those in other scales of the CKRS. An example is an 18-year-old patient who successfully returned to competitive soccer without problems or symptoms rated the overall knee condition as a 7 because he felt "slower than before the injury." Conversely, a 45-year-old patient with a triple varus knee who required an HTO, ACL reconstruction, and posterolateral reconstruction and was only able to return to low-impact activities, also rated her knee condition as a 7. She indicated that she was exceptionally pleased that her constant pain with daily activities had resolved and that she was able to swim and bicycle without problems. Because this portion of the CKRS is perhaps the most subjective of all of the assessment factors, it is not correlated with other outcome

Rate the overall condition of your knee at the present time. Circle one number below.

1	2	3	4	5	6	7	8	9	10
	poor		fair		good				normal

Poor - I have significant limitations that affect activities of daily living.
Fair - I have moderate limitations that affect activities of daily living, no sports possible.
Good - I have some limitations with sports but I can participate; I compensate.
Normal/excellent - I am able to do whatever I wish (any sport) with no problems.

FIG 41-4 Patient Perception of the Knee Condition.

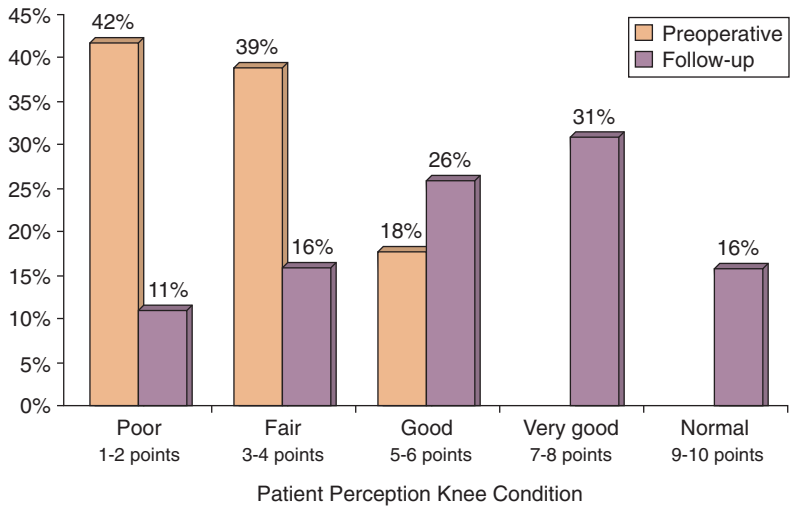


FIG 41-5 Distribution of patient perception of the overall knee condition from a clinical study on meniscus transplantation. The difference between preoperative and follow up was statistically significant ($P < .0001$). (From Noyes FR, Barber-Westin SD, Rankin M: Meniscal transplantation in symptomatic patients less than fifty years old. *J Bone Joint Surg Am.* 2004;86A:1392-1404.)

measures. This underscores the inconsistencies in reporting of patient outcome when only a patient perception rating is used to determine the results of an operation.

Rating of Sports and Daily Activities

In the sports medicine literature, the accurate assessment of sports activity levels and participation is crucial in the determination of the result of an operation or treatment of any knee problem. This is true for many situations. For instance, if a competitive athlete chooses an ACL reconstruction after an acute rupture to be able to return to a high activity level, the outcome instrument must be able to precisely define the level of sports participation before and after surgery. Or, if a sedentary individual with moderate arthrosis and giving-way symptoms chooses ACL reconstruction to reduce limitations with daily activities and adopt a more active lifestyle, the instrument must be able to detect a more subtle change (increase) in activity. An instrument must also be able to detect the knee abuser, or the patient who returns to athletics and experiences symptoms that may be harmful to the knee joint over the long term.[77] These individuals should be sorted from others who returned to athletics without problems. Therefore the accurate assessment of sports participation must span many levels of athletics, intensity, and frequency of participation; be able to sort populations according to changes in athletic levels or lifestyle; and identify patients who experience symptoms during athletic activities.

The CKRS Sports Activity Scale was first introduced in 1989 after an analysis of existing scales at that time period detected multiple biases and potential sources of error in reporting outcome of ACL reconstruction.[69] The problems identified included (1) the failure to precisely define sports activity levels according to specific sport and intensity of participation; (2) the failure to sort populations according to overall intensity of athletic participation before and after treatment; (3) the failure to detect and sort from the population patients who return to sports and experience significant symptoms; (4) the combination of work and sports activities into the same scale; and (5) the failure to detect alterations in athletics because of changes in lifestyle and non–knee-related factors.

The goal in the development of the Sports Activity Scale was to distinguish among categories of athletic activities in a manner that allowed investigators to apply the rating in a uniform manner to any type of athletic activity. Two criteria were selected to determine this rating. First, the frequency of participation was determined using a four-level gradient that assigned patients to a subgroup depending upon the number of days in a week (or month) of sports participation (Fig. 41-6). Second, the knee functions that occurred during various sports activities were determined and sorted into three subgroups. The first subgroup consisted of sports that involved the most difficult knee motions: jumping, hard pivoting, and cutting. The second subgroup included sports that involved running, twisting, and turning. The third subgroup consisted of sports that did not involve running, twisting, or jumping (e.g., swimming and cycling).

This sorting of sports activities according to frequency and intensity eliminates the ambiguous classification of athletes into categories such as recreational or competitive. Note that collegiate, professional, and adolescent athletes can be placed in the same category on this scale. Although some examples of sports are listed under the various subgroups, any athletic activity may be placed into the scale according to the knee functions that occur during that particular activity. The investigator may analyze the sports activity scale data according to either the frequency subgrouping or the intensity subgrouping categories. In addition, the sports scale incorporates a three-level gradient for patients who do not participate in athletics. This allows a determination of the overall severity of symptoms with ADLs.

The reporting of the patient responses to the Sports Activity Scale may be shown as a distribution according to either frequency or intensity of activities. An example is shown in Table 41-4 from a study on posterior cruciate ligament (PCL) reconstruction.[71] An average score should not be calculated from this scale, because the data are categorical in nature.

A second component of the assessment of sports activities is the change that occurs in activity levels between treatment periods, the most common being that which occurs between the preoperative and most recent follow-up evaluations (Fig. 41-7). The format is designed to determine changes in sports activities because of either knee-related or non–knee-related reasons and to detect knee abusers. The data from this analysis are usually displayed in publications in the same table as the Sports Activity Level data (see Table 41-4).

The third component of the assessment of sports activities is the rating of six individual functions that place varying loads on the knee joint (Fig. 41-8). Functions of sports are analyzed separately from those of daily activities to assess limitations in all patients, not just those participating in athletics. Even in cases in which the knee joint is markedly affected, patients are able to indicate the problems encountered with these types of activities. Each function is determined using a four-level gradient whose terminology was selected to decrease the subjective component inherent in this type of analysis. The data obtained for each of the six functions is reported individually using means, SD, and the distribution of responses in each of the four levels.

Rating of Occupational Activities

Little attention has been given in the sports medicine literature on the effect of ACL reconstruction on work activities. The results of knee

CRITICAL POINTS Rating of Sports and Daily Function and Activities

Accurate assessment of sports participation must span many levels of athletics, intensity, and frequency of participation; be able to sort populations according to changes in athletic levels or lifestyle; and identify patients who experience symptoms during athletic activities.

Biases and Potential Sources of Error in Other Rating Systems

- Failure to precisely define sports activity levels according to specific sport and intensity of participation
- Failure to sort populations according to overall intensity of athletic participation before and after treatment
- Failure to detect and sort from the population patients who return to sports and experience significant symptoms
- Combining work and sports activities into the same scale
- Failure to detect alterations in athletics because of changes in lifestyle and non-knee-related factors

Two Criteria to Determine Sports Rating, Allows All Sports to be Rated

- Frequency of participation
- Knee functions incurred during activity

Assess Change in Sports Activities Between Treatment Periods

- Determine whether change is because of knee-related or non–knee-related reasons.
- Detect knee abusers.
- Also rate individual functions of sports, daily activities.

Circle the number that describes your level of sports activity at this time.

Level I (participates 4-7 days/week)

100 Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
95 Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
90 No running, twisting, jumping (cycling, swimming)

Level II (participates 1-3 days/week)

85 Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
80 Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
75 No running, twisting, jumping (cycling, swimming)

Level III (participates 1-3 times/month)

65 Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
60 Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
55 No running, twisting, jumping (cycling, swimming)

Level IV (no sports)

40 I perform activites of daily living without problems
20 I have moderate problems with activities of daily living
0 I have severe problems with activities of daily living; on crutches, full disability

FIG 41-6 Sports Activity Scale.

TABLE 41-4 Example of Sports Activity Levels Before and After Posterior Cruciate Ligament Reconstruction

Type of Sport	Preoperative (*n* Patients)	Follow-up (*n* Patients)
Jumping, hard pivoting, cutting	0	2
Running, twisting, turning	1	2
Swimming, bicycling	7	11
None	11	4
Change in sports activities:		
Increased level, no symptoms		8
Same level, no symptoms		4
Decreased level, no symptoms		1
Playing with symptoms		2
No sports, knee-related reasons		3
No sports, non–knee-related reasons		1

From Noyes FR, Barber-Westin S. Posterior cruciate ligament replacement with a two-strand quadriceps tendon–patellar bone autograft and a tibial inlay technique. *J Bone Joint Surg Am.* 2005;87:1241-1252.

CRITICAL POINTS Rating of Occupational Activities

- Occupational activities should be rated separately from sports activities.
- Seven factors are graded to provide a general intensity rating of work conditions.
- 0-100 point scale:
  - Disabled (0 points)
  - Very light (1-20 points)
  - Light (21-40 points)
  - Moderate (41-60 points)
  - Heavy (61-80 points)
  - Very heavy (>80 points)
- Determine change in work activities in same manner as sports activities.
- Reliability of the Occupational Rating Scale is adequate for patients with ACL ruptures, chronic patellofemoral disorders, degenerative meniscal tears, and degenerative joint arthritis.

operations and treatment programs should be determined by assessing both occupational and sports activities, especially if patients are not involved in athletics because of lack of interest, time, ability, or other factors. In these cases, the ability of an operation or treatment program to successfully return patients to their occupation is a primary determinant of the program's effectiveness. This determination can only be made with a rating scale for work activities, which is separate from that of sports activities. Scales that combine work and sports into one activity rating do not allow for this analysis to be performed.[98]

A study was conducted on published occupational rating systems in which several bias and potential sources of error were detected when reporting outcomes of treatment programs.[76] One problem was the lack of a scale that sufficiently evaluated the amount of stress placed on the knee at work or whether the knee condition was limiting work activities. Ambiguous terminology, such as light, moderate, and heavy, was frequently encountered to describe occupations. No published scale incorporated a method to detect a change in work status because of factors not related to the knee condition. Based on this study, an Occupational Rating Scale (Fig. 41-9) was created. This was composed of seven factors that place varying amounts of load on the lower extremity (see Appendix A). Each factor was graded according to intensity, frequency, and duration of the task required on a daily basis. The factors chosen were commonly used to assess the condition of the knee joint in workers' compensation evaluations. This scale was found to be more effective and valid in assessing demands of occupations on the lower extremities than scales that used job titles or arbitrary numeric scales.[76]

The factor of "standing/walking" was selected because of the harmful effect prolonged weight bearing has on patients with certain knee disorders, including patellofemoral and tibiofemoral arthrosis.

Check the box that best describes the change you have had in sports activities since your injury or surgery. My sports activities have:

Not changed
- ☐ I have no/slight problems
- ☐ I have moderate/significant problems

Increased
- ☐ I have no/slight problems
- ☐ I have moderate/significant problems

Decreased
- ☐ I have no/slight problems
- ☐ I have moderate/significant problems
- ☐ For reasons not related to my knee

Stopped, given up all sports
- ☐ I have moderate/significant problems when I play sports
- ☐ For reasons not related to my knee

FIG 41-7 Change in sports activities.

Check the problems you have during:

1. Walking
check one box:
- ☐ Normal, unlimited (40)
- ☐ Some limitations (30)
- ☐ Only 3-4 blocks possible (20)
- ☐ Less than 1 block; cane, crutch (0)

2. Stairs
check one box:
- ☐ Normal, unlimited (40)
- ☐ Some limitations (30)
- ☐ Only 11-30 steps possible (20)
- ☐ Only 1-10 steps possible (0)

3. Squatting/kneeling
check one box:
- ☐ Normal, unlimited (40)
- ☐ Some limitations (30)
- ☐ Only 6-10 possible (20)
- ☐ Only 0-5 possible (0)

4. Straight running
check one box:
- ☐ Fully competitive (100)
- ☐ Some limitations, guarding (80)
- ☐ Definite limitations, 1/2 speed (60)
- ☐ Not able to do (40)

5. Jumping/landing
check one box:
- ☐ Fully competitive (100)
- ☐ Some limitations, guarding (80)
- ☐ Definite limitations, 1/2 speed (60)
- ☐ Not able to do (40)

6. Hard twists/cuts/pivots
check one box:
- ☐ Fully competitive (100)
- ☐ Some limitations, guarding (80)
- ☐ Definite limitations, 1/2 speed (60)
- ☐ Not able to do (40)

FIG 41-8 Activities of Daily Living and Sports Function Scales.

"Climbing" and "squatting" assess the ability of the knee to function under repetitive loading conditions. The factor "walking on uneven ground" is important for assessing joint instability in knees after a ligament injury or reconstruction. The factors "lifting/carrying" and "pounds carried" are helpful in assessing the general ability of the knee to tolerate specific loading conditions. The number of factors assessed was limited for the sake of brevity and simplicity, even though many others could have been included. These factors were not chosen to relate to one diagnosis or condition. Rather, they provide a general intensity rating of the work conditions on the lower extremity.

Each factor is graded according to one of two numeric scales: five factors are assigned a possible total of 10 points, and two factors are assigned a possible total of 5 points. In terms of rating loads placed on the knee joint, the numbers assigned to rate the work intensity of one factor do not necessarily equal the same numbers assigned to rate the work intensity of other factors. The actual loads placed on the knee joint are a function of multiple intrinsic and extrinsic factors that would require actual measurement. The scores for each factor are totaled, providing a numerical score for data reporting purposes. Occupations may then be categorized based on the total number of points as either disabled (0 points), very light (1-20 points), light (21-41 points), moderate (41-60 points), heavy (61-80 points), or very heavy (>80 points). The data may be expressed as means and SD for the population under study or through the distribution of patients in the six occupational categories before and after treatment.

The second major component in the assessment of work activities is the change that occurs in these activities between treatment periods, the most common occurring between preoperative and most recent follow-up evaluations. The format and terminology are the same as those used in the assessment of the change in sports activities between treatment periods, previously described in Figure 41-7. Importantly, the determination is made if changes in work activities are caused by knee-related or non–knee-related reasons and if patient is experiencing symptoms in her or his occupation.

The reliability of the Occupational Rating scale was demonstrated to be adequate in patients with ACL ruptures, chronic patellofemoral disorders, degenerative meniscal tears, and degenerative knee joint arthritis.[6] This scale is useful in the clinic to rate and categorize the occupational status of workers' compensation patients and in the

Check the response that best describes what you actually do at work. Check only one response per column.

Factor 1 Sitting	Factor 2 Standing/ walking	Factor 3 Walking on uneven ground	Factor 4 Squatting	Factor 5 Climbing	Factor 6 Lifting/ carrying	Factor 7 Pounds carried
0 ☐ 8-10 hr/day	*0* ☐ 0 hr/day	*0* ☐ 0 hr/day	*0* ☐ 0 times/day	*0* ☐ 0 times/day	*0* ☐ 0 times/day	*0* ☐ 0-5 lb
1 ☐ 6-7 hr/day	*2* ☐ 1 hr/day	*2* ☐ 1 hr/day	*1* ☐ 1-5 times/day	*2* ☐ 1 flight, 2 times/day	*1* ☐ 1-5 times/day	*1* ☐ 6-10 lb
2 ☐ 4-5 hr/day	*4* ☐ 2-3 hr/day	*4* ☐ 2-3 hr/day	*2* ☐ 6-10 times/day	*4* ☐ 3 flights, 2 times/day	*2* ☐ 6-10 times/day	*2* ☐ 11-20 lb
3 ☐ 2-3 hr/day	*6* ☐ 4-5 hr/day	*6* ☐ 4-5 hr/day	*3* ☐ 11-15 times/day	*6* ☐ 10 flights, ladders	*3* ☐ 11-15 times/day	*3* ☐ 21-25 lb
4 ☐ 1 hr/day	*8* ☐ 6-7 hr/day	*8* ☐ 6-7 hr/day	*4* ☐ 16-20 times/day	*8* ☐ ladders with weight 2-3 days/week	*4* ☐ 16-20 times/day	*4* ☐ 26-30 lb
5 ☐ 0 hr/day	*10* ☐ 8-10 hr/day	*10* ☐ 8-10 hr/day	*5* ☐ more than 20 times/day	*10* ☐ ladders daily with weight	*5* ☐ more than 20 times/day	*5* ☐ more than 30 lb

FIG 41-9 Occupational Rating Scale.

development of disability ratings. In addition, the Occupational Rating Scale has been used to assess the effect of insurance plans (private vs. workers' compensation) on the outcome of ACL reconstruction.[72,101]

Patient History

For research purposes, a specific data collection format was developed to ensure that accurate and consistent information is obtained for the patient history (Fig. 41-10). For instance, the coding of major reinjuries and prior surgical procedures to the involved knee is necessary to determine whether or not the patient meets the established criteria for a particular study. For example, an acute prospective study would include only patients who have sustained one major injury to the knee and no prior surgical intervention. In such an investigation, patients who had additional injuries or previous surgical procedures to the involved knee would be excluded. In addition, the condition of the noninvolved knee must be taken into consideration. Patients who have problems with the noninvolved knee are sorted into a separate subgroup to determine whether this factor affects the treatment outcome.

Only information related to orthopaedic conditions is included in the history portion of the CKRS. Patients are screened for additional medical problems, but these findings are usually not included unless they alter the treatment outcome. General demographic data are documented for identification and description purposes. The history of prior knee surgeries is coded by major operative categories to provide the basic information necessary for reporting prior treatment.

Knee Examination

The knee examination portion of the physical evaluation is designed to document all parameters of the knee condition (Fig. 41-11). The contents are divided into five sections. The general examination section includes joint effusion and range of motion. Joint effusion is rated as normal, mild (<25 mL of fluid), moderate (26-60 mL of fluid), or severe (>60 mL of fluid). Knee flexion and extension are measured with a goniometer; the heel-height method is also used to determine differences in extension between knees.

The tibiofemoral assessment includes joint line pain, crepitus, and compression pain. Pain is rated as none, mild, moderate, or severe. Crepitus is graded as none, mild, moderate, or severe. Moderate crepitus indicates that a cartilage abnormality (definite fibrillation) exists within 25 to 50 degrees of knee motion. Severe crepitus indicates that the abnormality is present in an arc greater than 50 degrees of knee motion. The patellofemoral exam includes crepitus, compression pain, lateral subluxation at 20 degrees, medial subluxation at 20 degrees, soft tissue pain, and soft tissue swelling. Crepitus and pain are rated as described for the tibiofemoral assessment. Lateral patellar subluxation at 20 degrees of flexion is rated as normal if the patella can be moved within 25% of its width; mild, 26% to 50%; moderate, 51% to 75%; and severe, greater than 75%. Medial patellar subluxation at 20 degrees of knee flexion is rated as normal if the patella can be moved 15 mm or less; mild, 11 to 15 mm; moderate, 6 to 10 mm; and severe, less than 6 mm.

The radiographic section assesses the three knee compartments as normal (no joint space narrowing), mild, moderate (narrowing <50% of the total joint space), or severe (narrowing >50% of the total joint space) using standing 45-degree posteroanterior and 30-degree axial patellofemoral radiographs. Studies regarding lower limb malalignment also require standing radiographs of the hip-knee-ankle to document the weight-bearing line and mechanical axis.[22]

The ligament subluxation section documents the results of the pivot shift test (scale, 0 to 3) and other knee ligament subluxation tests (see Fig. 41-11). The pivot shift test is recorded on a scale of 0 to 3, with a grade of 0 indicating no pivot shift; grade 1, a slip or glide; grade 2, a jerk with gross subluxation or clunk; and grade 3, gross subluxation with impingement of the posterior aspect of the lateral side of the tibial plateau against the femoral condyle. The posterior drawer test (palpation of the medial tibiofemoral step-off) is done at 90

Last Name _____ First Name _____ M.I. _____
Patient I.D.# _____ Street _____
City _____ State _____ Zip _____ Soc. Sec. #_____/____/_____
Date of birth _____/____/_____ Age _____ Sex (M/F) _____
Knee involved (L/R) _____ Date 1st injury/problem _____
Date 1st visit _____
1st injury occurred during:_____ (1 - sports, 2 - ADL, 3 - work, 4 - MVA, 5 - other, 6 - no injury)
Other full giving-way reinjuries (Y/N)? _____ Bilateral ACL? (Y/N) _____ Acute/chronic _____

Surgical History
Number of procedures, involved knee _____ Noninvolved knee _____

	Involved (Y/N)	Noninvolved (Y/N)
Arthroscopy, debridement	_____	_____
ACL reconstruction	_____	_____
PCL reconstruction	_____	_____
LCL, posterolateral reconstruction	_____	_____
MCL reconstruction	_____	_____
Meniscectomy (partial or total)	_____	_____
Meniscus repair	_____	_____
Meniscus allograft	_____	_____
High tibial osteotomy	_____	_____
Osteochondral autograft procedure	_____	_____
Patellofemoral (proximal-distal realignment, PF ligament reconstruction)	_____	_____

Surgery #1, involved
Date _____ M.D. _____
Procedures _____
Surgery #2, involved
Date _____ M.D. _____
Procedures _____
Surgery #3, involved
Date _____ M.D. _____
Procedures _____
Surgery #4, involved
Date _____ M.D. _____
Procedures _____
Surgery #5, involved
Date _____ M.D. _____
Procedures _____

Surgery #1, noninvolved
Date _____ M.D. _____
Procedures _____
Surgery #2, noninvolved
Date _____ M.D. _____
Procedures _____

FIG 41-10 Patient history. *ACL*, Anterior cruciate ligament; *LCL*, lateral collateral ligament; *MCL*, medial collateral ligament; *MVA*, motor vehicle accident; *PCL*, posterior cruciate ligament.

degrees of flexion, and the difference in posterior tibial translation between the reconstructed knee and the contralateral knee is recorded. The clinical tests for lateral and medial joint opening are based on the varus and valgus stress tests performed at 0 and 30 degrees of flexion. The examiner estimates the amount (in millimeters) of joint opening from the initial closed contact position of each tibiofemoral compartment to the maximal opened position, comparing the injured with the opposite normal knee. The tibiofemoral rotation test is used to detect posterior tibial subluxations in a qualitative manner at 30 and 90 degrees of knee flexion.[74]

Objective Testing

Objective testing of the lower extremity is performed to determine ligamentous, muscular, and limb symmetry deficits (Fig. 41-12). The KT-2000 knee arthrometer test is performed at 20 degrees of flexion at 134 N for ACL investigations. Total AP displacement is measured because this is more accurate than attempting to set a neutral point between anterior and posterior tibial displacement. The difference in the measurements between the reconstructed and contralateral knee is recorded. Any knee that has an ACL or PCL rupture on the

Rate each as either 4 = normal, 3 = mild, 2 = moderate, 1 = severe

	Involved	Noninvolved
I. General		
Effusion	_____	_____
Total flexion	_____	_____
Lack of extension	_____	_____
II. Tibiofemoral		
Joint line pain (medial)	_____	_____
Joint line pain (lateral)	_____	_____
Crepitus	_____	_____
Compression pain (medial)	_____	_____
Compression pain (lateral)	_____	_____
III. Patellofemoral		
Crepitus	_____	_____
Compression pain	_____	_____
Lateral subluxation 20°	_____	_____
Medial subluxation 20°	_____	_____
Soft tissue pain	_____	_____
Location soft tissue pain	_____	_____
Soft tissue swelling	_____	_____
Location soft tissue swelling	_____	_____
IV. X-ray		
Patellofemoral	_____	_____
Medial tibiofemoral	_____	_____
Lateral tibiofemoral	_____	_____

	Difference (Involved-Noninvolved)	
V. Ligament Subluxation		
Pivot shift (grade, 0 to 3)	_____ (inv)	_____ (noninv)
Anterior translation	_____ mm	
Lateral joint opening 5°	_____ mm	
Lateral joint opening 25°	_____ mm	
Medial joint opening 5°	_____ mm	
Medial joint opening 25°	_____ mm	
Posterior translation 90°	_____ mm	
External tibial rotation 30°	_____ degrees	
External tibial rotation 90°	_____ degrees	

FIG 41-11 Knee examination.

contralateral knee is excluded from KT-2000 testing. The manual maximum arthrometer examination is not used because the magnitude of the force applied is highly variable and not defined or measured. This problem results in inconsistent results among examiners and studies.

Posterior stress radiographs are done with an 89-N force applied to the proximal tibia in knees with PCL ruptures.[33] A lateral radiograph is taken of each knee at 90 degrees of flexion. The limb is placed in neutral rotation with the tibia unconstrained and the quadriceps relaxed. The difference in posterior tibial displacement between the reconstructed knee and the contralateral knee is recorded. More than 8 mm of increase in posterior tibial translation on stress testing indicates a complete PCL rupture. The knee arthrometer is the device most frequently used by investigators to measure posterior tibial translation after PCL reconstruction. However, this device underestimates the true amount of residual posterior translation in PCL-injured and reconstructed knees and, in our opinion, is unreliable for determining the results of PCL surgical procedures at high flexion angles.[33,54,94] Lateral stress radiographs are performed in knees with deficiency of the posterolateral structures. Both knees are radiographed at 20 degrees of flexion, neutral tibial rotation, and 67 N of varus force, and a comparison is made of the millimeters of lateral tibiofemoral compartment opening.

Muscular weaknesses or imbalances are assessed with isokinetic testing at either slow (60 degrees/sec) or fast (300 degrees/sec) speeds or in an isometric mode for patients with patellofemoral pain or symptomatic crepitus. Single-legged function hop tests are performed as previously described.[4,68] Patients perform any two of the hop tests shown in Figure 41-12 to determine functional limitations after ACL reconstruction and to continue the functional progression for return to sports activities.

KT-2000 (Difference total anterior-posterior displacement between involved and noninvolved knee, mm)

Anterior Cruciate Ligament
134 N, 20° _____

Posterior Cruciate Ligament
89 N, 70° _____

Stress Radiographs (Difference between involved and noninvolved knee, mm)

Posterior Cruciate Ligament
Posterior tibial translation, 90° _____

Fibular Collateral Ligament; Posterolateral Structures
Lateral tibiofemoral compartment opening, 20° _____

Isokinetic Testing (Difference between involved and noninvolved knee, %)

60°/second
Quadriceps _____
Hamstrings _____

300° to 450°/second
Quadriceps _____
Hamstrings _____

Isometric
Quadriceps _____
Hamstrings _____

Single-Leg Hop Function Testing (select any two tests)

	Limb symmetry index (%)
Single hop for distance	_____
Triple hop for distance	_____
Triple cross-over hop for distance	_____
Single-leg timed hop	_____

Average limb symmetry from any two tests _____

FIG 41-12 Objective testing.

Operative Procedures and Articular Cartilage Surfaces

Documentation of the operative procedures performed and the condition of all ligamentous structures, menisci, and articular cartilage in the patellofemoral and tibiofemoral compartments is essential (Fig. 41-13). The operative procedures and findings may be used as final exclusionary or inclusionary criteria as determined by the study protocol.

A classification system for the rating of articular cartilage has been described previously.[78] This system separates the description of the surface appearance of the cartilage from the extent or depth of the defect. Three surface grades are rated: (1) closed chondromalacia (surface intact), (2) open lesions of fibrillation and fragmentation (surface disrupted), and (3) bone exposed. Subtypes (a) and (b) then make a distinction regarding the depth of the lesion as described. The location and millimeters of surface involvement are recorded. Chapter 44 further details this and other articular cartilage rating systems. In addition, treatment of articular surfaces such as debridement, drilling/abrasion arthroplasty, osteochondral autograft transfer, or autologous chondrocyte implantation is also documented.

Postoperative Complications

Complications from surgical procedures or rehabilitation programs are documented on a prospective basis (Fig. 41-14). In addition, senior researchers or surgeons who did not participate in the care of the patient conduct a chart review to ensure complete and accurate reporting of complications and results of treatment.

Ligament Findings and Procedures

Anterior Cruciate Ligament _____
1 - normal, 2 - partial tear, no treatment, 3 - autograft (bone-patellar tendon-bone), 4 - autograft (quadriceps tendon-patellar bone), 5 - autograft (semitendinosus-gracilis tendons), 6 - allograft (bone-patellar tendon-bone), 7 - allograft (Achilles tendon), 8 - allograft (fascia lata), 9 - reattachment, advancement tibial fixation, 10 - thermal shrinkage

Lateral Iliotibial Band Extra articular Procedure _____
1 - no, 2 - yes

Posterior Cruciate Ligament _____
1 - normal, 2 - partial tear, no treatment, 3 - avulsion, repaired, 4 - primary repair, 5 - autograft (bone-patellar tendon-bone), 6 - two-strand autograft (quadriceps tendon-patellar bone), 7 - autograft (semitendinosus-gracilis tendons), 8 - allograft (bone-patellar tendon-bone), 9 - allograft (Achilles tendon), 10 - allograft (fascia lata), 11 - reattachment, advancement tibial fixation, 12 - thermal shrinkage, 13 - two-strand allograft (bone-patellar tendon-bone)

Medial Collateral Ligament _____
1 - normal, 2 - partial tear, no treatment, 3 - primary repair, 4 - autograft, 5 - allograft

Posteromedial Plication, Reconstruction _____
1 - no, 2 - yes

Fibular Collateral Ligament _____
1 - normal, 2 - partial tear, no treatment, 3 - direct repair, 4 - autograft (bone-patellar tendon-bone), 5 - autograft (semitendinosus-gracilis tendons), 6 - autograft (iliotibial band), 7 - allograft, 8 - biceps tendon augmentation

Posterolateral Complex _____, _____
1 - normal, 2 - partial tear, no treatment, 3 - direct repair, 4 - proximal advancement, 5 - autograft (bone-patellar tendon-bone), 6 - autograft (semitendinosus-gracilis tendons), 7 - autograft (iliotibial band), 8 - allograft

Meniscal Findings and Procedures

Medial Meniscus _____, _____
1 - normal, 2 - torn, no treatment, 3 - prior partial meniscectomy, 4 - prior total meniscectomy, 5 - prior meniscus repair, 6 - prior meniscus allograft

Treatment Medial Meniscus
1 - none, 2 - partial removal, 3 - total removal, 4 - repair, periphery, 5 - repair, avascular segment, 6 - allograft

Lateral Meniscus _____, _____
1 - normal, 2 - torn, no treatment, 3 - prior partial meniscectomy, 4 - prior total meniscectomy, 5 - prior meniscus repair, 6 - prior meniscus allograft

continues

FIG 41-13 Operative procedures, articular cartilage condition.

Fig 46-13 continued

Treatment Lateral Meniscus _____
1 - none, 2 - partial removal, 3 - total removal, 4 - repair, periphery, 5 - repair, avascular segment, 6 - allograft

Articular Cartilage Findings and Procedures

Patellofemoral
Patella Undersurface_____
1 - normal, 2 - softening (1B), 3 - fissuring <1/2 depth (2A), 4 - fissuring >1/2 depth (2B), 5 - bone (3A, B)

Treatment Patella_____
1 - none, 2 - debridement, 3 - drilling, abrasion, 4 - OAT, 5 - Carticel (ACI)

Femoral Sulcus_____
1 - normal, 2 - softening (1B), 3 - fissuring <1/2 depth (2A), 4 - fissuring >1/2 depth (2B), 5 - bone (3A, B)

Treatment Femoral Sulcus_____
1 - none, 2 - debridement, 3 - drilling, abrasion, 4 - OAT, 5 - Carticel (ACI)

Medial Tibiofemoral
Medial Femoral Condyle _____
1 - normal, 2 - softening (1B), 3 - fissuring <1/2 depth (2A), 4 - fissuring >1/2 depth (2B), 5 - bone (3A, B)

Treatment Medial Femoral Condyle_____
1 - none, 2 - debridement, 3 - drilling, abrasion, 4 - OAT, 5 - Carticel (ACI)

Medial Tibial Plateau _____
1 - normal, 2 - softening (1B), 3 - fissuring <1/2 depth (2A), 4 - fissuring >1/2 depth (2B), 5 - bone (3A, B)

Treatment Medial Tibial Plateau _____
1 - none, 2 - debridement, 3 - drilling, abrasion, 4 - OAT, 5 - Carticel (ACI)

Lateral Tibiofemoral
Lateral Femoral Condyle _____
1 - normal, 2 - softening (1B), 3 - fissuring <1/2 depth (2A), 4 - fissuring >1/2 depth (2B), 5 - bone (3A, B)

Treatment Lateral Femoral Condyle_____
1 - none, 2 - debridement, 3 - drilling, abrasion, 4 - OAT, 5 - Carticel (ACI)

Lateral Tibial Plateau _____
1 - normal, 2 - softening (1B), 3 - fissuring <1/2 depth (2A), 4 - fissuring >1/2 depth (2B), 5 - bone (3A, B)

continues

FIG 41-13, cont'd *Continued*

Fig 46-13 continued

Treatment Lateral Tibial Plateau _____
1 - none, 2 - debridement, 3 - drilling, abrasion, 4 - OAT, 5 - Carticel (ACI)

Other Operative Procedures

Patellofemoral _____
1 - proximal realignment, 2 - distal realignment, 3 - proximal-distal realignment, 4 - Maquet, 5 - patellectomy

High Tibial Osteotomy _____
1 - yes

Other _____
1 - yes, describe

FIG 41-13, cont'd

1. Infection, positive culture _____
1 - yes, resolved; 2 - yes, required additional hospitalization, resolved; 3 - yes, not resolved

2. Range of motion _____
1 - manipulation; 2 - epidural, inpatient physical therapy; 3 - surgical release

3. Pain dysfunction syndrome
(reflex sympathetic dystrophy, saphenous neuritis, etc.)_____
1 - yes, resolved; 2 - yes, not resolved

4. Patella infera _____
1 - yes, asymptomatic; 2 - yes, symptomatic

5. Reinjury _____
1 - yes, graft failed; 2 - yes, graft functional

6. Graft failure _____
1 - yes

7. Additional operation(s) required _____
1 - yes, describe _____

8. Other complication
1 - yes, describe _____

FIG 41-14 Complications.

Overall Rating Assessment

An overall rating assessment is performed that is based on the ratings from 20 factors, including symptoms, functional limitations, knee examination, stability, radiographs, and function testing (Appendix B). In patients in whom the ACL reconstruction is done for an acute injury (within 12 weeks of the original injury), the analysis of the overall rating is performed in a different manner from that for patients with chronic injuries, who often have compounding problems such as articular cartilage damage, prior meniscal loss, loss of secondary restraints, and associated ligamentous instabilities.

Patients with acute knee injuries are expected to have more favorable results, especially in the symptom and functional limitations analyses, and therefore a categorical analysis is used (along with a point scale) to determine the outcome of these patients. With this method, patients receive an overall rating grade of "excellent," "good," "fair," or "poor" from the 20 factors shown in Appendix B. To receive a rating of "excellent," all but one score must be in that category, with the remaining score being in the "good" category. A "good" result is given when all scores are in the "excellent," and "good" categories and none are in the "fair" or "poor" categories. A "fair" result is assigned when any 1 score is "fair," and a "poor" result, when any 1 score is "poor." In short, a knee can only be as good as the worst rating in any 1 of the 20 categories. This rationale was developed to solve the problem incurred with other systems that only use point scores to determine results and then arbitrarily assign categories for a certain number of point ("excellent" for 91-100 points, "good" for 81-90 points, and so on). In these systems, an ACL reconstruction that failed according to knee arthrometer testing could still receive an "excellent" or "good" rating if all other parameters score high numbers. Using this rationale, the CKRS is one of the strictest in terms of reporting results for acute knee injury studies.

The overall rating of knees with chronic injuries is not determined in the same categorical manner as that used for acute injuries because many of these individuals have preexisting problems that cannot be corrected with ACL reconstruction. In these instances, patients may be negatively biased into the "fair" or "poor" categories. For instance, a knee with preoperative moderate joint space narrowing on radiographs would not be expected to show improvement in this factor after an ACL reconstruction. This knee would, therefore, not have a chance of improving from the preoperative overall rating of "fair" to one of "good" or "excellent." Because of these problems, the results for chronic knees are determined in the following manner. First, special emphasis is placed on the results of the individual components that make up the overall rating categories such as symptoms, knee range of motion, arthrometer testing, and functional testing. These data are presented in separate tables and graphs to allow comparisons of these important parameters among investigations. Second, the overall point total is calculated before and after treatment, including the change in points between evaluations. A distribution of the change in points is provided to allow assessment of slight change (<10 points), moderate change (between 10 and 20 points), and significant change (>20 points) between evaluations.

RELIABILITY, VALIDITY, AND RESPONSIVENESS TESTING: OUR STUDY

Reliability testing of the scales and overall rating score of the CKRS was conducted on two groups of individuals.[6] The first group consisted of 50 patients who had a variety of chronic knee injuries and disorders, including meniscal tears, knee ligament tears, patellofemoral complaints, and degenerative joint disease. The second group consisted of 50 volunteers who had no current knee pathology and no history of prior knee operations. The questionnaires were given to these 100 individuals by an interviewer who was available to explain the instructions if required, but a formal interview was not accomplished. The questionnaires were completed an average of 7 days (range, 4-13 days) after the baseline evaluation.

Validity (construct, content, and item discriminant) and responsiveness testing of the CKRS were conducted on a group of 250 patients who were prospectively followed after ACL bone-patellar tendon-bone autogenous reconstruction a mean of 27 months (range, 23-74 months) postoperatively. The patients completed the questionnaires preoperatively and at the most recent follow-up evaluation.

All volunteers and patients completed 13 scales: (1) the four Symptom Rating Scales for pain, swelling, partial giving way, and full giving way; (2) the Patient Perception Scale; (3) the Activities of Daily Living Scales for walking, stair climbing, and squatting; (4) the Sports Activities Function Scales for running, jumping, and hard twisting/cutting/pivoting; (5) the Sports Activity Scale; and (6) the Occupational Rating Scale. The overall rating score was calculated before surgery and at the most recent follow-up evaluation for the ACL-reconstructed patients.

The 13 scales all demonstrated adequate test-retest reliability (Table 41-5, R >0.70). In the normal population, the ICCs ranged from 0.71 (jumping) to 1.0 (walking, full giving way). In the patient population, the ICCs ranged from 0.75 (squatting/kneeling) to 0.98 (Sports Activity Scale).

In the analysis of content validity, the CKRS overall rating score had no floor or ceiling effects preoperatively in the 250 patients (Table 41-6). At follow up, no floor scores were found, and limited ceiling effects were calculated (22 patients [9%]). Good construct validity was demonstrated because eight of the nine clinical hypotheses were confirmed using the overall rating score (Table 41-7). Item-discriminant validity was found for 59 of the 63 (94%) comparisons between the CKRS categories and the other variables shown in Table 41-8).

The CKRS was highly responsive to detecting changes from the preoperative to the follow-up evaluations. Seven of the eight

CRITICAL POINTS Reliability, Validity, and Responsiveness Testing: Our Study

- Reliability testing of the scales and overall rating score:
  - 50 patients with chronic knee injuries and disorders, including meniscal tears, knee ligament tears, patellofemoral complaints, and degenerative joint disease.
  - 50 volunteers with no current knee pathology and no history of prior knee operations.
- The questionnaires were completed an average of 7 days (range, 4-13 days) after the baseline evaluation.
- Validity (construct, content, and item-discriminant) and responsiveness testing in 250 patients prospectively followed after reconstruction a mean of 27 mo (range, 23-74 mo) postoperatively.
- 13 scales demonstrated adequate test-retest reliability.
- Content validity: overall rating score had no floor or ceiling effects preoperatively. At follow up, no floor scores were found, and limited ceiling effects were calculated in 9%.
- Construct validity: 8/9 clinical hypotheses were confirmed.
- Item-discriminant validity: 94% comparisons.
- Highly responsive in detecting change between evaluations.

categories showed large effects ranging from 1.07 to 2.48, and the remaining category (ADL average score) showed a moderate effect of 0.72 (Table 41-9).

ASSESSMENT OF THE CKRS BY INDEPENDENT INSTITUTIONS

Marx and colleagues[58] conducted reliability, validity, and responsiveness testing of the CKRS Symptom Rating Scale and the Sports and Daily Activity functional scales in 42 patients with a wide variety of knee disorders. These investigators found that these components had adequate reliability (ICC, >0.80), face and content validity, and

TABLE 41-5 Reliability of Cincinnati Knee Rating System Variables Using Intraclass Correlation Coefficients

Variable	Uninjured Subjects ($n = 50$)	Patients ($n = 50$)
Pain	0.83	0.84
Swelling	0.83	0.83
Partial giving way	0.88	0.87
Full giving way	1	0.87
Walking	1	0.88
Stair climbing	0.78	0.68
Squatting/kneeling	0.87	0.75
Running	0.88	0.86
Jumping	0.71	0.89
Twisting/turning	0.88	0.85
Patient perception of knee condition	0.91	0.88
Sports Activity Scale	0.98	0.98
Occupational Rating Scale	0.87	0.97

Intraclass correlation coefficient >0.70 required for adequate reliability.
From Barber-Westin SD, Noyes FR, McCloskey JW. Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati Knee Rating System in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. *Am J Sports Med.* 1999;27:402-416.

TABLE 41-7 Construct Validity: Clinical Hypotheses and Cincinnati Knee Rating System Overall Scores

Clinical Hypotheses	Hypotheses confirmed? (P value)	n	Mean Overall Score
Chronic injury	Yes (.001)		
Yes		170	87.17
No		80	93.99
Deterioration articular cartilage	Yes (.001)		
Yes		119	85.66
No		131	92.7
Prior failed ACL reconstruction	Yes (.001)		
Yes		33	82.09
No		217	90.46
Fair/poor patient perception	Yes (.001)		
Yes		25	68.08
No		225	91.72
Concurrent major operative procedure	No		
Yes		131	89.82
No		119	88.84
Surgical complications	Yes (.01)		
Yes		11	81.55
No		239	89.71
Symptoms with/no sports	Yes (.001)		
Yes		31	74.16
No		219	91.5
Symptoms with/no work	Yes (.001)		
Yes		16	69.5
No		234	90.71
Injured at work	Yes (.001)		
Yes		14	77.21
No		236	90.07

From Barber-Westin SD, Noyes FR, McCloskey JW. Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati Knee Rating System in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. *Am J Sports Med.* 1999;27:402-416.

TABLE 41-6 Content Validity of Cincinnati Knee Rating System Variables

Variable	Range of Points	Floor Score* Preoperative, n (%)	Floor Score* Postoperative, n (%)	Ceiling Score* Preoperative, n (%)	Ceiling Score* Postoperative, n (%)
Pain	0-10	6 (4)	1 (0.4)	5 (3)	100 (40)
Swelling	0-10	2 (1)	0	15 (9)	131 (52)
Partial giving way	0-10	0	0	9 (5)	185 (74)
Full giving way	0-10	0	0	18 (7)	190 (76)
Symptoms average	0-10	0	0	2 (1)	96 (38)
Patient perception	1-10	6 (4)	0	17 (11)	32 (13)
ADL function average	0-40	13 (5)	2 (1)	24 (10)	83 (33)
Sports function average	40-100	93 (37)	24 (10)	2 (1)	97 (39)
Overall rating score	0-100	0	0	0	22 (9)

*Floor or ceiling effects are present when more than 33% of the population marks best or worst score.
From Barber-Westin SD, Noyes FR, McCloskey JW. Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati Knee Rating System in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. *Am J Sports Med.* 1999;27:402-416.
ADL, Activities of daily living.

TABLE 41-8 Item-Discriminant Validity: Correlations Between Cincinnati Knee Rating System Categories and Dissimilar Items

CKRS Categories	Quadriceps Muscle Strength*	Hamstrings Muscle Strength	Age	Anterior-Posterior Displacement†	Patellofemoral Crepitus	Flexion	Extension
Pain	–0.16	–0.24	–0.21	–0.10	0.12	0.19	0.19
Swelling	–0.04	–0.13	–0.26	–0.12	0.05	0.24	0.22
Partial giving way	–0.13	–0.19	–0.12	–0.21	0.04	0.28	0.20
Full giving way	–0.08	–0.14	–0.16	–0.12	0.08	0.29	0.21
Symptoms average	–0.13	–0.21	–0.22	–0.14	0.09	0.25	0.22
Patient perception	–0.23	–0.30	–0.12	–0.23	0.07	0.18	0.17
ADL function average	–0.08	–0.16	–0.05	–0.05	0.06	0.29	0.26
Sports function average	–0.21	–0.19	–0.16	–0.21	0.09	0.21	0.16
Overall rating score	–0.17	–0.21	–0.18	–0.38	0.19	0.19	0.19

From Barber-Westin SD, Noyes FR, McCloskey JW. Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati Knee Rating System in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. *Am J Sports Med.* 1999;27:402-416.
Measures that are statistically dissimilar correlate at between –0.28 and +0.28, Pearson correlation test.
*Percent deficit, isometric test.
†KT-1000, 134 N.
ADL, Activities of daily living; *CKRS*, Cincinnati Knee Rating System.

TABLE 41-9 Outcome Scores Before and 2 Years After Anterior Cruciate Ligament Reconstruction and Responsiveness to Change

Variable	Scale	Preoperative Mean (SD)	Follow-up Mean (SD)	Standardized Response Mean	Effect Size*
Pain	0-10	4.3 (2.2)	7.8 (2.3)	1.18	1.40
Swelling	0-10	5.2 (2.5)	8.4 (2.1)	1.07	1.18
Partial giving way	0-10	4.3 (2.4)	9.1 (1.7)	1.70	1.87
Full giving way	0-10	5.6 (2.3)	9.2 (1.6)	1.44	1.49
Symptoms average	0-10	4.7 (1.9)	8.5 (1.8)	1.56	1.74
ADL function average	0-40	26.5 (11.5)	35.3 (6.6)	0.72	0.69
Sports function average	40-100	51.5 (15.4)	83.7 (19.7)	1.37	1.91
Overall rating score	0-100	56.2 (8.9)	89.4 (10.7)	2.48	3.49

From Barber-Westin SD, Noyes FR, McCloskey JW. Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati Knee Rating System in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. *Am J Sports Med.* 1999;27:402-416.
*Using the Cohen standard, small effects, >0.30; moderate effects, >0.50; and large effects, >0.80.
ADL, Activities of daily living; *SD*, standard deviation.

CRITICAL POINTS Assessment of Cincinnati Knee Rating by Independent Institutions

- CRKS has adequate psychometric properties.
- CKRS is highly sensitive to detecting significant changes over time in contrast to the Lysholm, IKDC, and visual analogue scales.
- CKRS score provides more effective estimate of disability than Lysholm.
- CKRS defines most precisely the outcome of anterior cruciate ligament reconstruction in athletically active patients.
- "Modified" CKRS scales should not be used because they do not represent the instruments developed that have undergone rigorous statistical testing and may not provide the data that was intended by the authors of the CKRS.

responsiveness (standardized response mean, 0.8). The authors found that the Lysholm scale, the American Academy of Orthopaedic Surgeons sports knee-rating scale, and the Activities of Daily Living Scale of the Knee Outcome Survey also had adequate reliability, validity, and responsiveness.

Risberg and coworkers[83] assessed the responsiveness of the CKRS Symptom Rating and the Sports and Daily Activity functional scales in 109 patients after ACL reconstruction. The patients completed the questionnaires 3, 6, 12, and 24 months postoperatively. The authors reported that the CKRS was highly sensitive to detecting significant changes over time in contrast to the Lysholm, IKDC, and visual analogue scales, which were not found to be effective in detecting such changes.

Borsa and colleagues[11] evaluated 29 patients with an ACL-deficient knee to determine if performance-based measures or patient-reported measures of function were more effective in estimating disability. Patients completed the CKRS Sports Activity Scale, Symptom Rating

Scale, Patient Perception of the Knee Condition questions, and Sports Activity Function questions. Patient also completed the Lysholm questionnaire and were taken through proprioception, balance, single-leg hop, and isokinetic strength testing. Stepwise regression analysis demonstrated that the CKRS score was the most effective estimate of disability ($R^2 = 0.56$). The addition of the Lysholm score into the model only increased R^2 to .58 and the addition of the hop test index score only slightly improved the adjusted R^2 to 0.60. The authors concluded that the inclusion of the Lysholm score and hop index did not significantly improve the ability to estimate disability induced by ACL deficiency.

Sgaglione and coworkers[91] used four separate knee rating outcome instruments to determine the outcome of 65 patients who underwent ACL reconstruction. The patients were evaluated a mean of 35 months (range, 24-58 months) postoperatively. The CKRS in its entirety was used in this investigation. The results demonstrated that the CKRS individual scaled scores were lower than the Hospital for Special Surgery (HSS) and Lysholm questionnaire scores. The investigators concluded that the CKRS defined most precisely the outcome of ACL reconstruction in athletically active patients. The conclusion was related to the fact that the CKRS incorporated physical findings and avoided combining raw scores into categoric score data (e.g., excellent = 90-100 points). According to the investigators, the Lysholm and HSS scores tended to inflate the outcome of the operation.

Anderson and associates[2] evaluated 70 patients a minimum of 5 years following ACL reconstruction with the HSS, Feagin and Blake, CKRS, Lysholm, and Zarins rating scales. The authors reported that the CKRS had a large number of measurements which reflected high precision in the analysis of subjective symptoms, subjective function, and objective examination. Substantial differences were noted among the results of the six scales evaluated. The conclusion was reached that future rating scales should provide a balance among subjective symptoms, subjective function, and objective findings.

Agel and LaPrade[1] collected "modified" CKRS and IKDC subjective questionnaires from 130 patients with a variety of complex knee disorders both before surgery and at intervals postoperatively (4-8 months, 9-15 months, 16-24 months, >24 months). The overall total scores for both questionnaires were equivalent in the analysis of the entire population at all time intervals. There were no differences between the questionnaires for ceiling and floor effects. There were differences when the individual patient scores were assessed and, across time intervals, between 9% and 21% of the population exhibited individual patient score differences of more than 10 points. The authors concluded that the decision of which questionnaire to use should be based on the specific diagnosis of the population under study, with careful consideration given to the individual questions contained in each system.

Greco and colleagues[29] compared reliability and responsiveness of the IKDC Subjective Knee Form to the "modified" CKRS, the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), and the SF-36 in patients with full-thickness articular cartilage defects treated with a variety of cartilage restoration procedures. The ICCs of three of the instruments were comparable (IKDC, 0.91; CKRS, 0.91; WOMAC, 0.81-0.93), as were the ES and SRM 12 months after surgery. The SF-36 subscales failed to show adequate reliability (across all ten scales) and responsiveness.

MODIFIED CKRS SCALES

We express concern and caution regarding the use of so-called modified CKRS scales. Although some authors who implement these scales in their investigations[1,12,92] provide the actual portion of the CKRS used along with the modifications, the reasons for changing the original scales are usually not provided. The interpretation of data is difficult and cannot be compared with studies that use unedited CKRS scales. In our opinion, modified CKRS scales should not be used because they do not represent the instruments developed, which have undergone rigorous statistical testing, and may not provide the data that was intended by the authors of the CKRS.

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APPENDIX A: SPORTS ACTIVITY AND FUNCTION FORM, SYMPTOM RATING FORM, OCCUPATIONAL RATING FORM

Patient Name	Involved Knee	Date of Visit
	Right____ Left____	mo____ day____ yr____

Sports Activity Scale

Check the box which describes your level of sports activity before your original knee injury. Then, check the box which describes your level of sports activity at this time

BEFORE INJURY		CURRENT LEVEL
☐	100	☐
☐	95	☐
☐	90	☐
☐	85	☐
☐	80	☐
☐	75	☐
☐	65	☐
☐	60	☐
☐	55	☐
☐	40	☐
☐	20	☐
☐	0	☐

Level I (participates 4-7 days/week)
Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
No running, twisting, jumping (cycling, swimming)

Level II (participates 1-3 days/week)
Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
No running, twisting, jumping (cycling, swimming)

Level III (participates 1-3 times/month)
Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
No running, twisting, jumping (cycling, swimming)

Level IV (no sports)
I perform activities of daily living without problems
I have moderate problems with activities of daily living
I have severe problems with activities of daily living; on crutches, full disability

Highest Level (before injury) ___/100
Highest Level (current) ___/100

Change in Sports Activities

Check the box which best describes any change you have had in sports activities since your injury / surgery.
My sports activities have:

Not Changed
If yes, check one box below:
☐ I have no / slight problems (*c*)
☐ I have moderate / significant problems (*d*)

Decreased
If yes, check one box below:
☐ I now have no / slight problems (*e*)
☐ I now have moderate / significant problems (*d*)
☐ For reasons not related to my knee (*g*)

Stopped -- given up all sports
If yes, check one box below:
☐ I have moderate / significant problems when I play sports (*f*)
☐ For reasons not related to my knee (*g*)

Level_____

Function ADL

Check the problems you have during:

1. Walking
check one box:
40 ☐ normal, unlimited
30 ☐ some limitations
20 ☐ only 3-4 blocks possible
0 ☐ less than 1 block; cane, crutch

2. Stairs
check one box:
40 ☐ normal, unlimited
30 ☐ some limitations
20 ☐ only 11-30 steps possible
0 ☐ only 1-10 steps possible

3. Squatting / kneeling
check one box:
40 ☐ normal, unlimited
30 ☐ some limitations
20 ☐ only 6-10 possible
0 ☐ only 0-5 possible

Level_____/ 3 =_____

Function Sports

Check the problems you have during:

1. Straight running
check one box:
100 ☐ fully competitive
80 ☐ some limitations, guarding
60 ☐ definite limitations, half speed
40 ☐ not able to do

2. Jumping / landing on affected leg
check one box:
100 ☐ fully competitive
80 ☐ some limitations, guarding
60 ☐ definite limitations, half speed
40 ☐ not able to do

3. Hard twists / cuts / pivots
check one box:
100 ☐ fully competitive
80 ☐ some limitations, guarding
60 ☐ definite limitations, half speed
40 ☐ not able to do

Level_____/ 3 =_____

Problems with Sports

Describe the problems you would have with your knee after participating for one hour without guarding or limitations in each of the three sports categories below. (___ check here if you are using a brace.)

Strenuous Sport
(soccer, football, basketball, volleyball)
check one box:
100 ☐ no problems
☐ moderate problems during or after game
☐ severe problems; cannot participate

Moderate Sport
(tennis, racquetball)
check one box:
80 ☐ no problems
☐ moderate problems during or after game
☐ severe problems; cannot participate

Light Sport
(golf, bowling, hiking)
check one box:
60 ☐ no problems
50 ☐ moderate problems during or after game
30 ☐ severe problems; cannot participate

Total Points_____

SPORTS ACTIVITY AND FUNCTION FORM — **CINCINNATI KNEE RATING SYSTEM (F07A)**

Patient Name	Date of Visit	Involved knee ☐right ☐left	Date of original injury

DIRECTIONS:

Using the KEY (at right), check the appropriate boxes on the four scales below which indicate the highest level you can reach WITHOUT having symptoms.

KEY:

Scale Description

10 Normal Knee, able to do strenuous work/sports with jumping, hard pivoting
8 Able to do moderate work/sports with running, turning and twisting; symptoms with strenuous work/sports
6 Able to do light work/sports with no running, twisting or jumping; symptoms with moderate work/sports
4 Able to do activities of daily living alone; symptoms with light work/sports
2 Moderate symptoms (frequent, limiting) with activities of daily living
0 Severe symptoms (constant, not relieved) with activities of daily living

1. PAIN _____/ 10

10 — 8 — 6 — 4 — 2 — 0

2. SWELLING (actual fluid in the knee, obvious puffiness) _____/ 10

10 — 8 — 6 — 4 — 2 — 0

3. PARTIAL GIVING-WAY (partial knee collapse, no fall to the ground) _____/ 10

10 — 8 — 6 — 4 — 2 — 0

4. FULL GIVING-WAY (knee collapse occurs with actual falling to the ground) _____/ 10

10 — 8 — 6 — 4 — 2 — 0

Pain	**Location of pain**	☐ inner side	☐ outer side	☐ front / kneecap	☐ back of knee	☐ all over
	Type of pain	☐ sharp	☐ aching	☐ throbbing	☐ burning	
	Pain occurs on	☐ sitting	☐ standing	☐ stairs	☐ squatting	☐ running / jumping
	Pain relieved	☐ by not doing sports	☐ by limiting daily activities		☐ by rest / medications	☐ pain not relieved
	Kneecap grinding? ☐ yes ☐ no		Knee stiffness? ☐ yes ☐ no			
Catching/ Locking	1. Check one box: ☐ yes ☐ no My knee **catches** -- it does not move for a few seconds but works out. 2. Check one box: ☐ yes ☐ no My knee **locks** -- it does not move for five or more minutes at a time.					
Work Activity	My job title is:		Work status: ☐ full time ☐ part time		☐ full duty ☐ light duty ☐ not working	
	When I work, I experience: ☐ no limitations ☐ mild limitations ☐ moderate limitations ☐ severe limitations					
Exercise Program	In my exercise program, I am: ☐ making good progress ☐ slow progress, but better ☐ some problems with exercise ☐ exercise causes pain, problems ☐ doesn't apply					
Follow-up Progress	Following my last visit, I am: ☐ making good progress ☐ slow progress, but better ☐ staying the same ☐ symptoms worse ☐ doesn't apply					
Patient Grade	***Rate the overall condition of your knee at the present time. Circle one number below.*** 1 — 2 poor — 3 — 4 fair — 5 — 6 good — 7 — 8 — 9 — 10 normal **poor** -- I have significant limitations that affect activities of daily living. **fair** -- I have moderate limitations that affect activities of daily living, no sports possible. **good** -- I have some limitations with sports but I can participate; I compensate. **normal/excellent** -- I am able to do whatever I wish (any sport) with no problems.					
Average	Pain (x2)_____ + swelling_____ + partial giving way_____ + full giving way_____				Subtotal = _____ / 5 = _____	

SYMPTOM RATING FORM

CINCINNATI KNEE RATING SYSTEM F02

Patient name	Date of Visit	Involved Knee ☐ right ☐ left	Date of Original Injury
Occupation	Current Work Status ☐ full-time ☐ part-time		

How soon after your injury/surgery/knee problem were you able to return to work activities?

☐ 0-3 months ☐ 4-6 months ☐ 7-12 months ☐ unable to return

Occupational Rating Scale

Check the response which best describes what you actually do at work. Check only one response per column.

Factor 1 sitting	Factor 2 standing/ walking	Factor 3 walking on un-even ground	Factor 4 squatting	Factor 5 climbing	Factor 6 lifting/carrying	Factor 7 pounds carried
0 ☐ 8-10 hrs/day	0 ☐ 0 hr/day	0 ☐ 0 hr/day	0 ☐ 0 times/day	0 ☐ 0 times/day	0 ☐ 0 times/day	0 ☐ 0-5 lbs
1 ☐ 6-7 hrs/day	1 ☐ 1 hr/day	1 ☐ 1 hr/day	1 ☐ 1-5 times/day	1 ☐ 1 flight, 2 times/day	1 ☐ 1-5 times/day	1 ☐ 6-10 lbs
2 ☐ 4-5 hrs/day	4 ☐ 2-3 hrs/day	4 ☐ 2-3 hrs/day	2 ☐ 6-10 times/day	4 ☐ 3 flights, 2 times/day	2 ☐ 6-10 times/day	2 ☐ 11-20 lbs
3 ☐ 2-3 hrs/day	6 ☐ 4-5 hrs/day	6 ☐ 4-5 hrs/day	3 ☐ 11-15 times/day	6 ☐ 10 flights/ ladders	3 ☐ 11-15 times/day	3 ☐ 21-25 lbs
4 ☐ 1 hr/day	8 ☐ 6-7 hrs/day	8 ☐ 6-7 hrs/day	4 ☐ 16-20 times/day	8 ☐ ladders with weight 2-3 days/week	4 ☐ 16-20 times/day	4 ☐ 26-30 lbs
5 ☐ 0 hr/day	10 ☐ 8-10 hrs/day	10 ☐ 8-10 hrs/day	5 ☐ more than 20 times/day	10 ☐ ladders daily with weight	5 ☐ more than 20 times/day	5 ☐ more than 30 lbs

Total Points _____ x 2 = _____

Change in Work Activities

Check the box which best describes any change you have had in work activities since your injury/surgery.

My work activities have:

☐ **Not Changed** *if yes, check one below*	☐ **Decreased** *if yes, check one below*	☐ **Unable to Work** *if yes, check one below*
☐ I have no/slight problems (vc)	☐ I now have no/slight problems (e)	☐ I have moderate/significant problems when I work (f)
☐ I have moderate/significant problems (d)	☐ I now have moderate significant problems (d)	☐ For reasons not related to my knee (g)
	☐ For reasons not related to my knee (g)	

Level _____

Symptoms

Check all of the problems that occur during the following activities:

	No problems	Pain	Swelling	Partial giving way	Full giving way
Sitting	☐	☐	☐	☐	☐
Standing/walking	☐	☐	☐	☐	☐
Walking on uneven ground	☐	☐	☐	☐	☐
Squatting	☐	☐	☐	☐	☐
Climbing	☐	☐	☐	☐	☐
Lifting/carrying	☐	☐	☐	☐	☐

OCCUPATIONAL RATING FORM

CINCINNATI KNEE RATING SYSTEM (F07B)

Name: Date:

		Excellent		Good		Fair		Poor	
		Level	Pts.	Level	Pts.	Level	Pts.	Level	Pts.
Subjective Pts 20	*KEY 10 = Normal knee, able to do strenuous work/sports with jumping, hard pivoting 8 = Able to do moderate work/sports with running, twisting, turning; symptoms with strenuous work/sports 6 = Able to do light work/sports with no running, twisting, jumping; symptoms with moderate work/sports 4 = Able to do activities of daily living alone; symptoms with light work/sports 2 = Moderate symptoms (frequent, limiting) with ADL 0 = Severe symptoms (constant, not relieved) with ADL *highest level possible with no or rare symptoms Pain 10 8 6 4 2 0 Swelling 10 8 6 4 2 0 Partial Giving-Way 10 8 6 4 2 0 Full Giving-Way 10 8 6 4 2 0	10 10 10 10	5 5 5 5	8 8 8 8	3 3 3 3	6-4 6-4 6-4 6-4	1 1 1 1	2-0 2-0 2-0 2-0	0 0 0 0

		Pts 3	Pts 2	Pts 1	Pts 0		Pts.	Pts.	Pts.	Pts.
Activity Level Pts 15	Walking	Normal, unlimited	Some limitations	Only 3-4 blocks possible	Less than 1 block, cane	> Score lowest	3	2	1	0
	Stairs	Normal, unlimited	Some limitations	Only 11-30 steps possible	Only 1-10 steps possible		3	2	1	0
	Squatting	Normal, unlimited	Some limitations	Only 6-10 possible	Only 0-5 possible		3	2	1-0	
	Running	Normal, unlimited	Some limitations	Run 1/2 speed	Not able to do		3	2	1-0	
	Jumping	Normal, unlimited	Some limitations	Definite limitations, 1/2 speed	Not able to do		3	2	1-0	
	Twists/Cuts	Normal, unlimited	Some limitations	Definite limitations, 1/2 speed	Not able to do		3	2	1-0	

		NL	Pts	MILD	Pts	MOD	Pts	SEV	Pts	Pts.	Pts.	Pts.	Pts.
Examination Pts 25	Effusion	NL	5	≤25 cc	4	26-60 cc	2	>60 cc	0	5	4	2	0
	Lack of Flexion	0-5°	5	6-15°	4	16-30°	2	>30°	0	5	4	2	0
	Lack of Extension	0-3°	5	4-5°	4	6-10°	2	>10°	0	5	4	2	0
	Tibiofemoral Crepitus	NL	5			Mod*	2	Sev*	0	5		2	0
	Patellofemoral Crepitus	NL	5			Mod*	2	Sev*	0	5	2		0
	(*indicates definite fibrillation, cartilage abnormally; moderate 25-50°, severe > 50°)												

			Pts		Pts		Pts		Pts				
Instability (Specify Ligament) Pts 20	Anterior	<3 mm	10	3-5 mm	7	6 mm	4	>6 mm	0	10	7	4	0
	Pivot Shift	negative	10	slip	7	definite	4	severe	0	10	7	4	0

		4	3	2 narrowing <1/2 joint	0 narrowing > 1/2 joint				
Radiographs Pts 10	Medial Tibiofemoral	NL	Mild	Mod	Sev		12	11-9	8-6	5-0
	Lateral Tibiofemoral	NL	Mild	Mod	Sev	(1 "severe" = poor)	10 pts	7 pts	4 pts	0 pts
	Patellofemoral	NL	Mild	Mod	Sev					

		Level	Pts.	Level	Pts.	Level	Pts.	Level	Pts.
Function Testing Pts 10	Use any two One-Legged Hop, 1 hop for distance ____ % limb symmetry One-Legged Hop, 3 hops for distance ____ % limb symmetry One-Legged Hop, timed hop over 6 meters ____ % limb symmetry One-Legged Hop, cross-over for distance ____ % limb symmetry ____ average % limb symmetry	100-85	10	84-75	7	74-65	4	<65	0

FINAL RATING

Acute Injury Studies:

Excellent: all in "excellent" (may have one in "good")
Good: all in "excellent" and "good"
Fair: any one in "fair"
Poor: any one in "poor"

Chronic Injury Studies:

Sum point total preoperatively and at follow-up; report difference. No point totals or differences equal "excellent, good, fair, or poor" for chronically-deficient populations.

CINCINNATI KNEE RATING SYSTEM **FINAL RATING FORM**

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International Knee Documentation Committee Rating System

Sue D. Barber-Westin, Frank R. Noyes

OUTLINE

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INTRODUCTION

To provide a comprehensive analysis of the knee condition and the effect of a treatment protocol on a knee injury or disorder, authors[2,4,29,30,37] have suggested that rating systems measure a variety of symptoms, sports and daily activity functions, and objective findings. To our knowledge, only three knee-specific rating systems are available that measure all of these factors and have established psychometric properties of reliability, validity and responsiveness: the Cincinnati Knee Rating System (CKRS),[4,19] the International Knee Documentation Committee (IKDC) Knee Evaluation system,[14,29] and the new Knee Society Scoring System.[18,27] The CKRS (see Chapter 41) and IKDC Knee Evaluation measure pain, swelling, giving way, functions of sports and daily activities, sports activity levels, patient perception of the knee condition, range of knee motion, joint effusion, tibiofemoral and patellofemoral crepitus, knee ligament subluxations, compartment narrowing on radiographs, and lower limb symmetry during single leg hop tests. The new Knee Society Scoring system (see Chapter 45) is designed specifically for arthroplasty research investigations. It includes an objective knee score completed by the physician (measuring alignment, instability, and joint motion) and multiple scales completed by the patient that assess symptoms, satisfaction, and daily and athletic functions and limitations.

The IKDC is one of the most commonly used instruments to determine the results of anterior cruciate ligament (ACL) reconstruction and other knee operations and injuries. This chapter describes the history, development, initial forms, and revisions of the IKDC system. Investigations which provided reliability, validity, and responsiveness data are summarized. The major sections of the current knee forms are described.

HISTORY OF THE IKDC

As early as 1983, some authors[7] expressed concern that comparing results of different methods of treatment of ACL ruptures was not possible without a standardized method of evaluation. At that time, a multitude of scoring systems had been proposed to quantify symptoms and functional limitations caused by ACL injuries and to evaluate the results of operative and conservative treatment. None of these systems were accepted internationally. One major problem was that the majority assigned numerical values to factors that were not quantifiable, weighted certain factors over others, and then added these scores together to provide either an excellent, good, fair, or poor overall outcome grade. Because the content and relative weight given to each component varied greatly from one system to another, individuals rated as excellent or good on one instrument could be rated as fair or poor on another.[30]

To develop a worldwide, standardized knee ligament rating system, a group of knee surgeons from Europe (European Society of Sports Traumatology, Knee Surgery and Arthroscopy [ESKA]) and America (American Orthopaedic Society for Sports Medicine [AOSSM]) founded the IKDC in 1987 (Table 42-1). Common terminology to describe knee motion and function were agreed upon by the committee members.[22] A set of measurements to determine knee motion limits was validated in formal investigations.[6,21,22] Methods to quantify knee function, activity levels, and symptoms were evaluated. A single-page Knee Ligament Standard Evaluation Form was then created (Fig. 42-1).[10,14] The goals of the evaluation form were to measure the essential criteria judged at that time to be necessary to determine the results of treatment and to be simple enough to complete so that research personnel were not required. The committee anticipated that a more

comprehensive system would eventually be developed. The form evaluated sports activity levels and eight domains, including patient's assessment of knee function, symptoms, range of knee motion, ligament evaluation, compartment findings, harvest site pathology, radiographic findings, and single-leg hop function testing.

The 1995 IKDC evaluation form adopted the philosophy of Noyes and coworkers (contained in the CKRS[20,23]) in the assessment of symptoms that were graded at the highest activity level possible without incurring pain, swelling, or giving way. Two questions determined the patient's assessment of knee function and its effect on activity level. A total of 24 factors were rated as normal, nearly normal, abnormal, or severely abnormal as shown in Figure 42-1. Four domains (patient's subjective assessment, symptoms, range of motion, and ligament evaluation) received a final rating, and an overall evaluation result was derived, also using the same philosophy as the CKRS.[4,19] In this manner, the lowest-graded factor determined the overall grade for each individual domain and the final evaluation. For example, a knee that had a positive pivot shift test and 6 mm of increased anteroposterior displacement on KT-2000 testing would receive an abnormal rating, even if all of the other categories were rated as normal or nearly normal. The form also rated sports activities according to a four-level gradient of strenuous, moderate, light, or sedentary.

Irrgang and associates[14] evaluated the construct and concurrent validity of the 1995 IKDC evaluation form in 133 patients who were 1 to 5 years post-ACL reconstruction. These authors reported that the form was useful for reporting outcome after ACL reconstruction. The scoring system clearly distinguished patients whose outcomes were normal or nearly normal from those who were abnormal or severely abnormal, thus preventing a positively biased result when a significant problem in the knee persisted postoperatively. All of the domains contributed to the final rating; however, symptoms and knee ligament evaluation accounted for 62% of the variance in the final rating. The authors did not conduct reliability or responsiveness testing in this investigation.

Paxton and colleagues[24] reported the reliability and internal consistency of the 1995 IKDC evaluation form in 153 patients who had sustained patellar dislocations. The patients completed the form 2 to 5 years after their injury. Adequate reliability and internal consistency (correlation coefficients, 0.82 and 0.84, respectively) were reported. However, high ceiling effects were noted that indicated poor content validity for this group of patients.

CRITICAL POINTS History

- The IKDC is one of the most commonly used instruments to determine the results of anterior cruciate ligament reconstructions and other knee operations and injuries.
- To develop a worldwide, standardized knee ligament rating system, a group of knee surgeons founded the IKDC in 1987.
- Committee members agreed on:
  - Common terminology to describe knee motion and function
  - Set of measurements to determine knee motion limits
  - Methods to quantify knee function, activity levels, and symptoms
- A single-page Knee Ligament Standard Evaluation Form was created.
- The 1995 IKDC Evaluation Form evaluated sports activity levels and eight domains, including patient assessment of knee function, symptoms, range of knee motion, ligament evaluation, compartment findings, harvest site pathology, x-ray findings, and functional testing.
- Symptoms are graded at the highest activity level possible without incurring pain, swelling, or giving way.
- Worst-graded factor determined the overall grade for each individual domain and the final evaluation.
- Scoring system clearly distinguished patients whose outcomes were normal or nearly normal from those who were abnormal or severely abnormal, thus preventing a positively biased result when a significant problem in the knee persisted postoperatively.
- Adequate reliability and internal consistency but high ceiling effects were reported.

TABLE 42-1 Members of the International Knee Documentation Committee, 1987

North American Members	European Members
Allen Anderson	Pierre Chambat
William Clancy	Ejnar Eriksson
Dale Daniel	Jan Gillquist
Ken DeHaven	Fritz Hefti
Peter Fowler	Rik Huiskes
John Feagin	Roland Jakob
Edward Grood	Bernard Moyen
Frank Noyes	Werner Mueller
Glen Terry	Hans-Uli Stäubli
Peter Torzilli	Albert van Kampen
Russell Warren	

COMPONENTS OF THE IKDC KNEE SCORING SYSTEM

The IKDC Knee Scoring System currently includes six forms for research investigations. The IKDC is copyrighted by the AOSSM and

CRITICAL POINTS Components of the International Knee Documentation Committee System

- 2000 IKDC Subjective Knee Evaluation Form
  - Focus of the second IKDC committee: create a general (knee problem) instrument for a variety of knee injuries and disorders.
  - 18 questions in the domains of symptoms, functions of daily and sports activities, current function of the knee, and participation in work and sports.
  - Form has acceptable psychometric properties.
  - Normative data obtained in a random sample of 5246 knees, used to compare a patient's score to those of age- and gender-matched normal subjects.
- 2000 IKDC Knee Examination Form
  - Markedly similar to the original 1995 IKDC Knee Ligament Standard Evaluation form.
  - Should be completed along with Subjective Knee Evaluation Form for research studies.
- IKDC Demographic Form
  - MODEMS-compatible questionnaire.
- IKDC Current Health Assessment Form
  - Composed of 35/36 questions from the Medical Outcomes Study Short Form-36 (SF-36) Health Survey.
- 2000 IKDC Knee History and Surgical Documentation Forms
  - Includes the articular cartilage classification system of the International Cartilage Repair Society.

1995
THE IKDC LIGAMENT STANDARD EVALUATION FORM

Patient Name_____ Date_____/ _____/ _____ Medical Record#_____

Occupation_____ Sport: 1st Choice_____ 2nd Choice_____

Age_____ Sex____ Ht_____ Wt_____ Involved Knee: ❑ Right ❑ Left Contralateral Normal: ❑ Yes ❑ No

Cause of Injury:
❑ ADL ❑ Traffic
❑ Contact ❑ Noncontact

Date of Injury____/ ____/ ____

Date of Index Operation____/ ____/ ____

Procedure_____

Postop Dx_____

ACTIVITY

	Pre-injury	*Pre-Rx*	*Post-Rx*
I. Strenuous Activity jumping, pivoting, hard cutting (football, soccer)			
II. Moderate Activity heavy manual work (skiing, tennis)			
III. Light Activity light manual work (jogging, running)			
IV. Sedentary Activity (housework, ADL)			

Eventual change knee related: ❑ Yes ❑ No

MENISCAL STATUS

	N1	1/3	2/3	Total
Med				
Lat				

Morphotype: Lax_____ Normal____ Tight____
Knee: Varus____ Normal____ Valgus____

PREVIOUS SURGERY

Date: _____ Procedure: _____

Date: _____ Procedure: _____

Date: _____ Procedure: _____

EIGHT GROUPS	*A. Normal*	*B. Nearly Normal*	*C. Abnormal*	*D. Sev. Abnorm.*	*** GROUP GRADE** *A*	*B*	*C*	*D*
FOUR GRADES								
1. Patient Subjective Assessment								
How does your knee function?	❑ 0	❑ 1	❑ 2	❑ 3				
On a scale of 0 to 3, how does your knee affect your activity level?	❑ 0	❑ 1	❑ 2	❑ 3	❑	❑	❑	❑
2. SYMPTOMS (Grade at highest activity level with no significant symptoms. Exclude 0 to slight symptoms.)	**I. Strenuous Activity**	**II. Moderate Activity**	**III. Light Activity**	**IV. Sedentary Activity**				
Pain	❑	❑	❑	❑				
Swelling	❑	❑	❑	❑				
Partial Giving Way	❑	❑	❑	❑				
Full Giving Way	❑	❑	❑	❑	❑	❑	❑	❑
3. Range of Motion Ext/Flex: Index side:____ / ____ / ____		Opposite side:____ / ____ / ____						
△ Lack of extension	❑ <3°	❑ 3 to 5°	❑ 6 to 10°	❑ >10°				
△ Lack of flexion	❑ 0 to 5°	❑ 6 to 15°	❑ 16 to 25°	❑ >25°	❑	❑	❑	❑
4. Ligament Evaluation (manual, instrumented, x-ray)								
△ LACHMAN (25° flex)	❑ -1 to 2mm	❑ 3 to 5mm <-1 to -3 stiff	❑ 6 to 10mm <-3 stiff	❑ >10mm				
Endpoint: firm/soft	❑ firm		❑ soft					
△ Total A.P. Transl. (70° flex)	❑ 0 to 2mm	❑ 3 to 5mm	❑ 6 to 10mm	❑ >10mm				
△ Post. sag (70° flex)	❑ 0 to 2mm	❑ 3 to 5mm	❑ 6 to 10mm	❑ >10mm				
△ Med jt opening (20° flex)(valgus rot)	❑ 0 to 2mm	❑ 3 to 5mm	❑ 6 to 10mm	❑ >10mm				
△ Lat jt opening (20° flex)(varus rot)	❑ 0 to 2mm	❑ 3 to 5mm	❑ 6 to 10mm	❑ >10mm				
△ Pivot shift	❑ equal	❑ + (glide)	❑ ++ (clunk)	❑ +++ (gross)				
△ Reverse pivot shift	❑ equal	❑ glide	❑ marked	❑ gross	❑	❑	❑	❑
5. Compartmental Findings			crepitation with	crepitation with				
△ Crepitus patellofemoral	❑ none	❑ moderate	❑ mild pain	❑ >mild pain				
△ Crepitus medial compartment	❑ none	❑ moderate	❑ mild pain	❑ >mild pain				
△ Crepitus lateral compartment	❑ none	❑ moderate	❑ mild pain	❑ >mild pain				
6. Harvest Sight Pathology	❑ none	❑ mild	❑ moderate	❑ severe				
7. X-Ray Findings								
Med Joint space	❑ none	❑ mild	❑ moderate	❑ severe				
Lat Joint space	❑ none	❑ mild	❑ moderate	❑ severe				
Patellofemoral	❑ none	❑ mild	❑ moderate	❑ severe				
8. Functional Test One leg hop (% of opposite side)	❑ ≥90%	❑ 89% to 76%	❑ 75% to 50%	❑ <50%				
****FINAL EVALUATION**					❑	❑	❑	❑

*Group Grade: The lowest grade within a group determines the group grade. **Final Evaluation: The worst group grade determines the final evaluation for acute and subacute patients. For chronic patients compare preoperative and postoperative evaluations. In a final evaluation, only the first 4 groups are evaluated but all groups must be documented.

△ Difference in involved knee compared to normal or what is assumed to be normal.

IKDC – INTERNATIONAL KNEE DOCUMENTATION COMMITTEE, Members of the Committee:

AOSSM: Anderson, AF, Clancy, WG, Daniel, D, DeHaven, KE, Fowler, PJ, Feagin, J, Grood, ES, Noyes, FR, Terry, GC, Torzilli, P, Warren, RF.

ESSKA: Chambat, P, Eriksson, E, Gillquist, J, Hefti, F, Huiskes, R, Jakob, RP, Moyen, B, Muller, W, Staeubli, H, vanKampen, A.

FIG 42-1 The 1995 International Knee Documentation Committee (IKDC) Knee Ligament Standard Evaluation Form. *ADL,* Activities of daily living; *AP,* anteroposterior. (Courtesy the American Orthopaedic Society for Sports Medicine.)

all of the forms are available on the website of the AOSSM at www.sportsmed.org. The forms have been translated into Portuguese, Chinese, French, German, Greek, Italian, Japanese, Korean, Spanish, and Swedish.

1. 2000 IKDC Subjective Knee Evaluation Form
2. 2000 IKDC Knee Examination Form
3. IKDC Demographic Form (Musculoskeletal Outcomes Data Evaluation and Management System [MODEMS] demographic form)
4. IKDC Current Health Assessment Form (Medical Outcomes Study 36-Item Short Form Health Survey [SF-36] form)
5. 2000 IKDC Knee History Form
6. 2000 IKDC Surgical Documentation Form

An online IKDC Scoring worksheet is also available on the website of the AOSSM. The patient's responses to each question are entered and the worksheet calculates a raw (overall) score and a percentile rank (relative to age- and gender-based norms). Also available on this website is the modified IKDC Subjective Knee Form (Pedi-IKDC), developed for children and adolescents who are between 10 and 18 years of age. This form was found to have adequate validity and internal consistency in a group of 673 patients.[26] However, its reliability and responsiveness have not been published.

2000 International Knee Documentation Committee Subjective Knee Evaluation Form

In 1997, the AOSSM elected to revise the IKDC rating system to broaden its application. The focus of the new committee (Table 42-2) shifted from designing and implementing a disease-specific (knee ligament) instrument to creating and testing a general (generic) knee problem instrument. Thus the 2000 IKDC Subjective Knee Evaluation Form (Fig. 42-2) was devised to rate symptoms and functional limitations for a variety of knee disorders and operations, including ligament and meniscus tears, patellofemoral problems, and articular cartilage lesions. This form comprises 18 questions in the domains of symptoms, functions of daily and sports activities, current function of the knee, and participation in work and sports. An overall score is calculated on the sum of the questions answered (at least 90% of the questions must be answered) divided by the maximum possible score, as shown in Figure 42-2. This form does not analyze findings from a physical examination, radiographs, knee arthrometer tests, function tests, or other objective tests.

TABLE 42-2 Members of the International Knee Documentation Committee, 1997

North American Members	European Members
Allen Anderson	Hans-Uli Staubli
John Bergfeld	Fritz Hefti
Art Boland	Jorgen Hoher
Scott Dye	Roland Jakob
Christopher Harner	Werner Mueller
Mininder Kocher	Phillippe Neyret
John Richmond	
Donald Shelbourne	**Pacific Rim Members**
Glenn Terry	K.M. Chan
	Masahiro Kurosaka
Ex-Officio Members	
John Feagin	
John Fulkerson	

The 2000 IKDC Subjective Knee Evaluation Form underwent reliability and validity testing in 533 patients[12] and responsiveness testing in 207 patients who had a wide variety of knee problems.[13] The overall score (scale, 0-100 points) had acceptable reliability (intraclass correlation coefficient, 0.94); convergent validity with the SF-36 scales of physical function and bodily pain and the physical component summary score (Pearson correlation coefficients, 0.63, 0.64, and 0.66, respectively); and discriminates validity with the SF-36 subscales of mental health, role limitations because of mental problems, general health, and the mental components summary score. Adequate responsiveness, with a large effect size of 1.13 and a large standard response mean of 0.94, was reported. An additional evaluation of responsiveness was determined by ascertaining the change in the overall score (between treatment evaluations) that best distinguished patients who improved from those who did not. A change of 20.5 points had the greatest specificity in making this distinction, whereas a change of less than 12 points was not considered clinically relevant for indicating improvement. Subsequently, Crawford and colleagues[5] reported acceptable reliability, validity, and responsiveness properties of the IKDC Subjective Knee Evaluation Form in patients with meniscus pathology.

Anderson and coworkers[3] reported normative data obtained in a random sample of 5246 knees. The data collected allow comparison of a patient's score to those of age- and gender-matched normal subjects. This investigation also demonstrated adequate construct validity of this form because the overall score was able to identify patients who had knee symptoms and low levels of function.

In 2008, Slobogean and associates[32] reported normative data obtained with the IKDC Subjective Knee Evaluation Form in a small random sample of 125 children aged 12 to 14 years. The mean score for this population (89.4 points) was similar to that of the young adulthood data published by Anderson and coworkers.[3] Subsequently, a modified IKDC Subjective Knee Form (Pedi-IKDC) was developed for children and adolescents between the ages of 10 and 18 years of age. This form was found to have adequate validity and internal consistency in a group of 673 patients.[26] However, its reliability and responsiveness have not been published.

2000 International Knee Documentation Committee Knee Examination Form

Because the 2000 IKDC Subjective Knee Evaluation Form does not incorporate data from the physical examination, radiographs, knee arthrometer tests, function tests, or other objective tests, researchers are encouraged to also complete the 2000 IKDC Knee Examination Form (Fig. 42-3) to provide comprehensive data for publication. The 2000 IKDC Knee Examination Form is markedly similar to the original 1995 IKDC Knee Ligament Standard Evaluation form, except the original categories of patient's subjective assessment and symptoms were eliminated and a rating of knee effusion was added to produce a total of seven domains. In addition, the original Sports Activity Scale was removed and inserted into the 2000 IKDC Subjective Knee Form.

International Knee Documentation Committee Demographic Form

The IKDC Demographic Form (Fig. 42-4) is a MODEMS-compatible questionnaire. The MODEMS project, developed by the American Academy of Orthopaedic Surgeons in 1995, was terminated in 2000. The system was expected to be the premier program for the collection and analysis of functional outcomes information on a variety of musculoskeletal conditions. The program was terminated because of lack of subscribers and interest to maintain financial viability.

Text continued on p. 1199

2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Your Full Name_____

Today's Date: _____ /_____ /_____ (Day / Month / Year)

Date of Injury: _____ /_____ /_____ (Day / Month / Year)

SYMPTOMS*:

*Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?

   4 ❑ Very strenuous activities like jumping or pivoting as in basketball or soccer
   3 ❑ Strenuous activities like heavy physical work, skiing or tennis
   2 ❑ Moderate activities like moderate physical work, running or jogging
   1 ❑ Light activities like walking, housework or yard work
   0 ❑ Unable to perform any of the above activities due to knee

2. During the past 4 weeks, or since your injury, how often have you had pain?

	10	9	8	7	6	5	4	3	2	1	0	
Never	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	Constant

3. If you have pain, how severe is it?

	10	9	8	7	6	5	4	3	2	1	0	
No pain	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	Worst pain imaginable

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

   4 ❑ Not at all
   3 ❑ Mildly
   2 ❑ Moderately
   1 ❑ Very
   0 ❑ Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?

   4 ❑ Very strenuous activities like jumping or pivoting as in basketball or soccer
   3 ❑ Strenuous activities like heavy physical work, skiing or tennis
   2 ❑ Moderate activities like moderate physical work, running or jogging
   1 ❑ Light activities like walking, housework, or yard work
   0 ❑ Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?

   0 ❑ Yes 1 ❑ No

7. What is the highest level of activity you can perform without significant giving way in your knee?

   4 ❑ Very strenuous activities like jumping or pivoting as in basketball or soccer
   3 ❑ Strenuous activities like heavy physical work, skiing or tennis
   2 ❑ Moderate activities like moderate physical work, running or jogging
   1 ❑ Light activities like walking, housework, or yard work
   0 ❑ Unable to perform any of the above activities due to giving way of the knee

FIG 42-2 The 2000 International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form. (Courtesy the American Orthopaedic Society for Sports Medicine.)

SPORTS ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?

- 4 ❑ Very strenuous activities like jumping or pivoting as in basketball or soccer
- 3 ❑ Strenuous activities like heavy physical work, skiing or tennis
- 2 ❑ Moderate activities like moderate physical work, running or jogging
- 1 ❑ Light activities like walking, housework or yard work
- 0 ❑ Unable to perform any of the above activities due to knee pain

9. How does your knee affect your ability to:

		Not difficult at all	Minimally difficult	Moderately difficult	Extremely difficult	Unable to do
a.	Go up stairs	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑
b.	Go down stairs	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑
c.	Kneel on the front of your knee	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑
d.	Squat	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑
e.	Sit with your knee bent	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑
f.	Rise from a chair	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑
g.	Run straight ahead	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑
h.	Jump and land on your involved leg	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑
i.	Stop and start quickly	4 ❑	3 ❑	2 ❑	1 ❑	0 ❑

FUNCTION:

10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

	0	1	2	3	4	5	6	7	8	9	10	
Couldn't perform daily activities	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	No limitation in daily activities

CURRENT FUNCTION OF YOUR KNEE:

	0	1	2	3	4	5	6	7	8	9	10	
Cannot perform daily activities	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	No limitation in daily activities

FIG 42-2, cont'd

Continued

Scoring Instructions for the 2000 IKDC Subjective Knee Evaluation Form

Several methods of scoring the IKDC Subjective Knee Evaluation Form were investigated. The results indicated that summing the scores for each item performed as well as more sophisticated scoring methods.

The responses to each item are scored using an ordinal method such that a score of 0 is given to responses that represent the lowest level of function or highest level of symptoms. For example, item 1, which is related to the highest level of activity without significant pain is scored by assigning a score of 0 to the response "Unable to perform any of the above activities due to knee pain" and a score of 4 to the response "Very strenuous activities like jumping or pivoting as in basketball or soccer". For item 2, which is related to the frequency of pain over the past 4 weeks, the response "Constant" is assigned a score of 0 and "Never" is assigned a score of 10. **Note:** Previous versions of the form had a minimum item score of 1 (for example, ranging from 1 to 11). In the most recent version, all items now have a minimum score of 0 (for example, 0 to 10). To score these prior versions, you would need to transform each item to the scaling for the current version.

The IKDC Subjective Knee Evaluation Form is scored by summing the scores for the individual items and then transforming the score to a scale that ranges from 0 to 100. **Note:** The response to item 10a "Function Prior to Knee Injury" is not included in the overall score. To score the current form of the IKDC, simply add the score for each item (the small number by each item checked) and divide by the maximum possible score, which is 87:

$$\text{IKDC Score} = \left[\frac{\text{Sum of Items}}{\text{Maximum Possible Score}} \right] \times 100$$

Thus, for the current version, if the sum of scores for the 18 items is 45, and the patient responded to all the items, the IKDC Score would be calculated as follows:

$$\text{IKDC Score} = \left[\frac{45}{87} \right] \times 100$$

$$\text{IKDC Score} = 51.7$$

The transformed score is interpreted as a measure of function such that higher scores represent higher levels of function and lower levels of symptoms. A score of 100 is interpreted to mean no limitation with activities of daily living or sports activities and the absence of symptoms.

The IKDC Subjective Knee Form score can be calculated when there are responses to at least 90% of the items (i.e., when responses have been provided for at least 16 items). In the original scoring instructions for the IKDC Subjective Knee Form, missing values are replaced by the average score of the items that have been answered. However, this method could slightly over- or under-estimate the score depending on the maximum value of the missing item(s) (2, 5 or 11 points). Therefore, in the revised scoring procedure for the current version of a form with up to two missing values, the IKDC Subjective Knee Form Score is calculated as (sum of the completed items) / (maximum possible sum of the completed items) * 100. This method of scoring the IKDC Subjective Knee Form is more accurate than the original scoring method.

A scoring spreadsheet is also available at: www.sportsmed.org/research/index.asp This spreadsheet uses the current form scores and the revised scoring method for calculating scores with missing values.

FIG 42-2, cont'd

2000
IKDC KNEE EXAMINATION FORM

Patient Name:_____ **Date of Birth:** _____/_____/_____ (Day / Month / Year)

Gender: F M **Age:** _____ **Date of Examination:** _____/_____/_____ (Day / Month / Year)

Generalized Laxity:	tight	normal	lax	
Alignment:	obvious varus	normal	obvious valgus	
Patella Position:	obvious baja	normal	obvious alta	
Patella Subluxation/Dislocation:	centered	subluxable	subluxed	dislocated
Range of Motion (Ext/Flex):	Index Side:	passive ____/____/____	active ____/____/____	
	Opposite Side:	passive ____/____/____	active ____/____/____	

SEVEN GROUPS	FOUR GRADES A Normal	B Nearly Normal	C Abnormal	D Severly Abnormal	*Group Grade A	B	C	D
1. Effusion	None	Mild	Moderate	Severe				
2. Passive Motion Deficit								
△ Lack of extension	<3°	3 to 5°	6 to 10°	>10°				
△ Lack of flexion	0 to 5°	6 to 15°	16 to 25°	>25°				
3. Ligament Examination (manual, instrumented, x-ray)								
△ Lachman (25° flex) (134N)	-1 to 2 mm	3 to 5 mm(1*) <-1 to -3	6 to 10 mm(2*) <-3 stiff	>10 mm(3*)				
△ Lachman (25° flex) manual max Anterior endpoint:	-1 to 2 mm firm	3 to 5 mm	6 to 10 mm soft	>10 mm				
△ Total AP Translation (25° flex)	0 to 2 mm	3 to 5 mm	6 to 10 mm	>10 mm				
△ Total AP Translation (70° flex)	0 to 2 mm	3 to 5 mm	6 to 10 mm	>10 mm				
△ Posterior Drawer Test (70° flex)	0 to 2 mm	3 to 5 mm	6 to 10 mm	>10 mm				
△ Med Joint Opening (20° flex/valgus rot)	0 to 2 mm	3 to 5 mm	6 to 10 mm	>10 mm				
△ Lat Joint Opening (20° flex/varus rot)	0 to 2 mm	3 to 5 mm	6 to 10 mm	>10 mm				
△ External Rotation Test (30° flex prone)	<5°	6 to 10°	11 to 19°	>20°				
△ External Rotation Test (90° flex prone)	<5°	6 to 10°	11 to 19°	>20°				
△ Pivot Shift	equal	+glide	++(clunk)	+++(gross)				
△ Reverse Pivot Shift	equal	glide	gross	marked				
4. Compartment Findings			crepitation with					
△ Crepitus Ant. Compartment	none	moderate	mild pain	>mild pain				
△ Crepitus Med. Compartment	none	moderate	mild pain	>mild pain				
△ Crepitus Lat. Compartment	none	moderate	mild pain	>mild pain				
5. Harvest Site Pathology	none	mild	moderate	severe				
6. X-ray Findings								
Med. Joint Space	none	mild	moderate	severe				
Lat. Joint Space	none	mild	moderate	severe				
Patellofemoral	none	mild	moderate	severe				
Ant. Joint Space (sagittal)	none	mild	moderate	severe				
Post. Joint Space (sagittal)	none	mild	moderate	severe				
7. Functional Test								
One Leg Hop (% of opposite side)	≥90%	89 to 76%	75 to 50%	<50%				
**** Final Evaluation**								

FIG 42-3 The 2000 International Knee Documentation Committee (IKDC) Knee Examination Form. (Courtesy the American Orthopaedic Society for Sports Medicine.)

IKDC DEMOGRAPHIC FORM

Your Full Name_____

Your Date of Birth_____/_____/_____
Day Month Year

Your Social Security Number ____-____-____ Your Gender: ❑ Male ❑ Female

Occupation_____

Today's Date _____/_____/_____
Day Month Year

The following is a list of common health problems. Please indicate "Yes" or "No" in the first column, and then skip to the next item. If you do have the problem, please indicate in the second column if you receive medications or some other type of treatment for the problem. In the last column, indicate if the problem limits any of your activites.

	Do you have the problem?		Do you receive treatment for it?		Does it limit your activities?	
	Yes	No	Yes	No	Yes	No
Heart disease	❑	❑	❑	❑	❑	❑
High blood pressure	❑	❑	❑	❑	❑	❑
Asthma or pulmonary disease	❑	❑	❑	❑	❑	❑
Diabetes	❑	❑	❑	❑	❑	❑
Ulcer or stomach disease	❑	❑	❑	❑	❑	❑
Bowel disease	❑	❑	❑	❑	❑	❑
Kidney disease	❑	❑	❑	❑	❑	❑
Liver disease	❑	❑	❑	❑	❑	❑
Anemia or other blood disease	❑	❑	❑	❑	❑	❑
Overweight	❑	❑	❑	❑	❑	❑
Cancer	❑	❑	❑	❑	❑	❑
Depression	❑	❑	❑	❑	❑	❑
Osteoarthritis, degenerative arthritis	❑	❑	❑	❑	❑	❑
Rheumatoid arthritis	❑	❑	❑	❑	❑	❑
Back pain	❑	❑	❑	❑	❑	❑
Lyme disease	❑	❑	❑	❑	❑	❑
Other medical problem	❑	❑	❑	❑	❑	❑
Alcoholism	❑	❑	❑	❑	❑	❑

FIG 42-4 The International Knee Documentation Committee (IKDC) Demographic Form. (Courtesy the American Orthopaedic Society for Sports Medicine.)

1. Do you smoke cigarettes?

❑Yes
❑No, I quit in the last six months.
❑No, I quit more than six months ago.
❑No, I have never smoked.

2. Your height ❑centimeters ❑inches

3. Your weight ❑kilograms ❑pounds

4. Your race (indicate all that apply)

❑White ❑Black or African-American ❑Hispanic

❑Asian or Pacific Islander ❑ Native American Indian ❑Other

5. How much school have you completed?

❑Less than high school ❑Graduated from high school ❑Some college

❑Graduated from college ❑Postgraduate school or degree

6. Activity level

❑Are you a high competitive sports person?

❑Are you well-trained and frequently sporting?

❑Sporting sometimes

❑Non-sporting

FIG 42-4, cont'd

International Knee Documentation Committee Current Health Assessment Form

The IKDC Current Health Assessment Form (Fig. 42-5) consists of 35 of the 36 questions from the SF-36. The reliability and validity of the SF-36 as a generic, patient-based health status instrument have been well documented.[17,35,36] Shapiro and colleagues[31] reported that the SF-36 was useful in showing significant changes with treatment for ACL ruptures treated either conservatively or surgically. These authors recommended including this outcome measure along with other disease-specific measures such as the IKDC Knee Examination Form when reporting outcome following ACL reconstruction.

2000 International Knee Documentation Committee Knee History and Surgical Documentation Forms

The 2000 IKDC Knee History Form (Fig. 42-6) allows documentation of injury history, previous knee surgery, and imaging studies. The 2000 IKDC Surgical Documentation Form (Fig. 42-7) includes the articular cartilage classification system of the International Cartilage Repair Society (ICRS),[10] described in further detail in Chapter 44. The size, location, and grade (normal; ICRS grade 1, nearly normal; ICRS grade 2, abnormal; ICRS grade 3, severely abnormal; ICRS grade 4, severely abnormal) of articular cartilage lesions are recorded. This form also documents surgical procedures for articular cartilage lesions and meniscus and ligament damage. However, the form does not record other surgical procedures such as extensor mechanism realignment or osteotomy.

COMPARISON OF IKDC OUTCOMES WITH THOSE OF OTHER KNEE RATING SYSTEMS

Investigators have compared the psychometric properties and outcome scores of the 1995 IKDC evaluation form with other knee rating scales and systems. Risberg and coworkers[25] compared the responsiveness of the IKDC, Cincinnati, and Lysholm knee scores in 109 patients who were evaluated 3, 6, 12, and 24 months after ACL reconstruction. The IKDC domains analyzed were patient's subjective assessment (IKDC-1), symptoms (IKDC-2), range of motion (IKDC-3), ligament examination (IKDC-4), and the final grade (IKDC-F). The IKDC-1 and IKDC-2 results changed significantly only between 12 and 24 months postoperatively. The IKDC-3 and IKDC-F changed only from 3 to 6 months but not thereafter. IKDC-4 did not change significantly postoperatively. In comparison, the Cincinnati score demonstrated significant changes throughout the follow-up period. The Lysholm score increased significantly only between 3 and 6 months postoperatively. High correlations were found between IKDC-1 and IKDC-2 and the

Text continued on p. 1208

IKDC CURRENT HEALTH ASSESSMENT FORM*

Your Full Name_____

Your Date of Birth_____/_____/_____
Day Month Year

Today's Date _____/_____/_____
Day Month Year

1. In general, would you say your health is: ❑Excellent ❑Very Good ❑Good ❑Fair ❑Poor

2. Compared to one year ago, how would you rate your health in general now?

❑Much better now than 1 year ago ❑Somewhat better now than 1 year ago ❑About the same as 1 year ago

❑Somewhat worse now than 1 year ago ❑Much worse now than 1 year ago

3. The following items are about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much?

		Yes, Limited A Lot	Yes, Limited A Little	No, Not Limited At All
a.	Vigorous activities, such as running, lifting heavy objects, participating in strenuous sports	❑	❑	❑
b.	Moderate activities, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf	❑	❑	❑
c.	Lifting or carrying groceries	❑	❑	❑
d.	Climbing several flights of stairs	❑	❑	❑
e.	Climbing one flight of stairs	❑	❑	❑
f.	Bending, kneeling or stooping	❑	❑	❑
g.	Walking more than a mile	❑	❑	❑
h.	Walking several blocks	❑	❑	❑
i.	Walking one block	❑	❑	❑
j.	Bathing or dressing yourself	❑	❑	❑

4. During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of your physical health?

		YES	NO
a.	Cut down on the amount of time you spent on work or other activities	❑	❑
b.	Accomplished less than you would like	❑	❑
c.	Were limited in the kind of work or other activities	❑	❑
d.	Had difficulty performing the work or other activities (for example, it took extra effort)	❑	❑

5. During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)?

		YES	NO
a.	Cut down on the amount of time you spent on work or other activities	❑	❑
b.	Accomplished less than you would like	❑	❑
c.	Didn't do work or other activities as carefully as usual	❑	❑

FIG 42-5 The International Knee Documentation Committee (IKDC) Current Health Assessment Form. (Courtesy the American Orthopaedic Society for Sports Medicine.)

6. During the past 4 weeks, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbors, or groups?

❑Not At All ❑Slightly ❑Moderately ❑Quite a Bit ❑Extremely

7. How much bodily pain have you had during the past 4 weeks?

❑None ❑Very Mild ❑Mild ❑Moderate ❑Severe ❑Very Severe

8. During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)?

❑Not at All ❑A Little Bit ❑Moderately ❑Quite a Bit ❑Extremely

9. These questions are about how you feel and how things have been with you during the past 4 weeks. For each question, please give the one answer that comes closest to the way you have been feeling. How much of the time during the past 4 weeks...

	All of the time	Most of the time	A good bit of the time	Some of the time	A little of the time	None of the time
a. Did you feel full of pep?	❑	❑	❑	❑	❑	❑
b. Have you been very nervous?	❑	❑	❑	❑	❑	❑
c. Have you felt calm and peaceful?	❑	❑	❑	❑	❑	❑
d. Did you have a lot of energy?	❑	❑	❑	❑	❑	❑
e. Have you felt down-hearted and blue?	❑	❑	❑	❑	❑	❑
f. Did you feel worn out?	❑	❑	❑	❑	❑	❑
g. Have you been a happy person	❑	❑	❑	❑	❑	❑
h. Did you feel tired?	❑	❑	❑	❑	❑	❑

10. During the past 4 weeks, how much of the time has your physical health or emotional problems interfered with your social activities (like visiting with friends, relatives, etc.)?

❑All of the time ❑Most of the time ❑Some of the time ❑A little of the time ❑None of the time

11. How TRUE or FALSE is each of the following statements for you?

	Definitely True	Mostly True	Don't Know	Mostly False	Definitely False
a. I seem to get sick a little easier than other people	❑	❑	❑	❑	❑
b. I am as healthy as anybody I know	❑	❑	❑	❑	❑
c. I expect my health to get worse	❑	❑	❑	❑	❑
d. My health is excellent	❑	❑	❑	❑	❑

FIG 42-5, cont'd

2000 IKDC KNEE HISTORY FORM

Patient Name _____ Birthdate _____ / _____ / _____
Day Month Year

Date of Injury _____ / _____ / _____ Date of Initial Exam _____ / _____ / _____ Today's Date _____ / _____ / _____
Day Month Year Day Month Year Day Month Year

Involved Knee: ❑ Right ❑ Left

Contralateral: ❑ Normal ❑ Nearly Normal ❑ Abnormal ❑ Severely abnormal

Onset of Symptoms: (date) _____ / _____ / _____
Day Month Year

Chief Complaint: _____

Activity at Injury: ❑ ADL ❑ Sports ❑ Traffic ❑ Work

Mechanism of Injury:

❑ Non-traumatic gradual onset
❑ Non-traumatic sudden onset
❑ Traumatic non-contact onset
❑ Traumatic contact onset

Previous Surgery:

Type of Surgery: (check all that apply)

Meniscal Surgery

❑ Medial meniscectomy
❑ Medial meniscal repair
❑ Medial meniscal transplant
❑ Lateral meniscectomy
❑ Lateral meniscal repair
❑ Lateral meniscal transplant

Ligament Surgery

❑ ACL Repair
❑ PCL Repair
❑ Intraarticular ACL reconstruction
❑ Intraarticular PCL reconstruction
❑ Extraarticular ACL reconstruction
❑ Posterolateral corner reconstruction
❑ Medial collateral ligament repair/reconstruction
❑ Lateral collateral ligament repair/reconstruction

Type of Graft

Patella tendon graft
❑ Single hamstring graft ❑ Ipsilateral ❑ Contralateral
❑ 2 Bundle hamstring graft
❑ 4 Bundle hamstring graft
❑ Quadriceps tendon graft
❑ Allograft
❑ Other

FIG 42-6 The 2000 International Knee Documentation Committee (IKDC) Knee History Form. *ACL*, Anterior cruciate ligament; *ADL*, activities of daily living; *CT*, computed tomography; *MRI*, magnetic resonance imaging; *PCL*, posterior cruciate ligament. (Courtesy the American Orthopaedic Society for Sports Medicine.)

Page 2 – 2000 IKDC KNEE HISTORY FORM

Extensor Mechanism Surgery

❑ Patella tendon repair ❑ Quadriceps tendon repair

Patellofemoral Surgery

❑ Extensor Mechanism Realignment

Soft Tissue Realignment

❑ Medial imbrication ❑ Lateral release

Bone Realignment

Movement of the tibial tubercle

❑ Proximal ❑ Distal ❑ Medial ❑ Lateral ❑ Anterior

❑ Trochleoplasty

❑ Patellectomy

Osteoarthritis Surgery

❑ Osteotomy
❑ Articular Surface Surgery ❑ Shaving ❑ Abrasion ❑ Drilling ❑ Microfracture
❑ Cell therapy ❑ Osteochondral autograft transfer/mosaic-plasty ❑ Other

Total number of previous surgeries _____

Imaging Studies:

❑ Structural ❑ MRI ❑ CT ❑ Arthrogram

❑ Metabolic (Bone Scan)

Findings:

Ligament _____

Meniscus _____

Articular Cartilage _____

Bone _____

FIG 42-6, cont'd

2000 IKDC SURGICAL DOCUMENTATION FORM

Patient's Name: _____ Date of Index Procedure: _____/_____/_____
Day Month Year

Postoperative Diagnosis:

1._____

2._____

3._____

Status After Procedure:

ARTICULAR CARTILAGE STATUS:

Document the size and location of articular cartilage defects on these figures according to the ICRS mapping system[c].

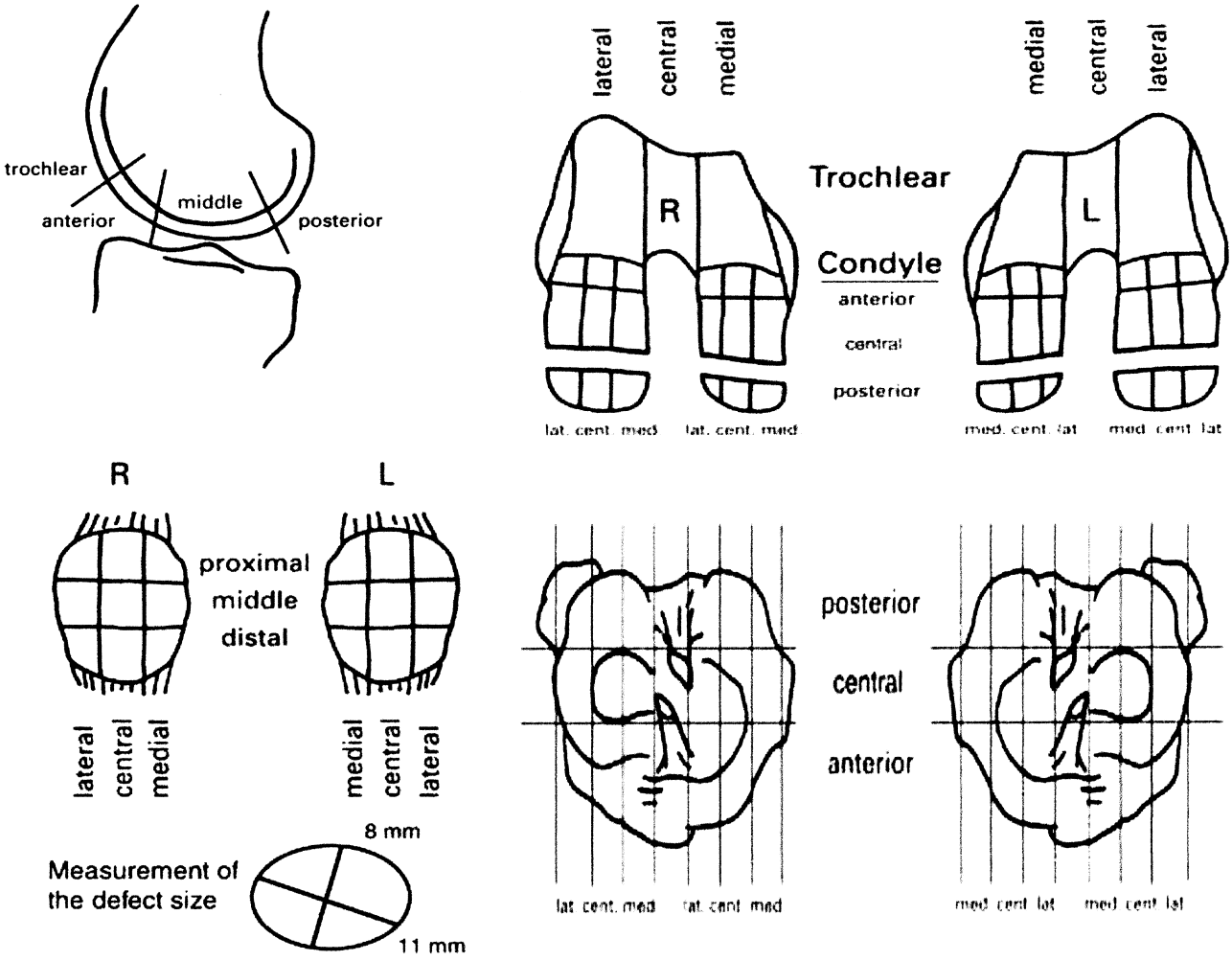


FIG 42-7 The 2000 International Knee Documentation Committee (IKDC) Surgical Documentation Form. *ACL*, Anterior cruciate ligament; *PCL*, posterior cruciate ligament. (Courtesy the American Orthopaedic Society for Sports Medicine.)

Page 2 – 2000 IKDC SURGICAL DOCUMENTATION FORM

Record size, location and grade of articular cartilage lesions.

Femur

					First lesion	Second Lesion
Side	Right	Left				
Condyle	Medial	Lateral				
Sagittal plane	Trochlear	Anterior	Middle	Posterior		
Frontal plane	Lateral	Central	Medial			
Cartilage lesion (Grade) (*)						
Defect size pre-debridement				mm		
Defect size post-debridement				mm		

Tibia

				First lesion	Second Lesion
Side	Right	Left			
Plateau	Medial	Lateral			
Sagittal Plane	Anterior	Middle	Posterior		
Frontal Plane	Lateral	Central	Medial		
Cartilage lesion (Grade) (*)					
Defect size pre-debridement			mm		
Defect size post-debridement			mm		

Patella

				First lesion	Second Lesion
Side	Right	Left			
Sagittal plane	Distal	Middle	Proximal		
Frontal plane	Lateral	Central	Medial		
Cartilage lesion (Grade) (*)					
Defect size pre-debridement			mm		
Defect size post-debridement			mm		

Diagnosis: ❑ Traumatic cartilage lesion ❑OD ❑OA ❑AVN ❑Others

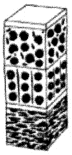
Biopsy/Osteochondral Plugs: Location: Number of Plugs:

Diameter of Plugs: mm

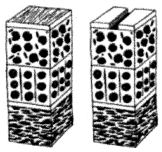
Treatment:
❑ Shaving ❑ Abrasion
❑ Drilling ❑ Microfracture
❑ Osteochondral autograft transfer/mosaic-plasty
❑ Cell therapy ❑ Other

Notes:

ICRS Grade 0 - Normal



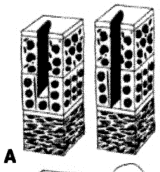
ICRS Grade 1 – Nearly Normal
Superficial lesions, Soft indentation (A) and/or superficial fissures and cracks (B)

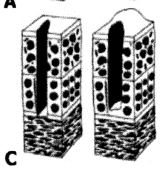


ICRS Grade 2 – Abnormal
Lesions extending down to <50% of cartilage depth



ICRS Grade 3 - Severely Abnormal
Cartilage defects extending down >50% of cartilage depth (A) as well as down to calcified layer (B) and down to Blisters are included in this Grade (D)





ICRS Grade 4 – Severely Abnormal
Osteochondral injuries, lesions extending just through the subchondra boneplate (A) or deeper defects down into trabecular bone (B). Defects that have been drilled are regarded as osteochondral defects and classified as ICRS-C.

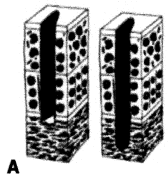


FIG 42-7, cont'd

Continued

Page 3 – 2000 IKDC SURGICAL DOCUMENTATION FORM

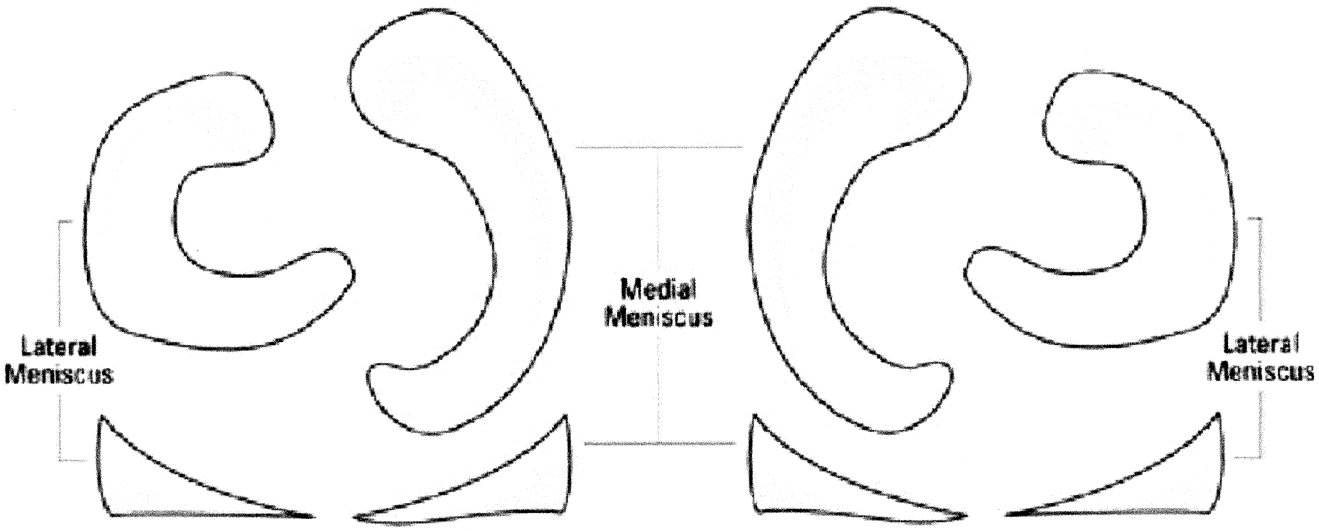
MENISCUS STATUS:

Procedure:

- ❑medial meniscectomy
- ❑medial meniscal repair
- ❑medial meniscal transplant
- ❑medial abrade & trephine
- ❑lateral meniscectomy
- ❑lateral meniscus repair
- ❑lateral meniscal transplant
- ❑lateral abrade & trephine

Right Knee **Left Knee**

Document tears of the menisci or meniscectomy on these figures



Medial:

❑Normal ❑1/3 Removed ❑2/3 Removed ❑3/3 Removed

Circumferential Hoop Fibers: ❑Intact ❑Disrupted

Remaining Meniscal Tissue: ❑Normal ❑Degenerative changes
❑Stable tear ❑Unstable tear
❑Tear left in situ

Lateral:

❑Normal ❑1/3 Removed ❑2/3 Removed ❑3/3 Removed

Circumferential Hoop Fibers: ❑Intact ❑Disrupted

Remaining Meniscal Tissue: ❑Normal ❑Degenerative changes
❑Stable tear ❑Unstable tear
❑Tear left in situ

FIG 42-7, cont'd

Page 4 – 2000 IKDC SURGICAL DOCUMENTATION FORM

LIGAMENT STATUS:

Procedure:
❑ACL repair ❑Intraarticular ACL reconstruction ❑Extraarticular ACL reconstruction
❑PCL repair ❑Intraarticular PCL reconstruction ❑Posterolateral corner repair/reconstruction
❑Medial collateral ligament repair/reconstruction
❑Lateral collateral ligament repair/reconstruction

Graft:
❑Autologous patella tendon ❑Hamstring tendons ❑Quadriceps tendon
❑Other_____

Previous Graft Harvest:
❑Autologous patella tendon ❑Hamstring tendons ❑Quadriceps tendon

Document drill hole placement for ligament reconstruction on these figures.

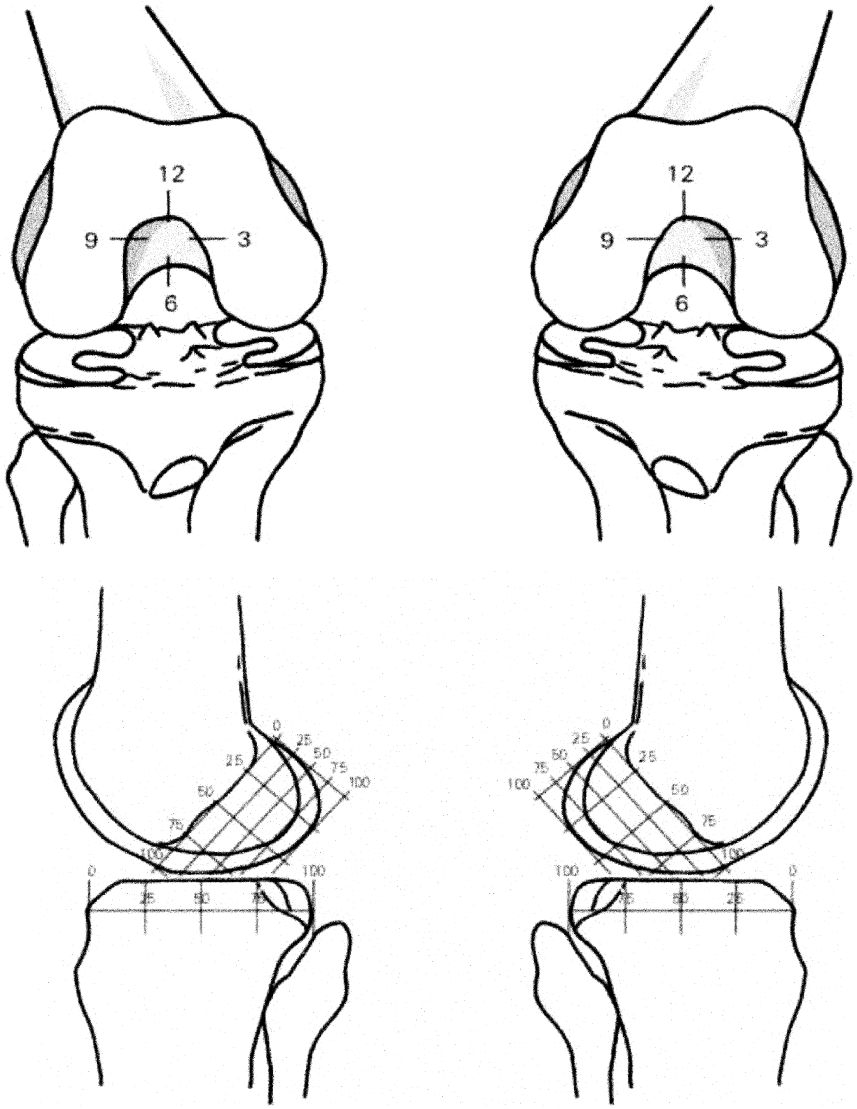


FIG 42-7, cont'd

Cincinnati knee score, and moderate correlations were detected between IKDC-2 and the Lysholm score. IKDC1-4 showed high criterion validity with the Cincinnati score and KT-1000 manual maximum testing.

Hrubesch and associates[11] failed to find significant correlations among the IKDC rating and the Cincinnati, Lysholm, Feagin and Blake, Zarins and Rowe, and Marshall scores. However, these authors did not use the entire Cincinnati Knee Rating System, which incorporates variables similar to the IKDC knee examination form. This was the reason that superior results were found using the Cincinnati score compared with the IKDC overall grade.

Kocher and colleagues[16] conducted a study to identify the determinants of patient satisfaction of the outcome of ACL reconstruction. Patient satisfaction was significantly associated with the IKDC-1 to IKDC-3 (subjective assessment, symptoms, range of motion) and IKDC-F. There was no association between IKDC-4 (ligament examination) and patient satisfaction.

The IKDC Subjective Evaluation Form was compared with the "modified" Cincinnati Knee Rating System by Agel and LaPrade.[1] These investigators collected "modified" CKRS and IKDC subjective questionnaires from 130 patients with a variety of complex knee disorders both before surgery and at intervals postoperatively (4-8 months, 9-15 months, 16-24 months, >24 months). The overall total scores for both questionnaires were equivalent in the analysis of the entire population at all time intervals. There were no differences between the questionnaires for ceiling and floor effects. There were differences when the individual patient's scores were assessed and, across time intervals, between 9% and 21% of the population exhibited individual patient's score differences of more than 10 points. The authors concluded that the decision of which questionnaire to use should be based on the specific diagnosis of the population under study, with careful consideration given to the individual questions contained in each system.

Greco and colleagues[8] compared reliability and responsiveness of the IKDC Subjective Knee Form to the "modified" CKRS, the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), and the SF-36 in patients with full-thickness articular cartilage defects treated with a variety of cartilage restoration procedures. The interclass correlation coefficients of three of the instruments were comparable (IKDC, 0.91; CKRS, 0.91; WOMAC, 0.81-0.93), as were the effect sizes and standardized response means 12 months after surgery. The SF-36 subscales failed to show adequate reliability (across all ten scales) and responsiveness.

To determine which questions were considered most important to patients that had undergone ACL reconstruction, Hambly and Griva[9] compared patients' responses on the IKDC Subjective Evaluation Form with those collected on the Knee Injury and Osteoarthritis Outcome Score (KOOS) form. These investigators reported that 78% of the items from the IKDC were experienced by more than half of the patients compared with 57% from the KOOS. However, items from the Function in Sports/Recreation and Quality of Life KOOS subscales were also very important to this cohort. In an investigation with a similar purpose, Tanner and associates[33] found that the IKDC Subjective Evaluation Form was one of the top general knee instruments (among five instruments evaluated) because it contained many questions on symptoms and limitations considered important to patients. This investigation assessed 153 patients who had ACL tears, meniscus tears, or mild/moderate knee osteoarthritis.

OUR COMMENTS

Clinical researchers must select a knee rating instrument composed of the essential variables required to study hypotheses and assess other variables that may potentially bias the study outcome. Researchers should understand the major differences that exist between available knee rating instruments that could affect the conclusions of studies. In our opinion, clinical studies must measure and report not only symptoms and functional limitations with athletic and daily activities but objective physical findings as well. Factors such as range of knee motion, joint effusion, tibiofemoral and patellofemoral crepitus, knee ligament subluxations, radiographic findings, and functional testing should be included in the results of investigations. Therefore, if the IKDC is chosen as the outcome instrument for a study, both the 2000 IKDC Subjective Knee Form and the 2000 IKDC Knee Examination Form should be completed and incorporated into the publication.

It is important to realize the limitations of the 2000 IKDC Subjective Knee Form. First, this form is, by intended design, a generic knee questionnaire. We believe that investigators should use instruments as sensitive to the condition under study as possible. Second, this form combines data from 18 questions that rate symptoms, functions of daily and sports activities, current function of the knee, and participation in work and sports into one numerical value. The IKDC to date has not recommended that researchers separately assess specific symptoms, functional limitations, or sports activity levels before and after treatment, even though the questionnaire format allows for such an assessment. Therefore given the current committee recommendations, the ability to detect specific limitations, such as pain or giving way during various activities, is not possible. Investigators and readers

CRITICAL POINTS Comparison of IKDC Outcomes with Those of Other Knee Rating Systems

- Not all IKDC domains are responsive to detecting change over time after anterior cruciate ligament (ACL) reconstruction.
- No difference in functional outcome reported between "modified" CKRS and IKDC Subjective questionnaires.
- No difference in reliability and responsiveness between the IKDC Subjective Knee Form, the "modified" CKRS, WOMAC, and SF-36 in patients with full-thickness articular cartilage defects treated with a variety of cartilage restoration procedures.
- IKDC Subjective Evaluation Form one of the top general knee instruments in determining which questions were considered most important to patients that had undergone ACL reconstruction.

CRITICAL POINTS Our Comments

- Clinical studies must measure and report symptoms and functional limitations with athletic and daily activities and objective physical findings.
- Limitations of the IKDC Subjective Knee Evaluation Form:
  - Combines symptoms and functions of work, sports, and daily activities into one score.
  - Sensitivity for detecting specific limitations is greatly reduced.
  - Cannot detect knee abusers, activity level, or changes in activity level from total score.
  - Researchers should analyze data from individual questions as well as total score.
  - Age- and gender-matched percentiles generated by the online scoring system are more useful than the total score.

cannot ascertain from a single numeric value if an individual is participating in athletics, and if so, whether problems are incurred. Changes in sports activity levels are not determined, nor are limitations in individual knee functions such as walking, running, and pivoting. We believe that it is important in athletically active populations to provide a specific analysis of the sports levels preoperatively and postoperatively, which may be easily done by reporting the distribution of patients in the five levels provided in question 8. It is equally important to report the percent of patients who returned to athletics without symptoms versus those who experienced problems and were considered knee abusers.[23]

We recommend that investigators provide pretreatment and posttreatment data from individual questions on the 2000 IKDC Subjective Knee Evaluation Form and not just the overall score. Investigators may choose the specific questions that are considered the most important according to the knee injury or disorder under study. For example, a study of the results of ACL reconstruction should separately analyze data from question 7, which ascertains whether giving way of the knee occurs with varying activity levels. In addition, the overall function of the knee determined by question 10 should be individually profiled by providing not only the mean values before and after treatment but a distribution of responses along the scale. Investigators should realize that this question measures daily activity function only because a score of 0 equals "cannot perform daily activities," and a score of 10 equals "no limitation in daily activities." Therefore this question (as it currently appears on the questionnaire) does not take into account the patients' ability to perform sports activities.

In our opinion, the age- and gender-matched percentiles generated by the AOSSM online scoring system for the 2000 IKDC Subjective Knee Evaluation Form are more useful than the total score. For instance, a 46-year-old woman who experiences only mild, occasional symptoms with strenuous activities could score an 87, which initially appears to be a good result and would compare favorably with scores of other systems such as the Lysholm[34] or Activities of Daily Living Scale of the Knee Outcome Survey.[15] However, this total score places this patient into only the 50th percentile according to the IKDC normative database. Therefore researchers should consider incorporating the age- and gender-matched percentiles in the results section of published studies, such as is commonly done with SF-36 data. An example of this type of analysis with SF-36 data may be found in the investigation of Sekiya and coworkers[28] who described the short-term (average, 2.8 years postoperative) outcome of combined meniscus transplantation and ACL reconstruction in 28 patients. The mean absolute scores were provided for the individual domains of the SF-36 questionnaire, along with scores standardized to age- and sex-matched U.S. population norms for each individual patient.

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43

Rating of Athletic and Daily Functional Activities: Knee-Specific Scales and Global Outcome Instruments

Sue D. Barber-Westin, Frank R. Noyes

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INTRODUCTION

This chapter reviews commonly used scales and outcome instruments that rate athletic and daily functional activities for a variety of knee injuries and disorders in younger active patients. The instruments are analyzed according to their strengths and potential biases as well as their measured reliability, validity, and responsiveness properties. Scales from the Cincinnati Knee Rating System (CKRS) and the International Documentation Committee Rating (IKDC) System are not included because they are described in detail in Chapters 41 and 42, respectively. Outcome measures typically used in older or sedentary populations with osteoarthritis, patients who undergo total knee arthroplasty (TKA), and individuals with patellofemoral pain are described in Chapter 45.[1,36,41] Generic health status instruments, such as the Short Form-36 Health Survey (SF-36) and the Musculoskeletal Function Assessment,[22] are also available but these are not discussed in this chapter.

It is important to stress that, in our opinion, clinical research studies should include the assessment of symptoms and athletic and daily functional activities, as well as objective physical findings. The determination of patient's outcome using subjective questionnaire data only does not provide an accurate understanding of the ability of the treatment protocol to restore normal knee function. Factors such as range of knee motion, joint effusion, tibiofemoral and patellofemoral crepitus, knee ligament subluxations, radiographic findings, and limb symmetry on functional testing should be included as required according to the diagnosis under study.

SPORTS ACTIVITY SCALES

Tegner Activity Scale

Tegner and Lysholm[42] developed one of the first rating scales to quantify activity levels in patients with anterior cruciate ligament (ACL) ruptures (Table 43-1). The Tegner Activity Scale classifies both sports and work activities into one questionnaire using an 11-level gradient. Competitive sports make up the top three levels (levels 10-8), competitive and recreational sports categories both appear in level 7, and "other recreational sports" make up level 6 (Table 43-2). Levels 5 through 1 combine work and sports together, and level 0 indicates sick leave or disability because of the knee condition. The original publication did not provide reliability, validity, or responsiveness data of this scale.

Several problems are incurred with this activity rating instrument. First, work activities are rated within the same scale as sports activities. Patients who work in heavy-labor occupations are only awarded a level 5 (out of a possible 10), but the analysis of the stress on the lower limb in some of these occupations would probably show that these knees are functioning at a level equivalent to those of competitive athletes. They should not be awarded a lower level simply because they are not athletes or did not return to highly competitive sports. Athletics and occupational activities should be measured on separate rating scales (see Chapter 41).

Second, this scale does not separate various sports levels according to frequency of participation or the intensity of the sport, which is determined by accounting for the forces placed on the lower extremity. For instance, only national and international elite soccer players are

CRITICAL POINTS Sports Activity Scales

- Tegner Activity Scale
  - Classifies both sports and work activities into one questionnaire using an 11-level gradient.
  - Does not separate sports levels according to frequency of participation or intensity of sport.
  - Cannot determine change in athletic participation between time periods owing to a change in lifestyle.
  - Does not detect knee abusers.
  - Adequate psychometric properties for meniscus injuries, acute patellar dislocations.
  - Less responsive to change after articular cartilage restorative procedures in comparison with the Knee Injury and Osteoarthritis Outcome Score subscales of sport/recreation and quality of life.
  - Unable to discriminate among patients sufficiently active and those insufficiently active after total knee arthroplasty.
- Hospital for Special Surgery Sports Scale
  - Sports levels sorted according to four stress categories.
  - Ambiguous terms are used to define sports categories.
  - Cannot determine change in athletic participation between time periods owing to a change in lifestyle.
  - Psychometric properties not evaluated.
- Seto Sports Participation Survey
  - Sports activity level and participation rated.
  - Allows analysis of athletic participation according to frequency of play and the detection of changes in levels between evaluations.
  - Psychometric properties not evaluated.
- Straub and Hunter's Sports Performance Index
  - Sports index based on rating of participation and intensity levels.
  - Sports not included in the rating cannot be placed on scale because the rationale for the classification of activities into the various categories is unknown.
  - Frequency and duration of activities not included.
  - Knee abusers cannot be detected.
  - Psychometric properties not evaluated.
- Daniel Sports Level Rating
  - Sports activity rated according to frequency of participation (number of hours played per year) and intensity. Frequency assessed retrospectively.
  - Knee abusers cannot be detected.
  - Cannot determine change in athletic participation between time periods owing to a change in lifestyle.
  - Psychometric properties not evaluated.
- Marx Sports Activity Scale
  - Scale based on frequency of participation and intensity of activities.
  - Satisfactory reliability, validity.
  - Unable to discriminate between patients sufficiently active and those insufficiently active after total knee arthroplasty.

TABLE 43-1 Tegner Activity Score

Level	Descriptor	Examples of Activities
10	Competitive sports	Soccer: national and international elite
9	Competitive sports	Soccer: lower divisions; ice hockey, wrestling, gymnastics
8	Competitive sports	Bandy, squash or badminton, athletics (e.g., jumping), downhill skiing
7	Competitive sports	Tennis, athletics (running), motocross: speedway, handball, basketball
	Recreational sports	Soccer, bandy and ice hockey, squash, athletics (jumping), cross country, track and field, findings both recreational and competitive
6	Recreational sports	Tennis and badminton, handball, basketball, downhill skiing, jogging at least five times/wk
5	Work	Heavy labor (e.g., building, forestry)
	Competitive sports	Cycling Cross-country skiing
	Recreational sports	Jogging on uneven ground at least twice/wk
4	Work	Moderately heavy labor (e.g., truck driving, heavy domestic work)
	Recreational sports	Cycling, cross-country skiing, jogging on uneven ground at least twice/wk
3	Work	Light labor (e.g., nursing)
	Competitive and recreational sports	Swimming
	Walking in forest possible	
2	Work	Light labor
	Walking on uneven ground possible but impossible to walk in forest	
1	Work	Sedentary work
	Walking on even ground possible	
0	Sick leave or disability pension because of knee problems	

From Tegner,Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries. Clin *Orthop Relat Res.* 1985;198:43-49.

listed on level 10, whereas basketball is listed on a level 7. In the United States, it could be argued that competitive high school, collegiate, or professional basketball players are asked to place similar demands on the knee joint and lower extremity as elite soccer players. For patients who play or return to sports not listed on the scale, problems are incurred in trying to determine exactly which level accurately defines their sport. Third, this scale does not allow an assessment of a change in athletic participation between time periods owing to a change in lifestyle (e.g., graduated from school and no longer participates in a league). In addition, one cannot detect knee abusers in either the sport or the work levels.

Independent investigations assessed the reliability, validity and responsiveness of the Tegner scale for a variety of knee injuries. Briggs and coworkers[6] determined its reliability, validity, and responsiveness in 122 patients with meniscus injuries. The scale was found to have adequate reliability (intraclass correlation coefficient [ICC], 0.817), content validity (no ceiling or floor effects), criterion validity with the Medical Outcomes Short Form-12 Health Survey (SF-12), and construct validity. However, only moderate effect sizes (ES) and standardized response mean (SRM) values were reported. The investigators concluded that the scale measures only moderate changes in activity

Table 43-2 Published Sports Activity Rating Scales

Scale, Year Published	Factors Rated	Reliability, Validity, Responsiveness Testing	Comments
Tegner, 1985	**11 levels:** Levels 8-10: competitive (lists of sports provided) Level 7: competitive and recreational (lists of sports provided) Level 6: recreational (lists of sports provided, jogging at least 5 times/wk) Level 5: work (heavy labor), competitive and recreational sports (cycling, cross-country skiing, jogging uneven ground at least twice/wk) Level 4: work (moderately heavy), recreational sports (cycling, cross-country skiing, jogging even ground at least twice/wk) Level 3: work (light), competitive and recreational sports (swimming), walking rough terrain Level 2: work (light), walking uneven ground Level 1: work (sedentary), walking even ground Level 0: sick leave, disability because of knee	ACL injuries/reconstructions: adequate reliability, content validity, criterion validity, construct validity, responsiveness Meniscus injuries: adequate reliability, content validity, criterion validity, construct validity; moderate responsiveness Acute patellar dislocations: adequate reliability, content validity Articular cartilage repairs: inadequate responsiveness Total knee arthroplasty: adequate reliability, validity	Developed to compare activity levels before and after treatment. Rationale for assignment of activities to each level unknown. Patients in United States may have difficulty completing scale; designed for European sports. Combines work and sports in 5 of the 11 levels.
Hospital for Special Surgery, 1987	**4 levels:** Very stressful (lists of sports provided) Moderately stressful (lists of sports provided) Mildly stressful (lists of sports provided) No sports	Not done	Frequency of participation not assessed
Seto Sport Participation Survey, 1988	13 sports, each assigned 0-4 points (see text). May assign points for activities not listed on scale. Each sport also rated according to frequency and duration of participation: assigned 1-3 points.	Not done	Allows detection of knee abusers, change in activity levels between evaluations. Reporting of data may be difficult if a population is composed of individuals who play a wide variety of sports because data are sorted according to each activity separately.
Straub & Hunter's Sport Performance Index, 1988	**Participation level score:** Professional (5 points) Intercollegiate (4 points) Intramural (college), varsity (high school), recreational (intense) (3 points) Recreational (casual) (2 points) Junior high school (1 point) No sports (0 points) Performance index score (intensity level): sport rated according to perceived stress on knee, levels 1-5 (lists of sports provided). Participation score added to intensity level score to calculate performance index.	Not done	Only certain sports listed on performance index scale. Sports not rated according to frequency and duration of participation. Rationale for classification of sports in levels 1-5 not given.

Continued

Table 43-2 Published Sports Activity Rating Scales—cont'd

Scale, Year Published	Factors Rated	Reliability, Validity, Responsiveness Testing	Comments
Daniel Sports Activity Rating, 1994	**4 levels:** I: jumping, pivoting, hard cutting II: lateral motion, less jumping or hard cutting than level I III: other sports IV: no sports Lists of sports provided for each level	Not done	Assessed frequency of participation; total hr/yr estimated retrospectively
Marx Sports Activity Scale, 2001	4 factors: running, cutting, decelerating, pivoting Each factor rated according to frequency of participation: <1 time/mo, 1 time/mo, 1 time/wk, 2-3 times/wk, >3 times/wk	Reliability ICC = 0.97. Validity: face, content, construct, divergent; acceptable, correlated with three other sports activity scales Responsiveness testing not done Scale showed inverse correlation with age	Tested in 40 normal subjects. No category available for low-impact activities (swimming, bicycling, low-impact aerobics).
High-Activity Arthroplasty Score, 2010	4 factors: walking, running, stair climbing, general activities; patient selects highest level of function in each domain, sum equals score	High internal consistency Validity: correlated with four other scales Reliability using ICC, responsiveness testing not done	Tested in 22 patients, pilot study

ACL, Anterior cruciate ligament; *ICC*, intraclass correlation coefficient.

levels, and noted that patients in the United States may have difficulty completing the scale because it was designed for sports commonly played in Europe.

Paxton and associates[28] assessed the reliability and validity of this scale in 153 patients followed 2 to 5 years after an acute patellar dislocation. The scale was found to have adequate reliability (ICC, 0.92) and content validity. Briggs and colleagues[7] found the Tegner scale had adequate reliability, validity, and responsiveness following ACL injury and reconstruction.

Ebert and associates[10] reported that the Tegner scale was less responsive to change following articular cartilage restorative procedures in comparison with the Knee Injury and Osteoarthritis Outcome Score (KOOS) subscales of sport/recreation and quality of life. There was no strong evidence that a change in the Tegner scale was associated with patient satisfaction of the outcome of the operation. A systematic review of the use of the Tegner scale following articular cartilage repair procedures[14] found that the majority of studies reported means values only, where nonparametric methods would be more relevant. The investigators concluded that if the instruments is used in a nonstandardized or inappropriate manner, its value as a clinical outcome measure will be compromised.

Naal and coworkers[26] compared data from three activity rating scales (Tegner, University of California, Los Angeles [UCLA],[48] and Marx Activity Rating Scale[24]) in patients who underwent total joint arthroplasty. Physical activity was assessed using the "last 7 days" version of the International Physical Activity Questionnaire (IPAQ).[8] The Tegner scale was found to be reliable and had acceptable validity in patients undergoing total knee arthroplasty (TKA). However, this scale had lower correlation coefficients and lower completion rates than the UCLA scale and was unable to discriminate between patients who were sufficiently active (moderate and vigorous activity levels according to IPAQ classification) and those who were insufficiently active.

Hospital for Special Surgery Sports Scale

Hanley and Warren[15] developed the Hospital for Special Surgery (HSS) knee assessment instrument for an investigation of 48 patients with ACL-deficient knees who underwent arthroscopic partial meniscectomy. The instrument includes a scale composed of four levels of various sports ranked "very stressful," "moderately stressful," "mildly stressful," and "no sports activities." Examples of sports are provided in categories A, B, and C to assist with the ratings. The advantages of this scale include the assessment of sports activities only (separately from occupations) and the attempt to sort sports participation according to the level of intensity. The problems with this scale are that ambiguous terms are used to rate the sports categories ("very stressful" may have different meanings to different patients), an assessment of reasons for change in athletics owing to non–knee-related reasons is not provided, and the detection of knee abusers is not possible. The authors did not conduct reliability, validity, or responsiveness testing of their outcome instrument.

Seto Sports Participation Survey

Seto and associates[37] developed a sports participation survey to determine activity levels in 19 patients who had undergone ACL reconstruction. In this survey, subjects rate their activity level for 13 sports, which are divided into cutting and noncutting categories. Each sports activity receives 0 to 4 points.[12]

4 = full activity with no significant signs or symptoms
3 = full activity with occasional or recurring mild episodes of pain, swelling, or instability
2 = limited activity because of moderate or severe episodes of pain, swelling, or instability
1 = does not participate in activity because of the injured knee
0 = does not participate in activity but not because of the injured knee

Patients also rate their sports participation according to frequency and duration as either competitive (6 to 7 times/week or regular participation in organized competition, 3 points), recreational (3 to 5 times/week, or 2 times/week and more than 2 hours/session, or seasonal sports 5 days or more/months, 2 points), or weekend (1 to 2 times/week for 1 hour or participation in seasonal sports ≤4 days/months, 1 point).

This scale allows the analysis of athletic participation according to frequency of play and the detection of changes in activity levels between evaluations. Knee abusers may be identified from the categories of "mild" or "moderate" symptoms occurring with activity. Because the activity level is rated per sport, reporting of data can be difficult if a population is composed of individuals who play a wide variety of sports. Reliability, validity, and responsiveness testing were not conducted on this survey.

Straub and Hunter's Sports Performance Index

Straub and Hunter[40] devised a sports performance index to determine the outcome of ACL reconstruction. The index is based on scores from two factors: a participation level rating and an intensity level rating. The participation level rating is accomplished on a six-level gradient that ranges from professional (5 points); intercollegiate (4 points); intramural (college), varsity (high school), or recreational (intense, 3 points); casual (2 points); junior high school (1 point); to no sports (0 points). The intensity rating scale sorts various sports into categories according to the authors' perception of the intensity of those activities on the lower extremity. The most intense activities receive 5 points, and the least intense receive 1 point. The two rating scores are summed up to produce a sports performance index.

This scale does not allow for the rating of sports that are not included in the intensity rating scale because the rationale for the classification of activities into the various categories is unknown. The frequency and duration of activities is not included in the sports level assessment. Knee abusers cannot be detected. The authors did not assess the reliability, validity, or responsiveness of this instrument.

Daniel Sports Activity Rating

Daniel and coworkers[9] described a sports rating scheme that was used to determine outcome in both ACL-deficient and ACL-reconstructed knees. The sports activity rating assessed frequency of participation (number of hours played per year) and intensity of the activities. Frequency of participation is determined in a retrospective manner; patients are asked to recall the two most frequent sports they played before their ACL rupture and to provide the number of weeks per year and the number of hours per week that they played each sport. The number of hours per year of participation in the two sports is summed up. A four-level intensity rating is also included in which level I comprises jumping, pivoting, and hard cutting activities; level II, lateral motion but less jumping or hard cutting than level I; level III, "other sports"; and level IV, no sports. A few examples of sports are provided for levels I, II, and III.

The retrospective analysis of hours of participation can be problematic, especially in long-term clinical studies where patients may be asked to recall hours of participation from many years ago. The scale does not allow for the detection of knee abusers or patients who decreased their activity level or stopped athletics owing to reasons not related to their knee condition. Reliability, validity, and responsiveness testing were not conducted by the investigators.

Marx Sports Activity Scale

Marx and associates[24] developed a sports activity rating scale to use as a general research tool to determine outcome for a variety of knee injuries and operations. This scale takes into account frequency of participation and intensity of the activity. Four separate activities are rated: running, cutting, decelerating, and pivoting. Frequency of participation for each activity is classified as "none," "1 time a month," "1 time a week," "2 or 3 times a week," and "4 or more times a week."

Reliability and construct validity were assessed in 40 volunteers with no history of knee problems. The scale showed acceptable reliability (ICC, 0.97) and correlated with the Tegner, Cincinnati, and Daniel sports activity scales. Responsiveness testing was not completed.

As previously described, Naal and coworkers[26] compared data from three activity rating scales (Tegner, UCLA,[48] and Marx Activity Rating Scale[24]) in patients who underwent total joint arthroplasty. The Marx Activity Rating Scale was found to be reliable and had acceptable validity in patients undergoing TKA. However, this scale had the weakest correlation coefficients with other scales, had large floor effects, and was unable to discriminate among patients who were sufficiently active (moderate and vigorous activity levels according to IPAQ classification) and those who were insufficiently active.

Although this scale is useful in rating activities that involve the specific motions selected by the authors, it cannot rate low-impact activities such as swimming, bicycling, or low-impact aerobics. If a patient swam or bicycled several times a week, he or she would receive 0 of a possible 16 points on this scale.

ACTIVITIES OF DAILY LIVING SCALES

Lysholm Knee Score

The Lysholm knee score, first introduced into the medical community in 1982[21] and modified in 1985[42] (Table 43-3), remains one of the most frequently used assessment tools for the results of ACL reconstruction even though it only measures activities of daily living (ADLs). Eight factors are rated to produce an overall score on a point scale of 0 to 100. Then an assignment is given as "excellent" for 95 to 100 points; "good" for 84 to 94 points, "fair" for 65 to 83 points, or "poor" for less than 65 points. The factors of limp, support, and locking are worth a potential of 23 points; pain and instability, 25 points each; swelling and stair climbing, 10 points each; and squatting, 5 points.

CRITICAL POINTS Activities of Daily Living Scales

- Lysholm Knee Score
  - Eight factors rated to produce an overall score on a point scale of 0 to 100
  - Symptoms of pain, swelling, and instability graded according to the activity in which they occur
  - Adequate reliability and responsiveness for ligament and meniscus injuries, patellofemoral pain, and degenerative joint disease
  - High ceiling effects for the domains of limp, instability, support, and locking found in patients with chondral lesion
  - High ceiling effects for the domains of limp, instability, support, and locking in patients with meniscus injuries
  - High ceiling effects and small-moderate effects sizes for the domains of support and locking in patients with anterior cruciate ligament reconstructions
- ADLS Scale of the Knee Outcome Survey
  - Seven symptoms and 10 functions rated
  - Acceptable psychometric properties for a variety of knee disorders
  - Ceiling effects possible in athletes

TABLE 43-3 Lysholm Knee Scoring Scale

Factor	Scale	Points
Limp	None	5
	Slight or periodic	3
	Severe and constant	0
Support	None	5
	Stick or crutch	2
	Weight-bearing impossible	0
Locking	No locking/catching sensations	15
	Catching sensation but no locking	10
	Locking: occasionally	6
	Locking: frequently	2
	Locked joint on examination	0
Instability	Never giving-way	25
	Rarely during athletics or other severe exertion	20
	Frequently during athletics or other severe exertion (or incapable of participation)	15
	Occasionally in daily activities	10
	Often in daily activities	5
	Every step	0
Pain	None	25
	Inconstant and slight during severe exertion	20
	Marked during severe exertion	15
	Marked on or after walking > 2 km	10
	Marked on or after walking < 2 km	5
	Constant	0
Swelling	None	10
	On severe exertion	6
	On ordinary exertion	2
	Constant	0
Stair-climbing	No problems	10
	Slightly impaired	6
	One step at a time	2
	Impossible	0
Squatting	No problems	5
	Slightly impaired	4
	Not beyond 90 degrees	2
	Impossible	0

The symptoms of pain, swelling, and instability are graded according to the activity in which they occur. For example, for the factor of instability, patients may receive 15 of a possible 25 points if they experience instability frequently during athletics or heavy exertion (or are unable to do these activities). Independent studies have demonstrated that the Lysholm system, "may inflate results, particularly if raw scores are combined to obtain an overall final rating"[38] and is "less sensitive for ACL patients…than three other diagnostic categories."[4] Risberg and colleagues[30] found poor sensitivity in detecting changes over time (responsiveness), and concluded that, "The Lysholm score was not sensitive to detect changes over time, and therefore it is not recommended as an outcome measurement after ACL reconstruction."[30]

Other authors have reported adequate reliability and responsiveness of this scale when tested in combined samples of patients with a variety of knee disorders including ligament and meniscus injuries, patellofemoral pain, and degenerative joint disease. Irrgang and coworkers[17] assessed internal consistency, criterion validity, and responsiveness of the Lysholm scale in a group of 397 patients who had a wide variety of knee disorders. Data collected at baseline and then 1, 4, and 8 weeks later were compared with those obtained with the authors' ADL Scale. The Lysholm scale demonstrated adequate criterion validity with the ADL scale (Pearson product-moment correlation coefficients ranged from $R = 0.78$ at baseline to $R = 0.86$ at 8 weeks after baseline) and with the patients' global rating of the overall knee condition. Large ES (> 0.80), indicating adequate responsiveness, were noted at 4 and 8 weeks after baseline testing. Internal consistency of the Lysholm scale was lower than that of the ADL scale, resulting in higher standard error of measurement for all time periods of data collection.

Marx and associates[23] determined reliability, validity, and responsiveness of the Lysholm scale along with the subjective components of the CKRS, the American Academy of Orthopaedic Surgeons (AAOS) sports knee-rating scale, and the ADL scale in a population of patients with a wide variety of knee disorders. All of the scales demonstrated high reliability (ICCs > 0.80), adequate face and content validity, and responsiveness (SRM > 0.80).

Paxton and associates[28] measured the reliability and validity of the Lysholm score in 153 patients followed 2 to 5 years after an acute patellar dislocation. The score demonstrated adequate reliability (ICC, 0.88), content validity, and construct validity. Kocher and colleagues[19] assessed the Lysholm scale in a population of 1657 patients with traumatic and degenerative chondral lesions. Adequate reliability was found for the overall score and all individual components of the scale except for pain and stair climbing. Adequate content validity was found for the overall score. However, unacceptably high ceiling effects were found for the domains of limp, instability, support, and locking and a high floor effect was found for the domain of squatting. Criterion validity was acceptable, with significant correlations between the overall score and SF-12 and the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scales. Construct validity was proven in the nine hypotheses generated by the investigators. Adequate responsiveness was found for the overall score and all of the individual components except for instability.

Briggs and coworkers[6] determined the reliability, validity, and responsiveness of the Lysholm scale in patients with meniscus injuries. Adequate reliability was reported for the overall score and all individual components except locking. Acceptable content validity was found for the overall score. However, high ceiling effects were reported for the domains of limp, instability, support, and locking and a high floor effect was found for the domain of squatting. Criterion validity was adequate, as the scale correlated with the physical component score of the SF-12. Acceptable construct validity was proven, with all eight hypotheses developed by the authors' found to be significant. The overall score had adequate responsiveness, with large ES and SRM. However, the individual domains of instability, locking, limping, support, and swelling had only small to moderate ES and SRM.

Briggs and colleagues[7] found that the Lysholm score had adequate reliability (ICC, 0.9), internal consistency, criterion validity, construct validity, and responsiveness in 1783 patients with ACL tears, 1071 of whom underwent reconstruction. High ceiling effects were found for the domains of support and locking. The domains of locking and support had small to moderate ES.

Ebert and associates[10] reported that the Lysholm score had high ES (1.22) and SRM (1.11) in a group of 81 patients analyzed before and 5 years after autologous chondrocyte implantation. However, there was no strong evidence that a change in the Lysholm was associated with patient satisfaction of the outcome of the operation.

Table 43-4 Activities of Daily Living Scale of the Knee Outcome Survey

Domain	Factors	Possible Responses	Points
Symptoms	1. Pain	I never have (factor) in my knee.	5
	2. Grinding/grating	I have (factor) in my knee, but it does not affect my daily activity.	4
	3. Stiffness	(Factor) affects activity slightly.	3
	4. Swelling	(Factor) affects activity moderately.	2
	5. Slipping	(Factor) affects activity severely.	1
	6. Buckling	(Factor) prevents from performing all daily activities.	0
	7. Lack of strength		
Functional Disability	8. Walk	My knee does not affect my ability to walk.	5
		I have pain in my knee when walking, but it does not affect my ability to walk.	4
		My knee prevents me from walking more than 1 mile.	3
		My knee prevents me from walking more than 1/2 mile.	2
		My knee prevents me from walking more than 1 block.	1
		My knee prevents me from walking.	0
	9. Walk with crutches or cane?	I can walk without crutches or a cane.	3
		My knee causes me to walk with 1 crutch or a cane.	2
		My knee causes me to walk with 2 crutches.	1
		Because of my knee, I cannot walk even with crutches.	0
	10. Limp while walking	I can walk without a limp.	2
		Sometimes my knee causes me to walk with a limp.	1
		Because of my knee, I cannot walk without a limp.	0
	11. Go up stairs	My knee does not affect my ability to go up stairs.	5
		I have pain in my knee when going up stairs, but it does not limit my ability to go up stairs.	4
		I am able to go up stairs normally, but I need to rely on use of a railing.	3
		I am able to go up stairs one step at a time with use of a railing.	2
		I have to use crutches or a cane to go up stairs.	1
		I cannot go up stairs.	0
	12. Go down stairs	My knee does not affect my ability to go down stairs.	5
		I have pain in my knee when going down stairs, but it does not limit my ability to go down stairs.	4
		I am able to go down stairs normally, but I need to rely on use of a railing.	3
		I am able to go down stairs one step at time with use of a railing.	2
		I have to use crutches or a cane to go down stairs.	1
		I cannot go down stairs.	0

From Irrgang JJ, Snyder-Mackler L, Wainner RS, Fu FH, Harner CD. Development of a patient-reported measure of function of the knee. *J Bone Joint Surg Am.* 1998;80: 1132-1145.

Instructions: The questionnaire is designed to determine the symptoms and limitations that you experience because of your knee while you perform your usual daily activities. Please answer each question by checking the statement that best describes you over the last 1 to 2 days. For a given question, more than one of the statements may describe you, but please mark ONLY the statement that best describes you during your usual daily activities.

Activities of Daily Living Scale of the Knee Outcome Survey

Irrgang and coworkers[17] developed the ADL Scale (Table 43-4) to measure limitations in patients with a variety of knee disorders including ligament ruptures, patellofemoral pain, meniscus tears, and articular cartilage damage. The scale rates seven symptoms and 10 functions. The responses to all 17 factors in the scale are summed up, divided by 80 (the total number of possible points), and multiplied by 100 to produce a final score that is expressed as a percentage. These investigators administered the scale to 397 patients at four treatment intervals (over an 8-week period) to determine its internal consistency, validity, and responsiveness. A subset of 52 patients completed the scale before and after one treatment session for reliability testing. The authors reported acceptable results for all psychometric properties. Because the reliability testing was accomplished during one treatment setting, the authors concluded that further analysis of this factor is required. In addition, ceiling effects may occur in athletes or patients involved with strenuous work activities.

Piva and associates[29] tested the responsiveness of the ADL scale in 60 patients with patellofemoral pain by administering the scale before and after 8 weeks of physical therapy. These authors reported a moderate ES (0.63). An increase of at least 7.1 percentage points was determined to represent clinically meaningful improvements in physical function. Williams and colleagues[46] compared the reliability and responsiveness of the ADL scale with the WOMAC and the Lower Extremity Functional Scale (LEFS) in patients with knee osteoarthritis. All three instruments had adequate reliability (ICCs ranged from 0.75 to 0.93). There were no differences in internal or external responsiveness, which tended to decrease over time. The authors concluded that all three outcome measures have similar psychometric properties in this particular patient population.

GLOBAL OUTCOME INSTRUMENTS

Western Ontario and McMaster Universities Osteoarthritis Index

In 1988, Bellamy and coworkers[3] first published the WOMAC, a 24-item, condition-specific questionnaire to be used for hip and knee osteoarthritis. Since its conception, the WOMAC has undergone several revisions and modifications, with the latest version (WOMAC 3.1) available in over 90 languages. The instrument is available in 5-point Likert, 100-mm visual analogue scale (VAS) and 11-box numerical rating scale formats by submitting a request to www.womac.org. It is one of the most widely used instruments in patients with knee or hip osteoarthritis and has proven psychometric properties.[13,20,31]

The WOMAC consists of three subscales: pain (five questions), stiffness (two questions), and physical function (17 questions). The subscale scores can vary, with pain ranging from 0 to 20 points; stiffness, 0 to 8 points; and physical function, 0 to 68 points. Higher scores represent worse pain, stiffness, and functional limitations. These investigators reported adequate face, content, and construct validity as well as responsiveness in patients with hip or knee osteoarthritis.

As described previously, Williams and colleagues[46] compared the reliability and responsiveness of the WOMAC with the ADL scale and the LEFS in patients with knee osteoarthritis. All three instruments had adequate reliability (ICCs ranged from 0.75 to 0.93). There were no differences in internal or external responsiveness. These three outcome measures had similar psychometric properties in this patient population.

Whitehouse and associates[45] introduced a reduced WOMAC function scale and reported acceptable reliability, convergent validity, and responsiveness in patients who underwent total joint arthroplasty. This scale retained the original pain and stiffness questions, but eliminated seven items from the physical function subscale. In a second study, Whitehouse and colleagues[44] found acceptable criterion validity and reliability in a similar group of patients.

Knee Injury and Osteoarthritis Outcome Score

Roos and coworkers[33] developed the Knee Injury and Osteoarthritis Outcome Score (KOOS) instrument to assess symptoms and functional limitations with activity for patients with a variety of knee problems. KOOS is composed of five subscales:

1. Pain (9 questions)
2. Symptoms (7 questions)
3. ADL Function (17 questions)
4. Sport/Recreation Function (5 questions)
5. Knee-related Quality of Life (4 questions)

The ADL questions are composed of the original 17 WOMAC Osteoarthritis Index Physical Function questions. Therefore, the score of the KOOS ADL dimension is equal to that of the WOMAC Osteoarthritis Index. The KOOS questionnaire, available at www.koos.nu, has been translated into many languages. Also available on the website are a user's guide, scoring instructions, and a scoring worksheet.

All questions are answered on a five-level frequency or severity gradient in which terms such as "none," "mild," "moderate," "severe," "extreme" or "always," "often," "sometimes," "rarely," and "never" are provided. Two questions assess frequency of pain and are answered as either "never," "monthly," "weekly," "daily," or "always."

In the first investigation on the psychometric properties of the KOOS in knees with ACL injury, meniscus injury, or posttraumatic osteoarthritis, Roos and associates [33] reported adequate reliability for all five subscales (ICC ≥0.75). Construct validity tested against the SF-36 subscales showed varying correlation coefficients. Responsiveness of the five subscales 6 months postoperatively was acceptable because all ES were 0.84 or greater. Later studies by Roos and associates[34] provided evidence of satisfactory reliability, validity, and responsiveness of the KOOS for patients who had total knee replacement, meniscectomy, or posttraumatic osteoarthritis.[32,34] Salavati and coworkers[35] found this instrument had adequate reliability, construct validity, and internal consistency after ACL reconstruction in a group of 57 athletes. Acceptable psychometric properties were also reported in a group of 40 patients after autologous chondrocyte implantation or microfracture.[2] Ebert and associates[10] found the KOOS subscales of sport/recreation and quality of life were the most responsive patient-reported outcome scales when compared with the Lysholm score, the Tegner scale, and the SF-36. These KOOS subscales also were the most predictive of patient satisfaction following autologous chondrocyte implantation. According to the KOOS User's Guide, August 2012, the questionnaire has been assessed in more than 20 studies worldwide.

The questionnaire format does not provide an analysis of the activity level in which symptoms occur, other than daily activities. Although the scales assess certain sports functions, an activity rating for athletics is not provided, and therefore, it is unknown what activities patients are actually participating in or whether a change in activity level occurred between evaluations. Ambiguous terminology to define gradient levels can be problematic because patients may interpret terms

CRITICAL POINTS Global Outcome Instruments

- WOMAC
  - 24-item, condition-specific questionnaire available in 5-point Likert, 100 mm VAS, and 11-box numerical rating scale formats.
  - Three subscales: pain (5 questions), stiffness (2 questions), and physical function (17 questions).
  - Acceptable psychometric properties for variety of knee injuries and disorders.
- Knee Injury and Osteoarthritis Outcome Score (KOOS)
  - Five subscales: pain (9 questions), symptoms (7 questions), activities of daily living (17 questions), sport/recreation (5 questions), knee-related quality of life (4 questions).
  - Acceptable psychometric properties for anterior cruciate ligament (ACL) injury and reconstruction, meniscus injury, posttraumatic osteoarthritis, total knee arthroplasty, autologous chondrocyte implantation.
  - Does not provide an analysis of the activity level in which symptoms occur, other than daily activities.
  - Activity rating for athletics is not provided.
- Lower Extremity Functional Scale
  - 20-item self-report measure
  - Acceptable psychometric properties for variety of knee injuries and disorders
- American Academy of Orthopaedic Surgeons Lower Limb Outcomes Questionnaire
  - Global instrument that combines seven items into three subscales: pain attributed to the lower limb, stiffness and swelling, and function.
  - Adequate construct validity, reliability, and responsiveness not tested.
- VAS for Quality of Life and Subjective Knee Symptoms
  - Mohtadi quality of life: 31 questions for ACL-deficient knees. Limited testing done of psychometric properties.
  - Subjective knee score: 28 questions for a variety of knee disorders. Limited testing done of psychometric properties.
  - Multiple problems with VAS questionnaires; not recommended.

such as "moderate," "severe," and "extreme" differently. Some may assign a grade according to the frequency of the problem, others may assign a grade according to the intensity of the problem, and still others may use a combination of frequency and intensity to assign a rating.

Lower Extremity Functional Scale

The LEFS was introduced by Binkley and coworkers[5] in an effort to provide a condition-specific measure that would be easy to administer and score and apply to a wide range of lower-extremity orthopedic conditions. It is a 20-item self-report measure in which each item is scored on a five-point gradient: 0, extreme difficulty or unable to perform activity; 1, quite a bit of difficulty; 2, moderate difficulty; 3, a little bit of difficulty; and 4, no difficulty. The total score may vary from 0 to 80 points, with higher scores indicating better levels of lower extremity function. The authors reported the scale had acceptable reliability and construct validity and had superior responsiveness than the SF-36 in a group of patients with a variety of lower-extremity injuries or disorders. Stratford and associates[39] found no difference in scores between the LEFS and WOMAC physical function subscale in patients who underwent total joint arthroplasty. Watson and colleagues[43] reported high reliability and responsiveness of this scale in patients with anterior knee pain treated with physical therapy. Yeung and associates[47] also reported adequate reliability, construct validity, and responsiveness of the LEFS in a sample of orthopedic inpatients treated for a variety of knee injuries and disorders. As described previously, Williams and colleagues[46] compared the reliability and responsiveness of the LEFS with the ADL scale and WOMAC in patients with knee osteoarthritis. All three instruments had adequate reliability (ICCs ranged from 0.75 to 0.93) and the conclusion was reached that all have similar psychometric properties in this cohort.

American Academy of Orthopaedic Surgeons Lower Limb Outcomes Questionnaire

The AAOS developed a Lower Limb Core Scale (now called the Lower Limb Outcomes Questionnaire), a global instrument that combines seven items into three subscales.[18] The subscales include pain attributed to the lower limb, stiffness and swelling, and function. The Lower Limb Outcomes Questionnaire, scoring algorithms, and description of normative data are available on the website of the AAOS (www.aaos.org).

Johanson and associates[18] administered this questionnaire to patients with ligament or meniscus injury or patellofemoral disorders. These investigators reported good construct validity, with adequate correlation coefficients of this scale to other instruments such as the SF-36 and the WOMAC. However, there were limitations to this study. Reliability was not assessed with ICC but rather with correlation coefficients that the authors expressed was a potential limitation. Responsiveness was not determined in a large sample size, and floor and ceiling effects were not calculated.

Visual Analogue Scales for Quality of Life and Subjective Knee Symptoms

Mohtadi devised a quality of life outcome instrument for ACL-deficient knees.[25] The questionnaire is composed of 31 questions in a VAS format and sorted into five domains. There are five items in the area of symptoms and physical complaints, four items in the area of work, 12 items in the area of sports, six items in the area of lifestyle, and five items in the area of social and emotion.

The instrument was tested for reliability and responsiveness in 25 patients with chronic ACL-deficient knees. Responsiveness was tested in 25 patients who completed the questionnaire 6 months apart and included patients with ACL-deficient or reconstructed knees. The author reported that the scale had adequate reliability using a paired *t* test (instead of ICC) and adequate responsiveness, although ES statistics were not provided. Face and construct validity was assessed in 50 patients with satisfactory results. Other validity measures such as content (floor and ceiling effects), criterion, and item-discriminant were not assessed.

A subjective knee score comprising 28 questions in a VAS format was originally described by Flandry and colleagues[11] and later by Hoher and coworkers.[16] The questionnaire combines symptoms and athletic and daily activity functions into one overall score. The instrument is weighted to an assessment of ADL because 12 questions (43%) refer to ADLs, but only 5 (18%) assess sports activities. The questionnaire's reliability was measured in 25 volunteers with normal knees and in 21 patients with a variety of knee disorders. The correlation coefficients of the score were 0.86 in the volunteers and 0.92 in the patients. Although the score was able to detect a significant difference between normal and injured subjects, only a highly competitive athlete could score the maximum of 100 points. Construct validity, tested against the Lysholm score and an older version of the CKRS,[27] showed adequate correlation coefficients. Other validity analysis were not conducted. Responsiveness effect size data were not provided.

There are problems with these global VAS questionnaires. VAS formats do not allow for an analysis of symptoms or functional limitations according to activity level. Therefore results of studies from different clinicians cannot be accurately compared with the knowledge of the percent of patients who have symptoms with strenuous, moderate, light sports activities or with ADL. Because these instruments combine a variety of factors including symptoms, work, athletics, social, and emotional issues into one final score, there is no effective manner to address these items separately. Mohtadi's final score[25] is weighted for sports, which is problematic for patients who do not return to sports for reasons not related to the knee condition. On the other hand, Hoher and coworker's[16] final score is weighted for ADLs and thereby loses sensitivity in defining functional limitations in athletic populations.

The VAS format does not allow for the detection of knee abusers, which can positively bias the final results and conclusions of the effectiveness of a specific treatment. These scales do not produce a measurable sports activity level according to frequency of participation and stress incurred to the lower extremity or allow the detection of a change in activity levels from one time period to another. In addition, overall patient satisfaction and perception of the knee condition are not addressed. These studies did not measure reliability, validity, or responsiveness of either the individual questions or domains.

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Articular Cartilage Rating Systems

Sue D. Barber-Westin, Frank R. Noyes

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INTRODUCTION

Many grading systems have been proposed to classify lesions of the articular cartilage in the knee joint at arthroscopy; however, only a few are commonly used in modern orthopedic literature (Table 44-1). The systems published in the 1960s and 1970s introduced grading schemes for lesions located only in the patellofemoral joint and documented the most frequent locations of damage in this compartment.[9,10,12,23] The first of these patellofemoral classification systems, proposed by Outerbridge,[23] remains one of the most commonly used schemes to grade lesions located in all three compartments of the knee (patellofemoral, medial tibiofemoral, and lateral tibiofemoral).[7] As arthroscopic and imaging techniques have evolved, a few investigators[11,22] and societies (French Society of Arthroscopy,[8] International Cartilage Repair Society [ICRS][3,4]) have proposed articular cartilage rating systems which are far greater in sophistication in classifying lesions (described later). These systems are useful for formal clinical investigations to determine the etiology and prognosis of partial and full-thickness cartilage injuries after various knee injuries[15] and to determine the indications and outcomes of cartilage resurfacing procedures such as mosaicplasty and autologous chondrocyte implantation (ACI).[5] This is especially true when practical and financial constraints limit or prohibit the use of advanced magnetic resonance imaging (MRI) or objective measurements done at surgery. These techniques are not discussed in this chapter, although we recognize their significance in this area.[24,28] This chapter focuses on the most commonly used arthroscopic articular cartilage rating systems today.

COMMONLY USED ARTICULAR CARTILAGE RATING SYSTEMS

Outerbridge

In 1961, Outerbridge[23] introduced a system for grading articular cartilage lesions in the patellofemoral joint. The four-gradient scale was based on the appearance of the cartilage and, in two of the levels, the size of the lesion. A *grade 1 lesion* was defined as softening and swelling of the cartilage. A *grade 2 lesion* involved fissuring and fragmentation in an area less than ½ inch in diameter. A *grade 3 lesion* involved fissuring and fragmentation in an area greater than ½ inch in diameter. In a *grade 4 lesion,* the cartilage was eroded down to subchondral bone. This rating system did not specify the location, depth, or exact size of the lesion.

Cincinnati Knee Rating System

In 1989, Noyes and Stabler[22] proposed an arthroscopic articular cartilage classification system that included four variables: the appearance of the cartilage, the depth of the lesion, the size (diameter) of the lesion, and the location of the lesion. A point scaling system was devised for research purposes to facilitate statistical analysis (Table 44-2).

The appearance of the cartilage is classified into one of three grades: *grade 1*, cartilage surface intact, closed lesion; *grade 2*, cartilage surface damaged, open lesion; or *grade 3*, subchondral bone exposed. Each grade is divided into subtypes *A* or *B*, depending upon the depth of involvement.

Grade 1A corresponds to a moderate degree of softening of the cartilage compared with its normal resilient appearance (Fig. 44-1, *A*). *Grade 1B* designates complete loss of resilience, resulting in full indentation of the surface when probed (see Fig. 44-1, *B*). This grade is reserved for lesions in which a severe softening of the cartilage exists without gross surface breakage. This description indicates the initial stage of cartilage deterioration characterized by diminished glycoproteins and early collagen fiber deterioration.[22] These lesions, which commonly involve the undersurface of the patella, have a high potential to progress to an open lesion.

A *grade 2A lesion* (Fig. 44-2, *A*) is an open disruption of the cartilage surface, including cracks, surface blisters, fissures, fibrillations, and fragmentations that extend less than one half of the thickness of the cartilage. *Grade 2B lesions* (Fig. 44-2, *B* and *C*) are similar in appearance but extend greater than one half of the thickness of the cartilage. Superficial lesions with fibrillation-type changes are usually easily distinguishable from deeper lesions that involve lacerations, clefts, and fragmentation down to bone. Chondrosclerosis is classified as a grade 2 lesion because the surface is abnormal. Lesions that have two or three deep lacerations that extend through the cartilage surrounded by otherwise normally appearing cartilage are graded as 2B.

TABLE 44-1 Commonly Used Articular Cartilage Rating Systems

Rating System	Surface Description of Articular Cartilage	Lesion Size (Diameter)	Location	Comments
Outerbridge	1 = Softening and swelling 2 = Fragmentation and fissuring 3 = Fragmentation and fissuring 4 = Bone exposed	1 = none 2 = ≤0.5 inch 3 = >0.5 inch 4 = none	Usually starts on medial facet of patella; later extends to lateral facet and then whole patella. Concomitant femoral condylar lesions usually not present; may have occasional "mirror" lesion on intercondylar area; erosion upper border medial femoral condyle.	Rating developed for patellar lesions only. Hypothesized majority initiated by pressure or friction of patella in high knee flexion angles.
Cincinnati Knee Rating System	1 = Cartilage surface intact 1A = Definite softening with some resilience remaining 1B = Extensive softening with loss of resilience (deformation) 2 = Cartilage surface damaged; cracks, surface blisters, fissures, fibrillations, fragmentations 2A = Less than half thickness 2B = Half thickness or greater 3 = Bone exposed 3A = Bone surface intact 3B = Bone surface cavitation	<10 mm, ≤15 mm ≤20 mm ≤25 mm >25 mm	Patella A = Proximal third B = Middle third C = Distal third Trochlea Medial and lateral femoral condyles A = Anterior third B = Middle third C = Posterior third Medial and lateral tibial plateaus A = Anterior third B = Middle third C = Posterior third	Also record degree of knee flexion where the lesion is in weight-bearing contact. Scoring system for lesions provided for research purposes (see Table 44-2).
International Cartilage Repair Society	Four grades for chondral defects, four types for osteochondral defects (see Table 44-5)	Record in mm	Mapping system (see Fig. 44-7) Medial, lateral femoral condyle Trochlea Medial, lateral tibial plateaus Patella Sagittal, frontal plane	Incorporated into IKDC rating system

IKDC, International Knee Documentations Committee.

CRITICAL POINTS Commonly Used Articular Cartilage Rating Systems

Outerbridge

- Four-gradient scale for grading articular cartilage lesions in patellofemoral joint based on the appearance of the cartilage and the size of the lesion

Cincinnati Knee Rating System

- Articular cartilage classification system based on four variables: the appearance of the cartilage, the depth of the lesion, the size (diameter) of the lesion, and the location of the lesion
- Point scaling system for research purposes
- Cartilage classified into one of three grades: grade 1, cartilage surface intact, closed lesion; grade 2, cartilage surface damaged, open lesion; or grade 3, subchondral bone exposed. Each grade is divided into subtypes A or B, depending upon the depth of involvement.

International Cartilage Repair Society

- Classification system of articular cartilage lesions according to the depth of lesion (graded from 0 to 4), the size of the lesion (in millimeters), and the area of damage (documented on a mapping system)
- Mapping system requires validation because it contains 46 zones that have minimal anatomic and functional referencing.

TABLE 44-2 Point Scaling System of the Cincinnati Articular Cartilage Classification System

Articular Cartilage Grade	Articular Cartilage Description	10-mm Lesion (Points)	15-mm Lesion (Points)
1. Closed lesion			
A	Softening	0	0
B	Softening, loss of resilience, indentation when probed	1	2
2. Open lesion			
A	Fissures, fragmentation extending less than half the depth of articular surface	2	4
B	Fissures, fragmentation extending more than half the depth of articular surface	3	6
3. Bone exposed			
A	Normal bony contour	5	10
B	Cavitation or erosion of bone surface	5	10

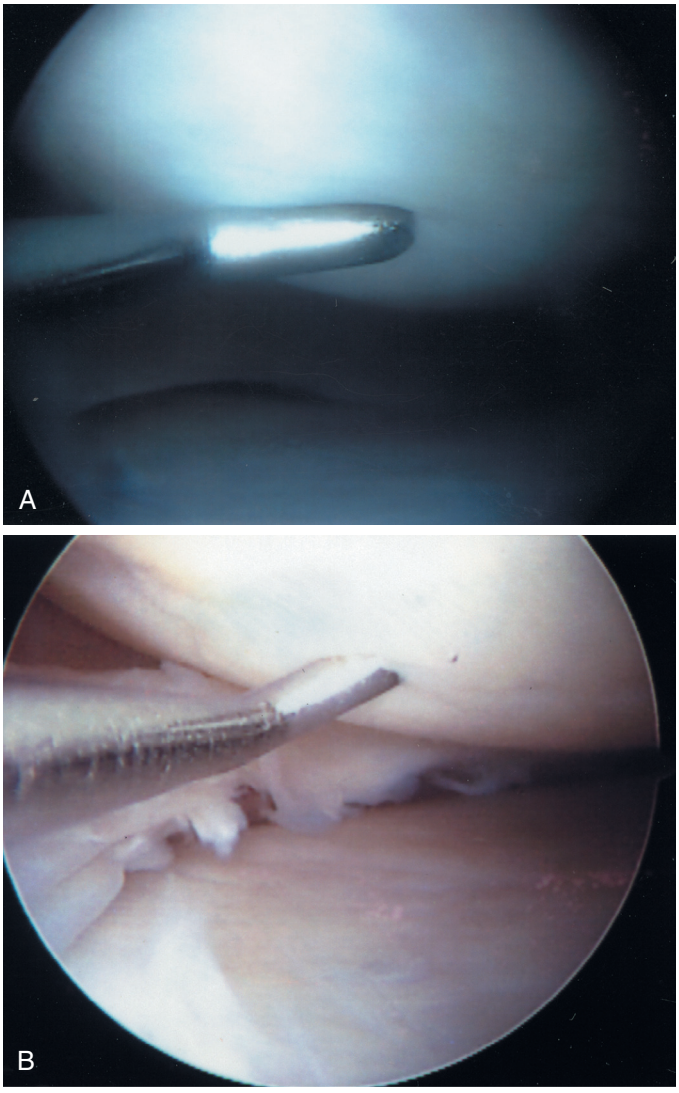


FIG 44-1 A, Arthroscopic image of a grade 1A articular cartilage lesion according to the Cincinnati Articular Cartilage Rating System. **B**, Arthroscopic image of a grade 1B articular cartilage lesion,

A *grade 3A lesion* (Fig. 44-3, *A*) indicates a surface with exposed bone in which the normal bony contour remains. The most severe lesion, *grade 3B* (Fig. 44-3, *B* and *C*), indicates cavitation or erosion of the bone surface. An example of a grade 3B lesion is an osteochondritis dissecans lesion where there is loss of the subchondral bone. Other examples are lesions in which grooving of the bony surface is visualized or those involving fractures that extend through the subchondral bone.

The size of all lesions is determined using a calibrated nerve hook probe. The size is recorded according to one of five categories ranging from less than 10 mm to greater than 25 mm (see Table 44-1). A schematic illustration of all grades is shown in Figure 44-3, *D*.

The anatomic location of the lesion is also recorded. The femoral articular surface is divided into the trochlea and anterior, middle, and posterior thirds of the femoral condyles and tibial condyles. The patella is anatomically classified in two ways: in a proximal-to-distal direction and according to facet (odd, medial, lateral). The range of degrees of knee flexion where patellofemoral and tibiofemoral lesions are in contact is documented. This information is provided to the physical therapist postoperatively so that modifications of exercises may be made to avoid placing forces on the affected area. Any lesion in contact

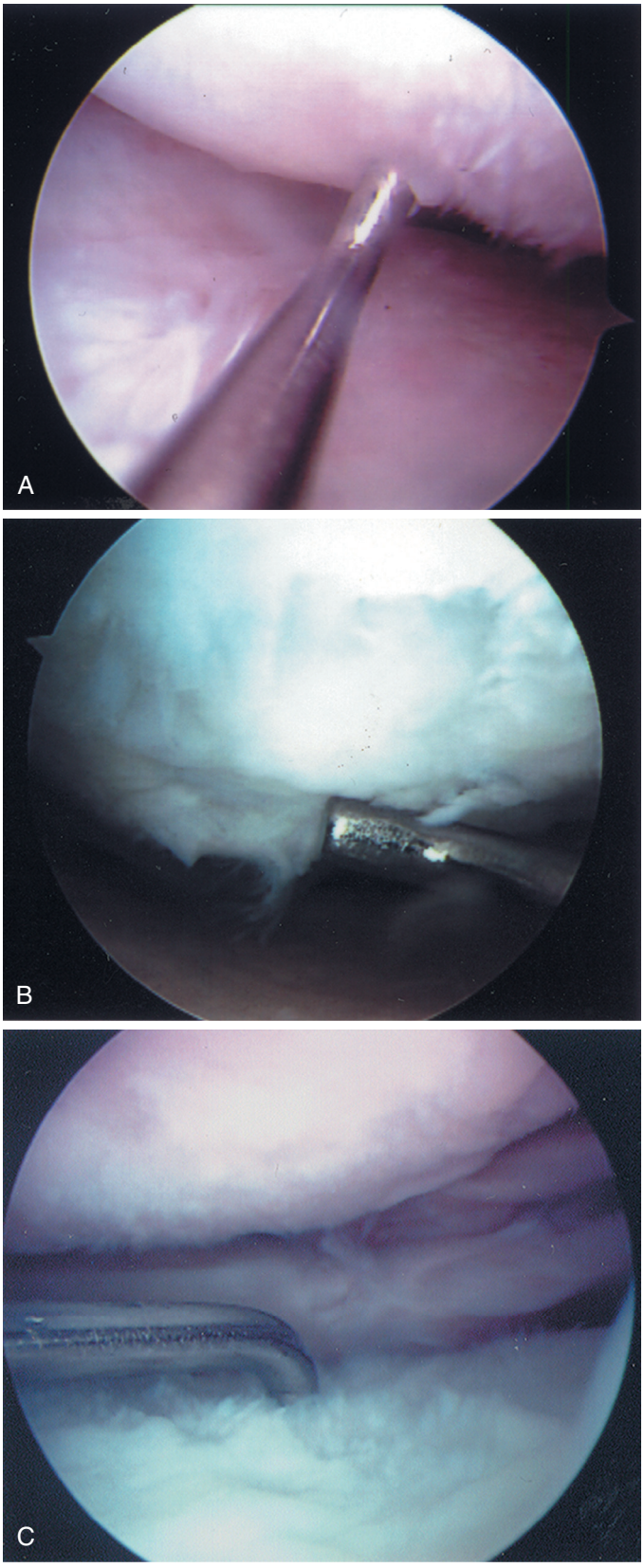


FIG 44-2 A, Arthroscopic image of a grade 2A articular cartilage lesion according to the Cincinnati Articular Cartilage Rating System. **B**, Arthroscopic image of a grade 2B articular cartilage lesion. **C**, A knee with a combined grade 2A lesion on the femoral condyle and a grade 2B lesion on the tibial plateau.

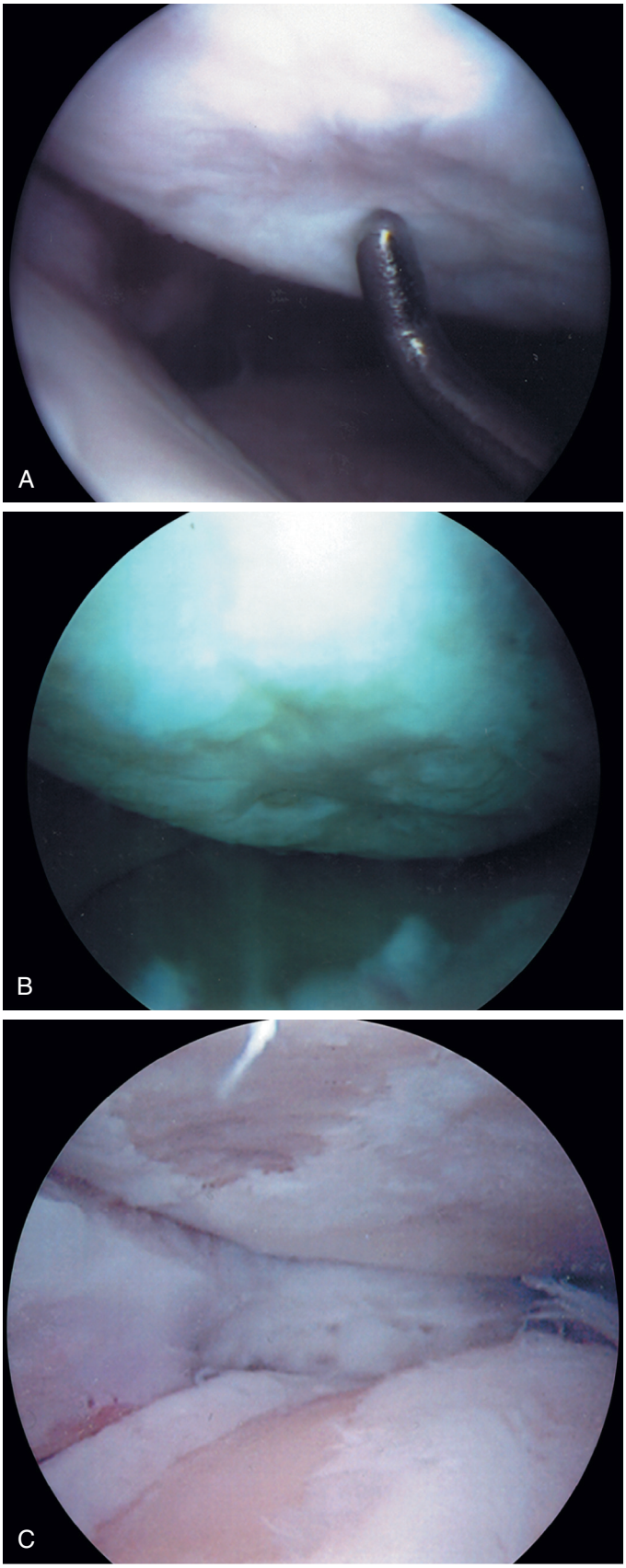
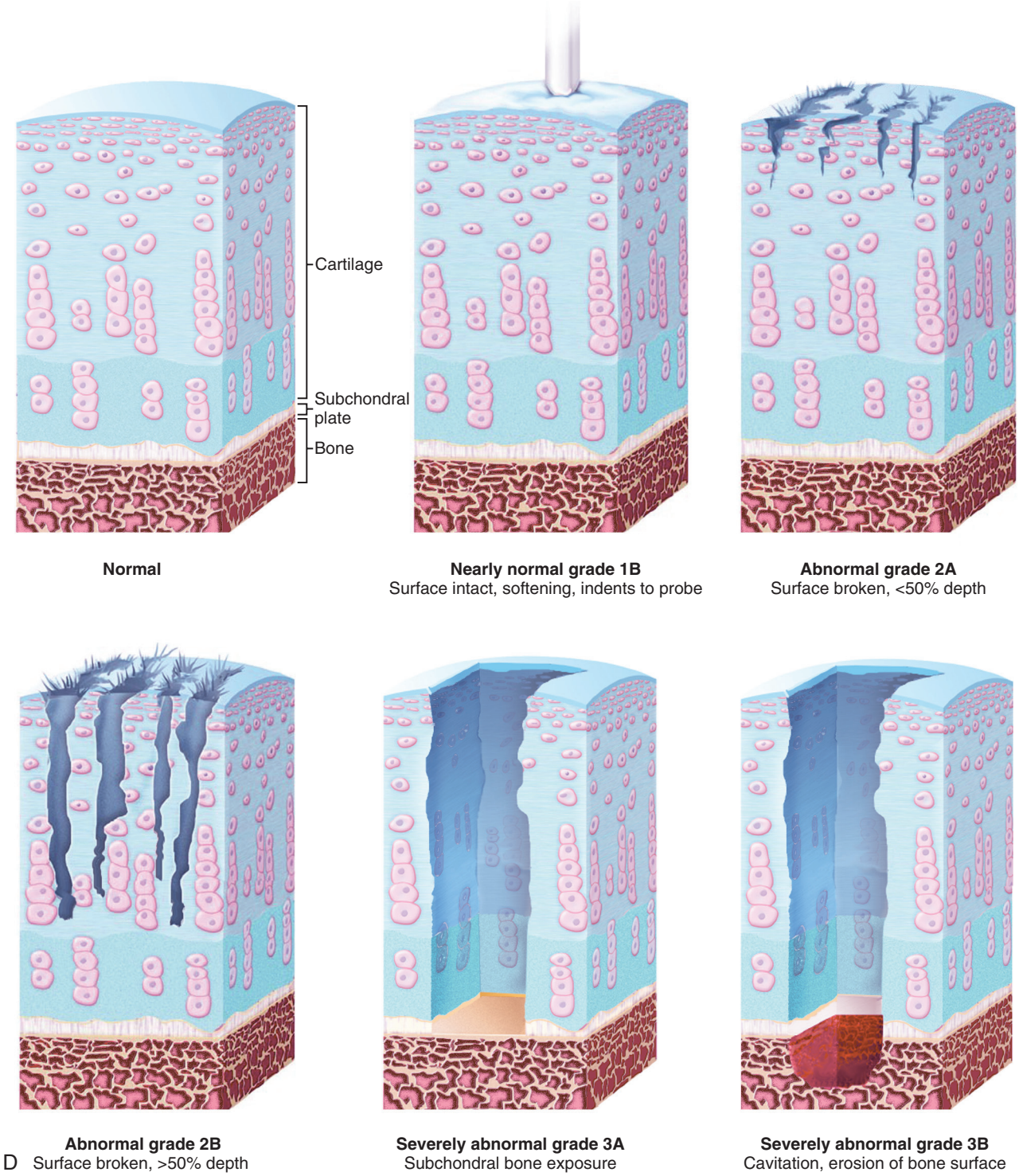


FIG 44-3 **A**, Arthroscopic image of a grade 3A articular cartilage lesion according to the Cincinnati Articular Cartilage Rating System. **B**, Arthroscopic image of a grade 3B articular cartilage lesion. **C**, A grade 3A lesion on both the femoral condyle and tibial plateau in a meniscectomized knee.

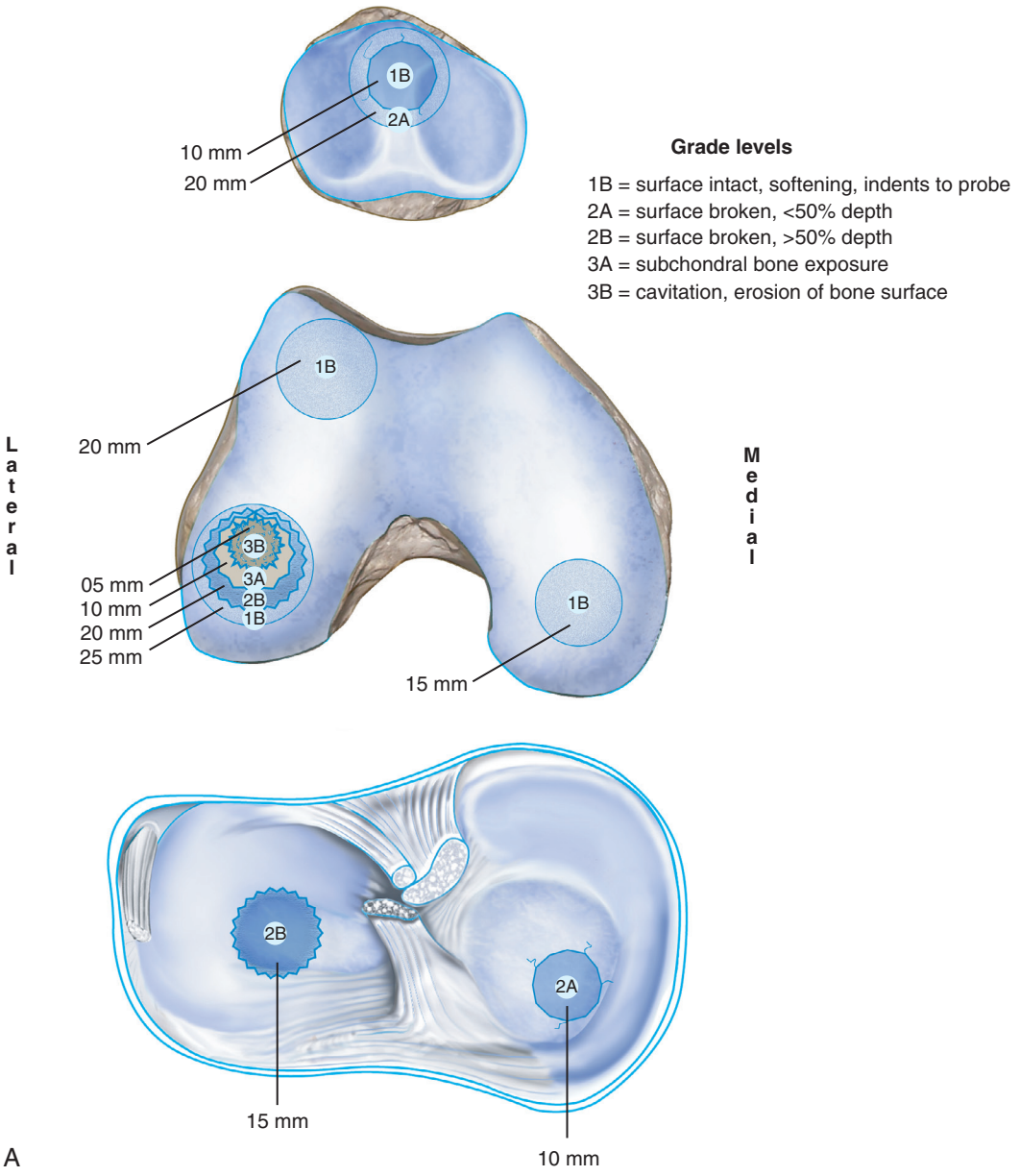


D

FIG 44-3, cont'd **D**, Schematic illustrations of grades according to the Cincinnati Knee Rating System.

from 0 to 45 degrees of flexion may affect normal walking activities and may have more implications than those that contact at greater degrees of knee flexion.

Figure 44-4, *A* illustrates how this classification system is used to record the visual appearance of articular cartilage lesions. The patella has a 10-mm grade 2A lesion that is surrounded by a larger closed area of softening (1B) that extends 20 mm in diameter. The trochlea has a large area of extensive softening as well, graded as a 1B that is 25 mm in diameter. The medial femoral condyle also has a large area of extensive softening, measuring 15 mm in diameter. A "kissing" lesion is found on the medial tibial plateau of a grade 2A lesion that is 10 mm in diameter. The lateral femoral condyle has a complex lesion; 10 mm of exposed bone (3A) is surrounded by an open lesion of fragmentation of 20 mm in diameter (2B), which is in turn surrounded by a closed lesion of soft cartilage that extends to 25 mm (1B). The lateral tibial plateau has a large 2B lesion,



A

Anatomic Location	Anatomic Location Score	Compartment Score	Compartment Percent*
Patella + Femoral sulcus	3 + 2	5	75%
Medial femur + Medial tibia	2 + 2	4	80%
Lateral femur + Lateral tibia	7 + 5	12	40%

B *To calculate percent: $\frac{(20 - \text{Score of compartment})}{20} \times 100$

FIG 44-4 **A**, An example of grading articular cartilage lesions found at arthroscopy. **B**, Scoring system for articular cartilage lesions (see Table 44-2).

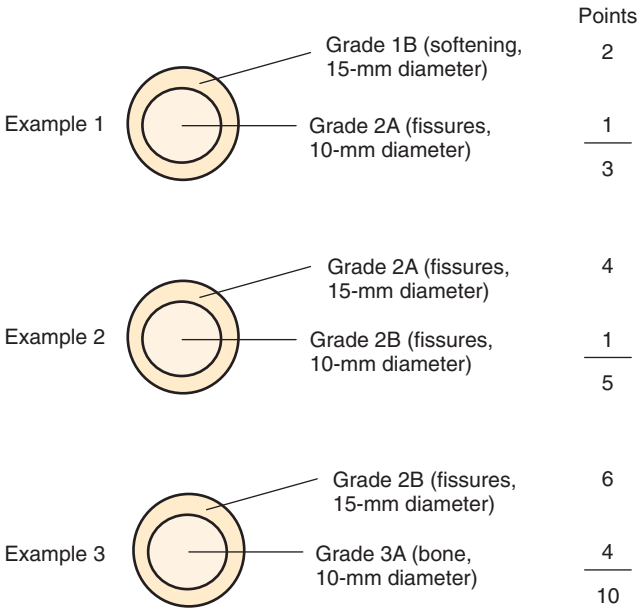


FIG 44-5 Three examples of scoring complex lesions (see Table 44-2 and text).

15 mm in diameter. For research purposes, the lesions may be quantified on a scaling system to allow statistical analysis (see Table 44-2). Any lesion that is less than 10 mm in diameter, or graded 1A, is not considered clinically significant and therefore no points are given. Figure 44-4, *B* illustrates the points awarded for the lesions noted in the example.

Occasionally, complex lesions are encountered such as a 2A circumferential fibrillation surrounding a 10-mm 2B lesion. For scoring purposes, additional points for complex lesions may be incorporated so that the total points to be subtracted are increased but still less than the corresponding 15-mm lesion. Examples for scoring complex lesions are shown in Figure 44-5.

This classification system allows clinical investigations to analyze results according to the condition of the articular cartilage and to determine the difference in outcome among patients with normal cartilage, noteworthy cartilage damage (grade 2B), and severe cartilage damage (grade 3).[18-20] For instance, in a study of 66 patients who had an anterior cruciate ligament (ACL) revision reconstruction,[21] we found that patients with grade 2B or 3A lesions had significantly poorer subjective and functional outcomes a mean of 42 months postoperatively compared with those with normal or grade 1 surfaces (Table 44-3). The factors included pain ($P = .03$), stair climbing ($P = .01$), kneeling ($P = .01$), running ($P = .001$), jumping ($P = .01$), twisting and turning ($P = .01$), and the overall Cincinnati Knee Rating Score (CKRS; $P = .0001$). Analysis of the preoperative data found significant differences among these subgroups as well for giving-way ($P = .004$), walking ($P = .04$), stair climbing ($P = .04$), kneeling ($P = .01$), running ($P = .004$), jumping ($P = .001$), twisting and turning ($P = .01$), and the overall CKRS ($P = .0001$). Differences were also noted in the sports activity levels patients resumed postoperatively (Table 44-4). The stratification of lesions according to the six compartments may be presented as shown in Figure 44-6. These findings allow appropriate patient counseling regarding the expected outcome of the operation according to, among other factors, the condition of the articular cartilage. Larger sample sizes would allow further analysis of the effect of not only the grade of lesions but their location as well.

TABLE 44-3 Effect of the Condition of the Articular Cartilage at the Index Operation on the Subjective Scores and Overall Rating at the Latest Follow-up Examination after Anterior Cruciate Ligament Revision Reconstruction

Cincinnati Knee Rating System	Point Scale	Patients Who Had Normal Articular Cartilage (Mean ± SD)	Patients Who Had Grade 2B or 3A Cartilage Lesions (Mean ± SD)	*P* Value
Pain	0-6	5.9 ± 0.5	4.6 ± 2.1	.03
Swelling	0-6	5.8 ± 0.6	5.2 ± 1.4	NS
Partial giving-way	0-6	5.9 ± 0.4	5.2 ± 1.5	NS
Full giving-way	0-6	6	5.5 ± 1.4	NS
Walking	0-40	38 ± 4	34 ± 8	NS
Stair climbing	0-40	36 ± 5	29 ± 11	.01
Kneeling	0-40	28 ± 14	21 ± 14	.01
Running	40-100	84 ± 18	61 ± 21	.001
Jumping	40-100	78 ± 21	57 ± 22	.01
Twisting, turning	40-100	73 ± 21	55 ± 20	.01
Overall rating	0-100	85 ± 9	71 ± 12	.0001

NS, Not significant; *SD,* standard deviation.

TABLE 44-4 Effect of the Condition of the Articular Cartilage at the Index Operation on the Sports Activity Level at the Latest Follow-up Examination after Anterior Cruciate Ligament Revision Reconstruction

Type of Sports Activity	Patients Who Had Normal Articular Cartilage (*n* = 28)	Patients Who Had Grade 2B or 3A Cartilage Lesions (*n* = 37)
Jumping, pivoting, cutting	8 (29%)	3 (8%)
Running, twisting, turning	7 (25%)	6 (16%)
Swimming, bicycling	9 (32%)	18 (49%)
No sports	4 (14%)	10 (27%)

International Cartilage Repair Society

The ICRS was founded in 1997 to develop a standardized system for the evaluation of articular cartilage injury and repair.[3,4] The ICRS Clinical Cartilage Injury Evaluation System-2000 was developed during a workshop held in 2000. The system consists of the ICRS Cartilage injury questionnaire, the Short Form-36 (SF-36) Health Survey, and the IKDC Subjective Knee Evaluation Form, all completed by the patient. The surgeon completes the ICRS Knee Surgery History Registration, the IKDC Knee Examination Form-2000, the ICRS articular cartilage injury mapping system, the ICRS articular cartilage injury classification, the ICRS osteochondritis dissecans classification (if required), and the ICRS macroscopic cartilage assessment score (if required). All of the forms are available on the society's website at www.cartilage.org/?pid=223.

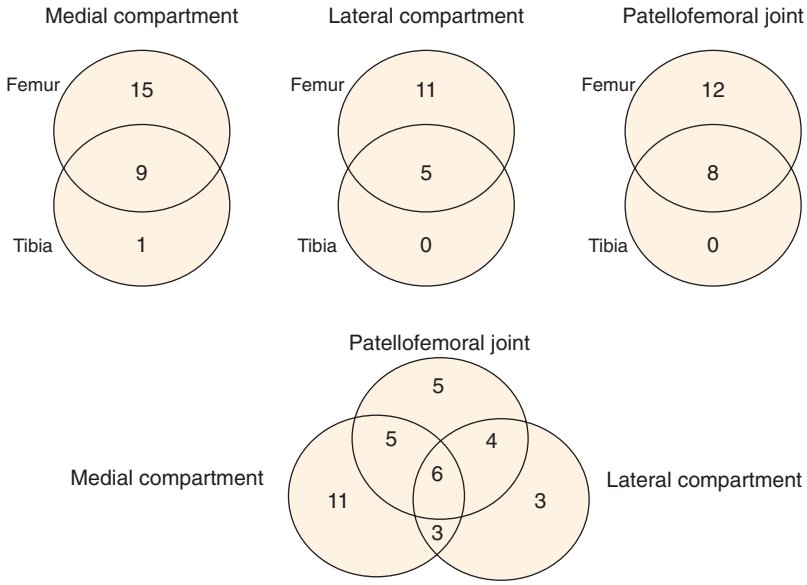


FIG 44-6 Venn diagrams of the number of patients who had an abnormal articular cartilage surface, according to each separate compartment. Thirty-seven patients (56%) had abnormal articular cartilage, defined as fissuring and fragmentation of more than half of the involved surface or any exposure of subchondral bone. (From Noyes FR, Barber-Westin SD, Roberts CS. Use of allografts after failed treatment of rupture of the anterior cruciate ligament. *J Bone Joint Surg Am.* 1994;76-A:1019-31.)

TABLE 44-5 International Cartilage Repair Society Cartilage Defect Description

Grade	Description
Chondral Defects	
Grade 0	Normal
Grade 1	Superficial lesions
Grade 1A	Soft indentation
Grade 1B	Superficial fissures and cracks
Grade 2	Cartilage lesions <50% of cartilage depth
Grade 3	Cartilage lesions >50% of cartilage depth
Grade 3A	Not extending down to calcified cartilage
Grade 3B	Down to calcified cartilage layer
Grade 3C	Down to but not through subchondral bone
Grade 3D	Down to subchondral bone with cartilage blisters
Grade 4	Defects penetrating subchondral bone
Grade 4A	Penetration of subchondral bone in part of the defect
Grade 4B	Subchondral bone penetration involving complete defect
Osteochondral Defects	
Type 1	Stable continuity, softened area covered by intact cartilage
Type 2	Partial discontinuity, stable on probing
Type 3	Complete discontinuity, "dead in situ," not dislocated
Type 4A	Dislocated fragment, loose within the bed or empty defect
Type 4B	Loose and dislocated fragment >10 mm in depth

The ICRS system focuses on the depth of lesions (Table 44-5), the size of the lesion (recorded in millimeters), and the area of damage (documented on a mapping system; Fig. 44-7).[5,17] The ICRS mapping system requires validation because it contains 46 zones that have minimal anatomic and functional referencing.[11] Brittberg and Winalski[5] expressed that "If the total joint involvement can be assessed with percentages and/or with such a scoring system, perhaps with the aid of a computer-based system, the progression or improvement of cartilage disease can be followed."[5]

The ICRS proposed and validated a scoring system for the assessment of cartilage resurfacing procedures such as mosaicplasty, osteochondral autograft transfer, and ACI. The assessment includes consideration of the volume of the defect that is filled with repair tissue, the integration of repair tissue with surrounding articular cartilage, and the macroscopic surface appearance (Table 44-6).[5,26,29] A grading system is incorporated that allows both statistical analysis of the total points obtained (scale, 1-12 points) and placement of patients into International Knee Documentations Committee (IKDC) rating system overall rating categories of normal, nearly normal, abnormal, or severely abnormal.

RELIABILITY AND VALIDATION STUDIES OF CARTILAGE RATING SYSTEMS

Only a select number of reliability and validation studies of various articular cartilage rating systems have been conducted to date.[1,2,6,15,16,25,29] Cameron and colleagues[6] used six cadaveric knees aged 50 to 79 years in their study in which standard arthroscopy was first performed followed by arthrotomy and measurement of lesions using calipers to assign the appropriate Outerbridge grade. Nine orthopedic surgeons reviewed each videotape twice during the same session and graded any lesions viewed. The results demonstrated moderate accuracy (68%) and agreement (kappa score, 0.602) of the observers in correctly grading the lesions from the arthroscopic videotapes compared with the grade assigned during the arthrotomy. The lower grade lesions were diagnosed with less accuracy than the higher grade lesions. The observers tended to grade lesions higher than that assigned during the arthrotomy. The authors concluded that orthopedic surgeons can "accurately grade chondral lesions" with the Outerbridge classification system. The number of years of orthopedic experience did not significantly influence the study findings.

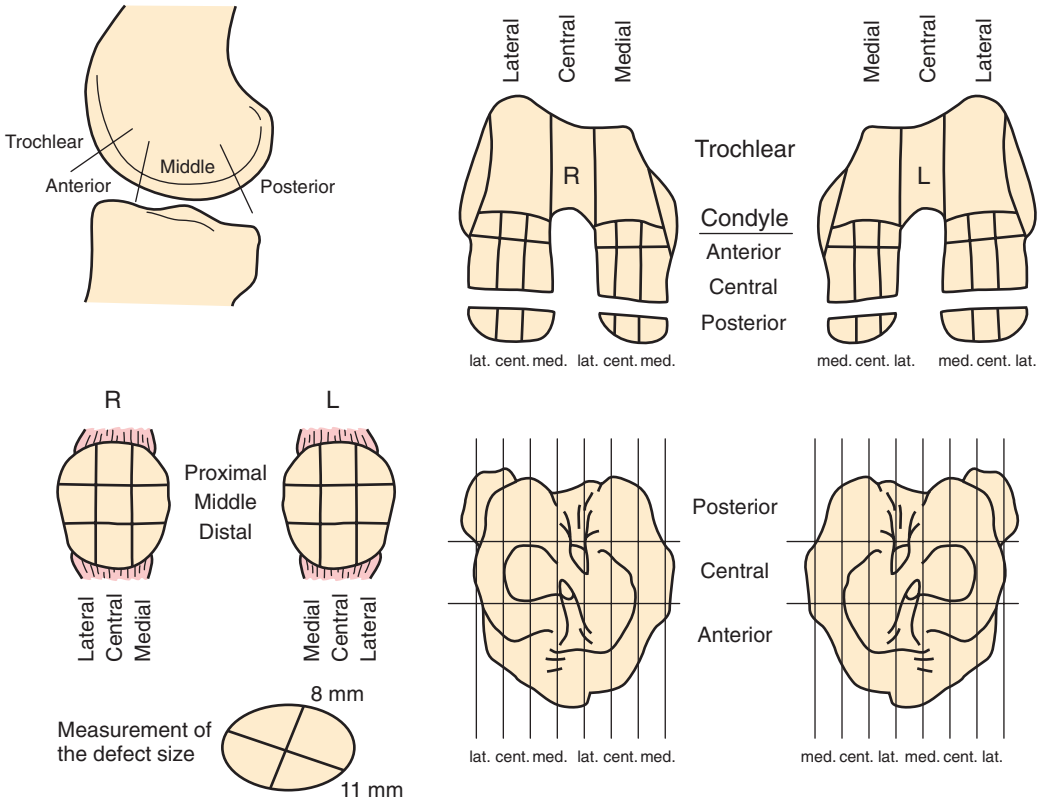


FIG 44-7 International Cartilage Repair Society knee cartilage mapping system. (Courtesy the International Cartilage Repair Society.)

TABLE 44-6 International Cartilage Repair Society Macroscopic Cartilage Assessment Score

Criteria	Findings	Points
1. Degree of defect repair: autologous chondrocyte implantation, periosteal or perichondrial transplantation, subchondral drilling, microfracturing, carbon fiber implants	Level with surrounding cartilage	4
	75% repair of defect depth	3
	50% repair of defect depth	2
	25% repair of defect depth	1
	0% repair of defect depth	0
1. Degree of defect repair: mosaicplasty, osteochondral autograft transfer, osteochondral allograft	100% survival of initially grafted surface	4
	75% survival of initially grafted surface	3
	50% survival of initially grafted surface	2
	25% survival of initially grafted surface	1
	0% survival of initially grafted surface	0
II. Integration	Complete integration with surrounding cartilage	4
	Demarcating border <1 mm	3
	75% integrated, 25% with notable border >1 mm	2
	50% integrated, 50% with notable border >1 mm	1
	0-25% integrated	0
III. Appearance	Intact smooth surface	4
	Fibrillated surface	3
	Small, scattered fissures or cracks	2
	Several, small or few but large fissures	1
	Total degeneration of grafted area	0
Overall Repair Assessment:	**Grade 1 (normal)**	**12 points**
	Grade 2 (nearly normal)	**8-11 points**
	Grade 3 (abnormal)	**4-7 points**
	Grade 4 (severely abnormal)	**1-3 points**

CRITICAL POINTS Reliability and Validation Studies of Cartilage Rating Systems

- Outerbridge classification system: moderate accuracy (68%) and agreement (kappa score, 0.602) of nine observers in correctly grading the lesions from arthroscopic videotapes compared with grades assigned during arthrotomy in cadavers.
- ICRS system: adequate reliability for test-retest data and interrater reliability, satisfactory internal consistency. Tested on articular cartilage repair operations.
- Investigation to determine the relationship between stages of articular cartilage deterioration, as rated macroscopically by the ICRS system, and changes in tissue mechanical properties. Correlation noted between increasing ICRS grade and reduction in stiffness. The relationship between cartilage stiffness and ICRS scoring predicted a 25% loss of stiffness for each ICRS grade.

Marx and coworkers[15] measured the interobserver variability in the grading of articular cartilage lesions using the Outerbridge system as observed on surgical videotapes. Six surgeons provided grades for each articular surface in 53 knees. In the first 31 knees, grades 2 and 3 were combined, whereas in the remaining 22 knees, these grades were not combined. Multirater kappa statistics demonstrated high interrater agreement for all joint surfaces except the medial and lateral tibial plateaus when grades 2 and 3 were combined. However, in the knees in which grades were not combined, only moderate interrater agreement was reported.

Smith and associates[26] tested the validity and reliability of the ICRS system and the previously unpublished Oswestry Arthroscopy Score (OAS), as used to rate repair of articular cartilage after procedures such as osteochondral autograft transfer and ACI. The OAS score showed five macroscopic parameters of graft level with surrounding cartilage, integration with surrounding cartilage, appearance of surface, color of graft, and stiffness on probing to reveal an overall point score from 0 to 10 points. Six orthopedic surgeons viewed five arthroscopic videotapes in patients who had undergone ACI and scored the chondral surfaces according to both rating systems two times, 6 weeks apart. The intraclass correlation coefficient (ICC) demonstrated adequate reliability for the test-retest data (0.94 for both rating systems) and interrater reliability (0.83 for ICRS; 0.76 for OAS). Both systems had satisfactory internal consistency for use in research investigations. The OAS score was slightly superior in terms of content validity because it measured stiffness and provided an indication of hypertrophy of a grafted area, whereas the ICRS score did not measure these parameters and could therefore induce a positively biased score.

van den Born and associates[29] tested the reliability and validity of the ICRS and OAS systems. Seven observers rated a total of 101 images (prints or videos) made during arthroscopy that was performed 12 months after cartilage repair surgery. There were 52 cases of microfracture and 49 cases of ACI. Good reliability was found for the ICRS and OAS systems (ICC, 0.073 and 0.65, respectively), as well as internal consistency. These investigators concluded that their large study demonstrated that both scoring systems may be used as research tools, although the ICRS system scored slightly higher and was the preferred method to determine the result of articular cartilage repair operations.

A study by Spahn and colleagues[27] revealed poor interobserver agreement for the ICRS grade determined by four orthopedic surgeons in 15 patients (60 difference cartilage areas). This study was unique in that all surgeons rated the cartilage appearance during an arthroscopic examination and not from prints or videotapes. Only six (10%) cartilage areas were scored the same by the four surgeons. The authors expressed concern that the real-time subjective grading of cartilage lesions using the ICRS system was unsatisfactory and that more precise objective measurement methods need to be developed. Moderate interrater reliability was observed by Reed and coworkers[25] in both the Outerbridge and ICRS rating systems (kappa scores, 0.54 and 0.41, respectively) in a study involving 96 articular surfaces evaluated by three surgeons.

Kleemann and colleagues[13] conducted an investigation to determine the relationship between various stages of articular cartilage deterioration, as rated macroscopically by the ICRS system (grades 0-4) and changes in tissue mechanical properties. Tibial plateaus were collected in 21 patients who underwent total knee arthroplasty and ICRS grades assigned by three surgeons. The specimens were examined biomechanically and histologically using a modified Mankin scoring system (Table 44-7).[14] The mechanical properties were measured with a custom-made material testing device which determined the Young modulus of the cartilage by unconfined compression. Histologic analysis used haematozylin and eosin staining and Safranin-O staining for the evaluation of the Mankin score. The results showed a correlation between increasing ICRS grade and reduction in stiffness (Young's modulus) ($R^2 = 0.69$, $P < .01$, Fig. 44-8). Progressive thinning of the cartilage was noted in specimens rated ICRS grade 3.

TABLE 44-7 Mankin Histologic and Histochemical Grading System for Evaluation of Articular Cartilage Degeneration

		Grade
I	Structure	
	a. Normal	0
	b. Surface irregularity	1
	c. Pannus and surface irregularity	2
	d. Clefts to transitional zone	3
	e. Clefts to radial zone	4
	f. Clefts to calcified zone	5
	g. Complete disorganization	6
II	Cells	
	a. Normal	0
	b. Diffuse hypercellularity	1
	c. Cloning	2
	d. Hypocellularity	3
III	Safranin-O staining	
	a. Normal	0
	b. Slight reduction	1
	c. Moderate reduction	2
	d. Severe reduction	3
	e. No dye noted	4
IV	Tidemark integrity	
	a. Intact	0
	b. Crossed by blood vessels	1

From Mankin HJ, Dorfman H, Lippiello L, Zarins A. Biochemical and metabolic abnormalities in articular cartilage from osteoarthritic human hips. II. Correlation of morphology with biochemical and metabolic data. *J Bone Joint Surg Am.* 1971;53:523-537.

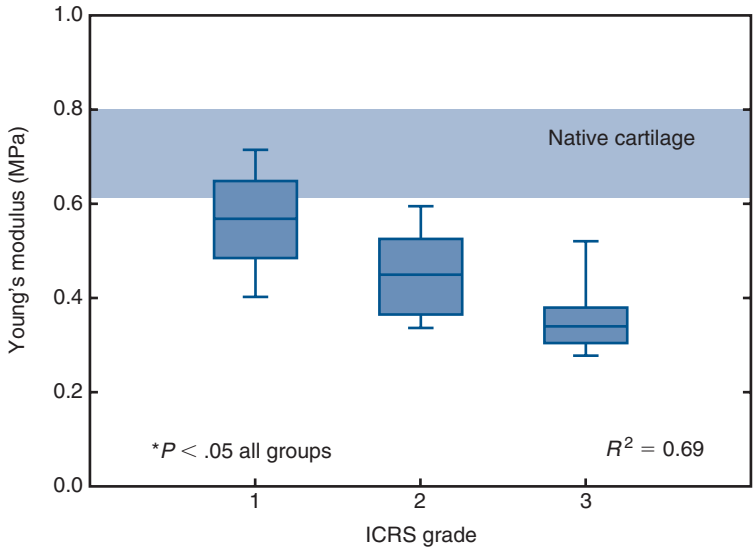


FIG 44-8 Stiffness reduction of degenerated cartilage (increasing International Cartilage Repair Society [ICRS] grade) related to Young's modulus; the band layer represents native human articular cartilage. Boxplots display median values and interquartile range. (From Kleemann RY, Krocker D, Cedraro A, Tuischer J, Duda GN. Altered cartilage mechanics and histology in knee osteoarthritis: relation to clinical assessment (ICRS Grade). *Osteoarthritis Cartilage*. 2005;13:958-963.)

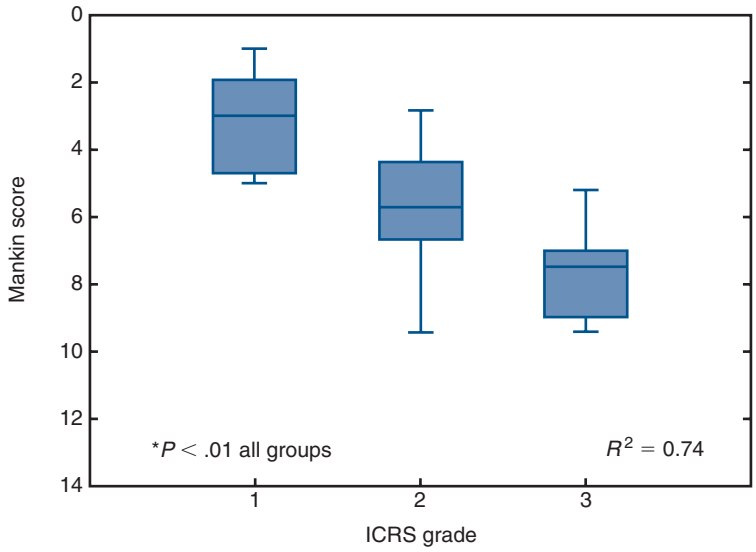


FIG 44-9 Stiffness reduction in degenerated cartilage (increasing International Cartilage Repair Society [ICRS] grade) related to histologic appearance (Mankin score). (From Kleemann RY, Krocker D, Cedraro A, Tuischer J, Duda GN. Altered cartilage mechanics and histology in knee osteoarthritis: relation to clinical assessment (ICRS Grade). *Osteoarthritis Cartilage*. 2005;13:958-963.)

Histologic analysis showed a significant correlation between Mankin scores and ICRS grades ($R^2 = 0.74$, $P < .01$, Figs. 44-9 and 44-10). Higher Mankin scores were obtained with increasing ICRS grades. The mean Mankin scores according to ICRS grades were 3.2 ± 1.5 points for grade 1, 5.7 ± 2.0 points for grade 2, and 7.6 ± 1.7 points for grade 3. A moderate correlation was found between the Mankin score and the Young modulus ($R^2 = 0.47$, $P < .02$). The authors reported that early stage of degenerative joint disease, ICRS grade 1, was very difficult to detect because of the "inconspicuous changes of the surface appearance between ICRS Grade 1 and native cartilage." The investigation found that the relationship between cartilage stiffness and ICRS scoring predicted a 25% loss of stiffness for each ICRS grade. The macroscopic or visual surface cartilage appearance gave an impression of the mechanical behavior of the tissue and was considered a reliable method for classifying degenerated articular cartilage.

A survey of orthopaedic surgeons in Germany was performed (in approximately 2007 to 2008) to determine which grading systems were preferred and the perception of the arthroscopists of the usefulness of these systems.[28] The Outerbridge classification system was by far the

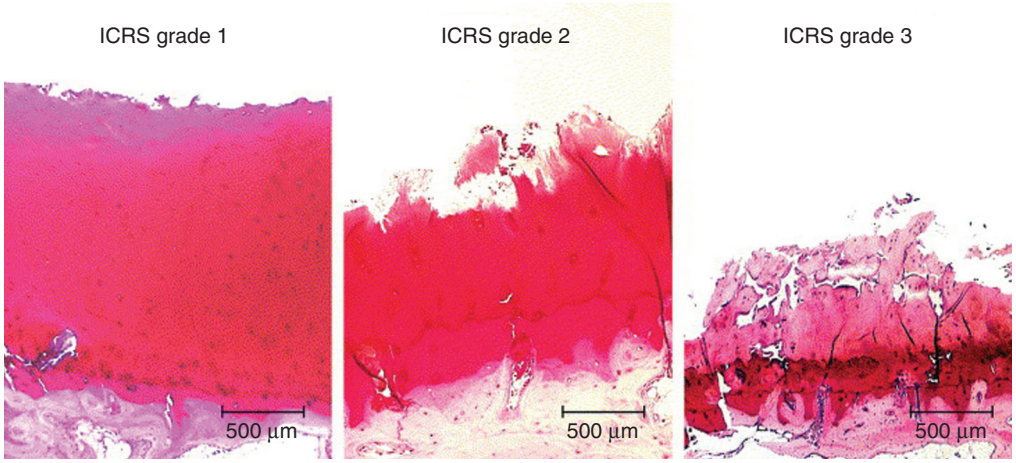


FIG 44-10 Histologic views of safranin-O-stained cartilage examples for International Cartilage Repair Society (ICRS) grade 1, including surface irregularities *(left)*, ICRS grade 2 showing thinning and clefts of cartilage *(middle)*, and ICRS grade 3 with complete disorganization of cartilage *(right)*. (From Kleemann RY, Krocker D, Cedraro A, Tuischer J, Duda GN. Altered cartilage mechanics and histology in knee osteoarthritis: relation to clinical assessment (ICRS Grade). *Osteoarthritis Cartilage*. 2005;13:958-963.)

most frequently used ($n = 87$ surgeons), followed by the ICRS ($n = 8$) and the Insall score ($n = 3$). The majority of surgeons indicated improvement was needed in the grading system they used to be able to differentiate between low-grade and high-grade cartilage lesions. A majority of participants indicated that they would use a practical tool (if available) to quantify cartilage lesions in "questionable cases". However, since 83% of the participating surgeons used the Outerbridge system, this study's conclusions can only be applied to this rating instrument.

CONCLUSION

Many surgeons and arthroscopic operative reports use inaccurate articular cartilage grading systems and language such as "the lesion was between a grade 2 and grade 3" without specifying the cartilage changes that were noted. Arthroscopic examination of the knee joint provides an opportunity to rate the articular cartilage according to the size, depth, and location of lesions, which have clinical significance both in the short and long term. In addition, the detailed rating of articular cartilage is important in clinical knee studies. We recommend the use of detailed systems, such as the Cincinnati Knee Rating or ICRS, to provide a sophisticated analysis of the condition of the articular cartilage. Clinical investigations should assess the effect of noteworthy cartilage damage on the subjective and functional outcome of various operative procedures. When feasible, advanced MRI or objective measuring instruments should be used to more accurately determine the status of articular cartilage.

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Knee Arthroplasty and Patellofemoral Rating Systems

Sue D. Barber-Westin, Frank R. Noyes

OUTLINE

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TOTAL KNEE ARTHROPLASTY OUTCOME INSTRUMENTS

Introduction

Many outcome scales and systems have been used to assess the results of total knee arthroplasty (TKA). These include scales specifically designed for this operation, as well as general health measures and outcome instruments that were originally developed for a variety of knee diagnoses. Although some scales only rate levels of physical activity, others are more encompassing in terms of providing a detailed analysis of the knee condition and function. The American Knee Society Scoring System, the University of California Los Angeles (UCLA) Activity-Level Rating Score, and the Oxford Knee Score were devised specifically to determine the outcome of TKA and currently are the most frequently used instruments. The Short Form 36 (SF-36) Health Survey[26] is a common general health measure that is also used in many TKA studies. Disease-specific (osteoarthritis) instruments typically found in TKA investigations are the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and the Knee Injury and Osteoarthritis Outcome Score (KOOS).

A lack of consensus exists regarding which instrument or rating system should be selected to determine the results of TKA, caused in part by the moderate to poor quality of investigations that determined their psychometric properties.[1,32] One systematic review found that, of 28 instruments assessed, only three had been studied at length in regard to their measurement properties.[1] These were the WOMAC, the Oxford Knee Score, and the SF-36. Another review of instruments used in hip or knee osteoarthritis studies reported that none of the instruments received positive ratings for all psychometric properties.[32] It is important to note that these reviews were conducted before the publication of the two newest outcome instruments and scales for TKA, the new Knee Society Scoring System and the High-Activity Arthroplasty Score. Some of the more commonly used outcome measures are described below, presented in chronological order of publication. The WOMAC and KOOS outcome assessments are described in Chapter 43 and are not repeated in this chapter.

University of California Los Angeles Activity-Level Rating Score

In 1984, Amstutz and colleagues[2] introduced the UCLA activity rating scale for patients undergoing TKA. The scale has 10 activity levels ranging from "wholly inactive" to "regularly participate in impact sports" (Table 45-1). Subsequently, Zahiri and associates[37] compared this activity score with a quantitative assessment of the walking activity of 100 total joint replacement patients. These investigators found the UCLA score strongly correlated with average steps per day as recorded by a pedometer. The recommendation was made to adjust the score for frequency and intensity of activity to increase its accuracy. Naal and coworkers[21] compared the psychometric properties of the UCLA scale with the Tegner and Marx Sports Activity scales in 105 patients undergoing total hip arthroplasty and 100 patients undergoing TKA. The UCLA scale had the best reliability, the highest completion rate, and the strongest correlations with other measures and was the only scale that discriminated between active and sedentary patients. The score also had no floor effects. These investigators concluded that the UCLA scale appeared to be the most appropriate for assessment of physical activity levels following total joint arthroplasty.

American Knee Society Scoring System

In 1989, the Knee Society (of the American Academy of Orthopaedic Surgeons) published its scoring system, which was intended to quantify the results of TKA.[16] In 2011, an extensive update was performed, and a new system was published in 2012.[23,29] The goals of the updated version are to better characterize patient expectations and satisfaction of the operation and measure physical activities of younger individuals undergoing TKA. This system consists of an objective knee score completed by the physician (Table 45-2) and several scales completed by

the patient that assess satisfaction (Table 45-3), symptoms, expectations (Table 45-4), and knee function (Table 45-5). Noble and associates[23] reported adequate internal consistency, reliability, and construct and convergent validity for the four subscales: objective knee score, satisfaction score, expectation score, and functional activity score. The objective knee score consists of seven items; the satisfaction score, five items; the expectation score; three items; and the functional activity score, 19 items. The questionnaires are available by contacting the Knee Society at knee@aaos.org; further information, including the user manual, may be found at www.kneesociety.org/web/outcomes.html.

CRITICAL POINTS Total Knee Arthroplasty Outcome Instruments

- Lack of consensus exists regarding which instrument or rating system should be selected, due in part to the moderate to poor quality of investigations that determined their psychometric properties.
- UCLA activity rating scale: 10 levels ranging from wholly inactive and dependent on others to regular participation in impact sports. Superior to Tegner and Marx for reliability, completion rate, ability to discriminate varying activity levels.
- New Knee Society Scoring System: adequate internal consistency, reliability, and construct and convergent validity for four subscales.
- Oxford knee score: assesses knee-related pain and functional limitations with usual daily and work activities. Adequate reliability, internal consistency, and responsiveness. Adopted in the United Kingdom as a primary outcome measure for patients undergoing TKA as a part of the UK National Patient Reported Outcome Measures Program.
- High-Activity Arthroplasty Score: assesses functional abilities of younger active patients who undergo lower limb arthroplasty. Correlates with Oxford, Knee Society, reduced WOMAC scores; high internal consistency.

Oxford Knee Score

In 1998, Dawson and associates,[9] within the Public Health and Primary Health Care at the University of Oxford, developed a 12-item questionnaire to determine the outcome of TKA. The Oxford knee score (OKS) represents an assessment of knee-related pain and functional limitations with usual daily and work activities (Table 45-6). Each question has five possible responses, scored from 1 to 5, from least to most difficult. The OKS instrument has been translated into 17 languages. Information regarding the scoring system, user manual, and requests for a license may be obtained at www.isis-innovation.com/outcomes/orthopaedic/oks.html.

TABLE 45-1 University of California Los Angeles Activity-Level Rating

Activity	Level
Regularly participate in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor, or backpacking	10
Sometimes participate in impact sports	9
Regularly participate in very active events, such as bowling or golf	8
Regularly participate in active events, such as bicycling	7
Regularly participate in moderate activities, such as swimming and unlimited housework or shopping	6
Sometimes participate in moderate activities	5
Regularly participate in mild activities, such as walking, limited housework, and limited shopping	4
Sometimes participate in mild activities	3
Mostly inactive: restricted to minimal activities of daily living	2
Wholly inactive: dependent on others, cannot leave residence	1

TABLE 45-2 Knee Society Objective Knee Score

Item	Measurement Method	Possible Responses	Points
1. Alignment	AP standing x-ray (anatomic alignment)	Neutral: 2-10 degrees valgus	25
		Varus: <2 degrees valgus	–10
		Valgus: >10 degrees valgus	–10
2. Medial/lateral instability	Measured at 0 degrees extension	None	15
		Little or <5 mm	10
		Moderate or 5 mm	5
		Severe or >5 mm	0
3. Anterior/posterior instability	Measured at 90 degrees	None	10
		Moderate <5 mm	5
		Severe >5 mm	0
4. Joint motion	Deductions		
	Flexion contracture	1-5 degrees	–2
		6-10 degrees	–5
		11-15 degrees	–10
		>15 degrees	–15
	Extension lag	<10 degrees	–5
		10-20 degrees	–10
		>20 degrees	–15
5. Pain with level walking	Patient's response	0-10 scale	10-score of patient's response
6. Pain with stairs or inclines	Patient's response	0-10 scale	10-score of patient's response
7. Does knee feel "normal" to patient	Patient's response	Always	5
		Sometimes	3
		Never	0

0-100 points.

TABLE 45-3 Knee Society Satisfaction Score

Patient Questions

Currently, how satisfied are you with the pain level of your knee while sitting?
Currently, how satisfied are you with the pain level of your knee while lying in bed?
Currently, how satisfied are you with your knee function while getting out of bed?
Currently, how satisfied are you with your knee function while performing light household duties?
Currently, how satisfied are you with your knee function while performing leisure recreational activities?

Response Options for Each Question

Very satisfied (8 points)
Satisfied (6 points)
Neutral (4 points)
Dissatisfied (2 points)
Very dissatisfied (0 points)

0-40 points.

TABLE 45-4 Knee Society Expectation Score

Patient Questions

My expectations for pain relief were…
My expectations for being able to do my normal activities of daily living were…
My expectations for being able to do my leisure, recreational or sports activities were…

Response Options for Each Question

Too high: "I'm a lot worse than I thought" (1 point)
Too high: "I'm somewhat worse than I thought" (2 points)
Just right: "My expectations were met" (3 points)
Too low: "I'm somewhat better than I thought" (4 points)
Too low: "I'm a lot better than I thought" (5 points)

15 points.

TABLE 45-5 Knee Society Functional Activity Score

Question	Response Options	Points
Walking and standing: Can you walk without any aids (e.g., cane, crutches, or wheelchair)?	Yes or no	0
If no, which of the following aid(s) to you use?	Wheelchair	–10
	Walker	–8
	Crutches	–8
	Two canes	–6
	One crutch	–4
	One cane	–4
	Knee sleeve/brace	–2
Do you use these aid(s) because of your knees?	Yes or no	0
For how long can you stand (with or without aid) before sitting because of knee discomfort?	Cannot stand	0
	0-5 minutes	3
	6-15 minutes	6
	16-30 minutes	9
	31-60 minutes	12
	More than an hour	15
For how long can you walk (with or without aid) before stopping because of knee discomfort?	Cannot walk	0
	0-5 minutes	3
	6-15 minutes	6
	16-30 minutes	9
	31-60 minutes	12
	More than an hour	15
Standard activities: How much does your knee bother you during each of the following activities?	I never do this	0
	Cannot do because of knee	0
1. Walking on an uneven surface	Very severe	1
2. Turning or pivoting on your leg	Severe	2
3. Climbing up or down a flight of stairs	Moderate	3
4. Getting up from a low couch or a chair without arms	Slight	4
5. Getting into or out of a car	No bother	5
6. Moving laterally (stepping to the side)		
Advanced activities: How much does your knee bother you during each of the following activities?	I never do this	0
	Cannot do because of knee	0
1. Climbing a ladder or step stool	Very severe	1
2. Carrying a shopping bag for a block	Severe	2
3. Squatting	Moderate	3
4. Kneeling	Slight	4
5. Running	No bother	5

Continued

TABLE 45-5 Knee Society Functional Activity Score—cont'd

Question	Response Options	Points
Discretionary knee activities: Check 3 of the activities below that you consider most important to you. How much does your knee bother you during each of these activities?		
Recreational activities: swimming, golfing (18 holes), road cycling (>30 min), gardening, bowling, racquet sports, distance walking, dancing/ballet, stretching exercises	Cannot do because of knee	0
	Very severe	1
	Severe	2
Workout and gym activities: weightlifting, leg extensions, stair-climbing machine, stationary biking/spinning, leg press, jogging, elliptical trainer, aerobic exercise	Moderate	3
	Slight	4
	No bother	5

0-100 points.

TABLE 45-6 Oxford Knee Score

Question	Possible Responses	Points
1. How would you describe the pain you usually have from your knee?	None	1
	Very mild	2
	Mild	3
	Moderate	4
	Severe	5
2. Have you had any trouble with washing and drying yourself (all over) because of your knee?	No trouble at all	1
	Very little trouble	2
	Moderate trouble	3
	Extreme trouble	4
	Impossible to do	5
3. Have you had any trouble getting in and out of a car or using public transport because of your knee (whichever you tend to use)?	No trouble at all	1
	Very little trouble	2
	Moderate trouble	3
	Extreme trouble	4
	Impossible to do	5
4. For how long have you been able to walk before the pain in your knee becomes severe (with or without a stick)?	No pain/>30 min	1
	16-30 min	2
	5-15 min	3
	Around the house only	4
	Not at all; severe on walking	5
5. After a meal (sitting at a table), how painful has it been for you to stand up from a chair because of your knee?	Not at all painful	1
	Slightly painful	2
	Moderately painful	3
	Very painful	4
	Unbearable	5
6. Have you been limping when walking because of your knee?	Rarely/never	1
	Sometimes or just at first	2
	Often, not just at first	3
	Most of the time	4
	All of the time	5
7. Could you kneel down and get back up again afterwards?	Yes, easily	1
	With little difficulty	2
	With moderate difficulty	3
	With extreme difficulty	4
	No, impossible	5
8. Have you been troubled by pain from your knee in bed at night?	No nights	1
	Only 1 or 2 nights	2
	Some nights	3
	Most nights	4
	Every night	5

TABLE 45-6 Oxford Knee Score—cont'd

Question	Possible Responses	Points
9. How much has pain from your knee interfered with your usual work (including housework)?	Not at all	1
	A little bit	2
	Moderately	3
	Greatly	4
	Totally	5
10. Have you felt that your knee might suddenly "give way" or let you down?	Rarely/never	1
	Sometimes or just at first	2
	Often, not just at first	3
	Most of the time	4
	All of the time	5
11. Could you do the household shopping on your own?	Yes, easily	1
	With little difficulty	2
	With moderate difficulty	3
	With extreme difficulty	4
	No, impossible	5
12. Could you walk down a flight of stairs?	Yes, easily	1
	With little difficulty	2
	With moderate difficulty	3
	With extreme difficulty	4
	No, impossible	5

Dawson and associates[9] found that TKA patients completed the OKS at a higher rate than the SF-36, the original American Knee Society score,[16] and the Stanford Health Assessment Questionnaire. These investigators reported the OKS had adequate reliability, internal consistency, and responsiveness for this patient cohort. Other authors have confirmed these findings.[13,17] The OKS is predictive of patient satisfaction postoperatively.[6] However, Whitehouse and coworkers[34] reported patients had problems with the questionnaire in terms of items left blank because of a lack of understanding or inability to answer with the responses provided. There is no allowance for comorbidities, which is a problem with many elderly patients undergoing TKA. Recommendations were made for consideration of reformulation of questions and response categories. Even so, in 2009, the OKS was adopted in the United Kingdom (UK) as a primary outcome measure for patients undergoing TKA as a part of the UK National Patient Reported Outcome Measures Program.

High-Activity Arthroplasty Score

In 2010, Talbot and associates[31] devised the High-Activity Arthroplasty Score to assess the functional abilities of younger and more active patients who undergo lower limb arthroplasty. This scale is markedly different from other general activity analysis previously published for this population.[2,11,27] The scale consists of four domains (walking, running, stair climbing, activity level) shown in Table 45-7. A pilot study composed of 22 patients (11 post–total hip arthroplasty, 11 post-TKA) showed the score correlated significantly with the Oxford,[9] Knee Society,[16] Harris Hip,[14] and reduced WOMAC[35,36] scores. Internal consistency was high. Reliability as determined by ICC and responsiveness were not assessed by the investigators.

PATELLOFEMORAL OUTCOME INSTRUMENTS

Introduction

Several disease-specific outcome instruments have been used to rate symptoms and function in patients with patellofemoral pain and disorders. No consensus exists regarding which instrument or rating system should be selected. One problem is that many studies use the generic term "patellofemoral pain syndrome" (PFPS) to describe the cohort under investigation. PFPS encompasses a multitude of potential (more specific) diagnoses such as extensor mechanism malalignment, infrapatellar fat pad syndrome, lateral patellar compression syndrome, patellar dislocation/subluxation, or an inflammatory condition such as bursitis. A recent systematic review of psychometric properties of self-reported questionnaires used for PFPS defined this term as "anterior or retropatellar knee pain or pain along the lateral and medial borders of the patella, which could be caused by anterior knee structures such as the infrapatellar fat pad, patellar subchondral bone, anterior synovium and medial or lateral retinaculae."[10]

A systematic review conducted by Esculier and associates[10] found several questionnaires with measured psychometric properties used to assess PFPS: the Activities of Daily Living Scale (ADLS), the Anterior Knee Pain Scale (AKPS, also known as the Kujala Scale), the International Knee Documentation Committee (IKDC) Subjective Knee scale,

CRITICAL POINTS Patellofemoral Outcome Instruments

- No consensus regarding which instrument or rating system should be used for patellofemoral pain, injuries, and disorders
- Functional Index Questionnaire: eight-item questionnaire assesses problems with daily and sports activities in patients with PFPS. Reliability varies, responsiveness low.
- AKPS or Kujala Scale: adequate psychometric properties, able to discriminate between knee conditions and levels of severity in patients with PFPS
- Samsung Medical Center Patellofemoral Scoring System: pain score (8 items) and function score (9 items). Acceptable reliability, internal consistency, content validity.
- Saltzman Patellofemoral Score: 3 sections, 0-100 points, includes self-reported questionnaire and objective and radiographic analyses. Psychometric properties not analyzed.

TABLE 45-7 High-Activity Arthroplasty Score

Domain	Levels	Points
Walking	Over rough ground >1 hr	5
	Unlimited on flat, rough ground with difficulty	4
	Unlimited on flat, no rough ground	3
	On flat at least 30 minutes	2
	Short distances unassisted (up to 20 m)	1
	Using walking aids for short distances or worse	0
Running	More than 5 km	4
	Jog slowly up to 5 km	3
	Run easily across the road	2
	Run a few steps to avoid traffic if necessary	1
	Cannot run	0
Stair-climbing	Climb stairs two at a time	3
	Climb without handrail	2
	Climb with hand rail or stick	1
	Cannot climb stairs	0
Activity level	Competitive sports (e.g., singles tennis, running >10 km, cycling >80 km)	6
	Social sports (e.g., doubles tennis, skiing, jogging <10 km, high-impact aerobics	5
	Vigorous recreational activities (e.g., hill-walking, low impact aerobics, heavy gardening or manual work/farming	4
	Moderate recreational activities (e.g., golf, light gardening, light working activities)	3
	Light recreational activities (e.g., short walks, lawn bowls)	2
	Required outdoor activities only (e.g., walk short distance to shop)	1
	Housebound without assistance	0

The patient selects the highest level of function in each of the four domains.

the Functional Index Questionnaire (FIQ), and the Lysholm Scale. These investigators recommended the ADLS, followed by the AKPS and the IKDC, to evaluate patients with PFPS. The IKDC is described in detail in Chapter 42, and the ADLS and Lysholm scales are discussed in Chapter 43 and therefore are not repeated in this chapter. It is important to note that it is unknown whether or not an outcome instrument or rating system exists that contains adequate psychometric properties for all patellofemoral-related injuries and disorders. Clinical investigations regarding specific patellofemoral diagnoses, injuries, and operations typically use several rating instruments to determine outcome. These include those described above, as well as general health questionnaires such as the SF-36 and osteoarthritis-specific instruments such as the WOMAC and KOOS.

Functional Index Questionnaire

The FIQ is a commonly used instrument to rate patellofemoral problems.[7,8,10,22,24,25] Published in 1989 by Chesworth and coworkers,[4] the eight-item questionnaire assesses problems with daily and sports activities in patients with PFPS. Items measured are walking, stair climbing, squatting, kneeling, and running. Responses are determined from a three-level gradient of "unable to do," "can do with problem," and "no problem." A modified version of this instrument provides a fourth level of "not appropriate."[30] Chesworth and coworkers[4] reported poor reliability (ICC, 0.48), but acceptable validity in detecting change after a mean of 11 weeks of physical therapy (determined with repeated-measures analysis of variance). However, Harrison and colleagues[15] and MacIntyre and associates[20] conducted more rigorous investigations of this instrument in patients with patellofemoral pain who underwent a program of physical therapy and found acceptable values for reliability, validity, and responsiveness. A high reliability ICC of 0.94 was also reported by Bennell and associates.[3] However, poor reliability (ICC, 0.49) was found by Crossley and coworkers.[8] In a systematic review of articles that measured the psychometric properties of PFPS outcome instruments, Esculier and colleagues[10] reported a weighted average (calculated from a total of 47 patients) ICC of 0.61. Because of the poor reliability and low responsiveness of the FIQ, these investigators did not recommend the use of this instrument in patients with PFPS.

Anterior Knee Pain Scale (Kujala Scale)

The Anterior Knee Pain Scale (AKPS), frequently referred to as the Kujala Scale,[18] is another commonly used instrument to determine function and outcome in PFPS.[5,7,8,10,12] First published in 1993, this scale consists of 13 factors (0-100 point scale) shown in Table 45-8. Watson and associates[33] found high reliability (ICC, 0.95) and moderate responsiveness of the AKPS in 30 patients treated with physical therapy for anterior knee pain. Excellent reliability of this instruments was also reported by others.[3,8,10] Esculier and colleagues[10] found adequate internal consistency, responsiveness, and validity. These investigators recommended use of the AKPS for PFPS studies because it had the highest weighted average ICC and responsiveness and the lowest measurement error among five scales assessed. Another advantage of the AKPS was its ability to discriminate between knee conditions and levels of severity in patients with PFPS.

Samsung Medical Center Patellofemoral Scoring System

Recently, Lee and associates[19] introduced the Samsung Medical Center (SMC) patellofemoral scoring system. The system is composed of two scores: a patellofemoral pain score (eight items) and a patellofemoral function score (nine items, Table 45-9). These investigators reported excellent reliability and internal consistency in a group of 179 patients. There were 123 patients with isolated anterior knee pain, 28 patients with knee pain in another location, and 28 healthy volunteers. Acceptable floor and ceiling effects (content validity) were found for all items except sitting down on a chair in the patellofemoral function score. The investigators concluded that their scoring system was unique because it was able to distinguish patients with anterior knee pain or patellofemoral dysfunction from patients with knee pain or problems arising from other diagnoses, and from individuals without knee pain or problems.

Saltzman Patellofemoral Score

A comprehensive rating system was devised by Saltzman and associates[28] to determine the outcome of treatment of displaced patellar fractures. The system comprised three sections: a self-reported patient questionnaire (five items, 45 points), an objective analysis (six items, 43 points), and a radiographic analysis (three items, 12 points). The subjective portion of the score was developed (based on the Cincinnati Knee Rating System) to determine the symptoms of pain, swelling, and giving-way according to activity levels (Table 45-10). The scores of all items are summed up to produce one final score, which is then categorized as "excellent" (90-100 points), "good" (80-89 points), "fair" (70-79 points), or "poor" (<70 points). This system's psychometric properties have not been evaluated. Even so, it is included here because it represents one of the few patellofemoral outcome instruments that assesses both subjective and objective factors.

TABLE 45-8 Anterior Knee Pain Scale

Question	Possible Responses	Points
1. Limp	None	5
	Slight or periodical	3
	Constant	0
2. Support	Full support without pain	5
	Painful	3
	Weight-bearing impossible	0
3. Walking	Unlimited	5
	More than 2 km	3
	1-2 km	2
	Unable	0
4. Stairs	No difficulty	10
	Slight pain when descending	8
	Pain both when descending and ascending	5
	Unable	0
5. Squatting	No difficulty	5
	Repeated squatting painful	4
	Painful each time	3
	Possible with partial weight-bearing	2
	Unable	0
6. Running	No difficulty	10
	Pain after more than 2 km	8
	Slight pain from start	6
	Severe pain	3
	Unable	0
7. Jumping	No difficulty	10
	Slight difficulty	7
	Constant pain	2
	Unable	0
8. Prolonged sitting with the knees flexed	No difficulty	10
	Pain after exercise	8
	Constant pain	6
	Pain forces to extend knees temporarily	4
	Unable	0
9. Pain	None	10
	Slight and occasional	8
	Interferes with sleep	6
	Occasionally severe	3
	Constant and severe	0
10. Swelling	None	10
	After severe exertion	8
	After daily activities	6
	Every evening	4
	Constant	0
11. Abnormal painful kneecap (patellar) movements (subluxations)	None	10
	Occasionally in sports activities	6
	Occasionally in daily activities	4
	At least one documented dislocation	2
	More than two dislocations	0
12. Atrophy of thigh	None	5
	Slight	3
	Severe	0
13. Flexion deficiency	None	5
	Slight	3
	Severe	0

Patients are asked to indicate the duration of their symptoms and, for each question, to circle the latest choice that corresponds to their knee symptoms.

TABLE 45-9 Samsung Medical Center Patellofemoral Scoring System

Factors	Scoring
Patellofemoral Pain Score	0 (no pain) to 10 (intractable pain) in increments of 1; the higher the number, the more painful. Subtotal score ranges from 0-80 points.
1. Climbing up stairs	
2. Walking down stairs	
3. Rising from floor	
4. Sitting down on floor	
5. Rising from a chair	
6. Rising from squatting position	
7. Squatting	
8. Sitting on a chair for 10 minutes	
Patellofemoral Function Score	0 = no difficulty
1. Climbing up stairs	2.5 = mild
2. Walking down stairs	5 = moderate
3. Rising from floor	7.5 = severe
4. Sitting down on floor	10 = extreme difficulty (unable to do)
5. Rising from a chair	Subtotal score ranges from 0-90 points.
6. Sitting down on a chair	
7. Rising from squatting position	
8. Squatting	
9. Sitting on a chair for 10 minutes	

TABLE 45-10 Saltzman Patellofemoral Score

Factor	Responses	Points
Pain	None	10
Do you have knee pain when you do strenuous sports or heavy work?	Yes, definite pain, moderate limitations	8
Do you have knee pain when you do recreational sports or moderate work?	Yes, definite pain, moderate limitations	6
	Yes, definite pain, mild limitations	4
Do you have knee pain when you do daily living activities (walking) or light work (office)?	Yes, definite pain, moderate limitations	2
	Constant pain, severe limitations	0
Swelling	None	5
Do you have knee swelling when you do strenuous sports or heavy work?	Yes, definite swelling, moderate limitations	4
Do you have knee swelling when you do recreational sports or moderate work?	Yes, definite swelling, moderate limitations	3
	Yes, definite swelling, mild limitations	2
Do you have knee swelling when you do daily living activities (walking) or light work (office)?	Yes, definite swelling, moderate limitations	1
	Constant swelling, severe limitations, relieved by rest	0
Giving way	None	5
Do you have giving-way when you do strenuous sports or heavy work?	Yes, definite giving way, moderate limitations	4
Do you have giving-way when you do recreational sports or moderate work?	Yes, definite giving way, moderate limitations	3
	Yes, giving-way, mild limitations	2
Do you have giving-way when you do daily living activities (walking) or light work (office)?	Giving-way, moderate limitations	1
	Giving-way, severe limitations	0
Movement	No pain or swelling	15
Sitting	Each factor rated as either yes or no; each pain factor rated as yes equals –2 points; each swelling factor rated as yes equals –1 point	
Standing/walking		
Climbing stairs		
Squatting		
Lifting/carrying		
Work	Work activities have not changed or have increased	10
	Work activities decreased because of problems with knee	5
	Unable to work because of problems with knee	0
Effusion	None	6
	Mild	4
	Moderate	2
	Severe	0

TABLE 45-10 Saltzman Patellofemoral Score—cont'd

Factor	Responses	Points
Active range of motion (involved/noninvolved)	>90%	12
	80%-90%	9
	70%-80%	6
	60%-70%	3
	<60%	0
Extensor lag	None	4
	–1 point for each 5 degrees of extensor lag	
Patellofemoral compression pain	None	3
	Mild	2
	Moderate	1
	Severe	0
Thigh atrophy (noninvolved-involved)	<12 mm	8
	12-25 mm	4
	>25 mm	0
Isokinetic quadriceps strength (noninvolved-involved); 60 degrees/sec	<10%	10
	10%-20%	8
	20%-30%	6
	30%-40%	4
	40%-50%	2
	>50%	0
Radiographs	None	12
Patellofemoral compartment Medial compartment Lateral compartment	–1 point if narrowing, sclerosis, cysts, osteophytes in any compartment; subtract 1 point for all that exist	

90-100 points = excellent; 80-89 points = good; 70-79 points = fair; <70 points = poor.

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