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ISBN 978-3-319-29726-2 ISBN 978-3-319-29728-6 (eBook)
DOI 10.1007/978-3-319-29728-6

Library of Congress Control Number: 2016930543



Printed on acid-free paper

This Springer imprint is published by SpringerNature
The registered company is Springer International Publishing AG Switzerland

# Contents

# Chapter 1
# Physiological Aspects of Marathon Running

**Billy Sperlich**

**Abstract** Marathon running has evolved as one of the world's popular running experiences. Independent of the runner's performance level the marathon event represent a major challenge to the runner's biology. Multiple integrated physiological processes operate to resist fatigue during marathon running. The physical preparation for a marathon involves a series of complex biological adaptations to counteract exercise induced fatigue. The following chapter aims at describing important physiological components that are proposed to constrain a champion's physiological capacity for ultimate endurance performance. Further, potential limiting factors of the lungs, cardio-vascular system, blood oxygen carrying capacity, muscle properties and metabolism are explained in order to understand the underlying mechanisms for developing specific training methods and to estimate the race pace during marathon running. Other important biological aspects involved in marathon running such as nutrition, thermoregulation, biomechanics will be discusses in detail in the following chapters.

**Keywords** Marathon · Oxygen uptake · Central limitations · Pulmonary diffusion · Blood oxygen carrying capacity · Muscle adaptation · Lactate threshold · Substrate regulation · Running · Running economy

## 1.1 Introduction

The question, "the two-hour marathon: who and when?" (Joyner et al. 2011) was mentioned in 2011, initiating a lively debate about who, how, and when an exciting barrier of human performance would be broken. The query instigated a search to identify an outstanding human with extraordinary physiological and mental stamina.

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C. Zinner and B. Sperlich (eds.), *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*, DOI 10.1007/978-3-319-29728-6_1

During marathon running and prolonged endurance exercise, perceptions of mental and muscular fatigue eventually occur accompanied by a decline in muscular performance (Kay et al. 2001; Green 1997; Kay and Marino 2000; Wilmore and Costill 1999; Millet et al. 2000, 2002; Pinniger et al. 2000; Gibson et al. 2001). To date several cognitive, bio-chemical and mechanical models have been proposed to explain the process of fatigue (Noakes 2000, 2007; Hampson et al. 2001; Hunter et al. 2003). However, the fatigue-related process is a complex interplay of neuro-humoral, metabolic, cardio-vascular and cognitive factors. It has been suggested that the action of a central (brain-derived) neural regulator controls marathon performance in anticipation to avoid physical harm (Noakes 2007). This constellation of factors appears highly individual and remains under investigation (Bouchard et al. 1986).

The mental and physical fatigue occurring during marathon eventually defines the velocity achieved during marathon running. To date numerous physiological and mental components limiting the performance during marathon have been identified. So far, three important physiological components are proposed to constrain a champion's physiological capacity for ultimate endurance performance. These components include: the involvement of aerobic and anaerobic energy production—as reflected by the runner's peak oxygen uptake ($\dot{V}O_{2peak}$), velocity at lactate threshold ($v_{LT}$), and running economy (RE) (Joyner and Coyle 2008). More than 70 % of the inter-individual variance in long-distance running has been attributed to $\dot{V}O_{2peak}$, lactate threshold, and running economy (di Prampero et al. 1986) and together, can to a great extent, explain variation in marathon performance (Sjodin and Svedenhag 1985).

Of course, other factors such as climate, nutrition, mental stamina, and motivation also significantly affect marathon performance (Fig. 1.1 for more details). For this reason, we have dedicated separate chapters to each of the aforementioned aspects of marathon science.

It is well known that aerobic metabolism depends highly on oxygen availability of contracting muscle cells dictated by central (cardio-respiratory and hemodynamic) and peripheral (oxygen extraction) processes (Bassett and Howley 2000). A substantial body of evidence has shown the $\dot{V}O_{2peak}$ to be one of the most salient predictors of endurance performance since (i) $\dot{V}O_{2peak}$ determines the upper limit for endurance performance (i.e., a runner cannot sustain exercise above 100 % $\dot{V}O_{2peak}$ for prolonged bouts) (Bassett 2002) and (ii) there exists a strong correlation between $\dot{V}O_{2peak}$ and performance during a long distance run (Costill 1970).

However, significant variations in $\dot{V}O_{2peak}$ have been observed among runners with a similar level of performance, indicating that other components play an important role in inter-individual performance variability. From a physiological standpoint, the oxygen cost of running (expressed as oxygen uptake at submaximal running), and lactate threshold are additional factors effecting marathon performance. Basically, $\dot{V}O_{2peak}$ and lactate threshold define the duration that aerobic and anaerobic processes can be maintained, while the runner's economy regulates marathon velocity for a given amount of energy consumption.

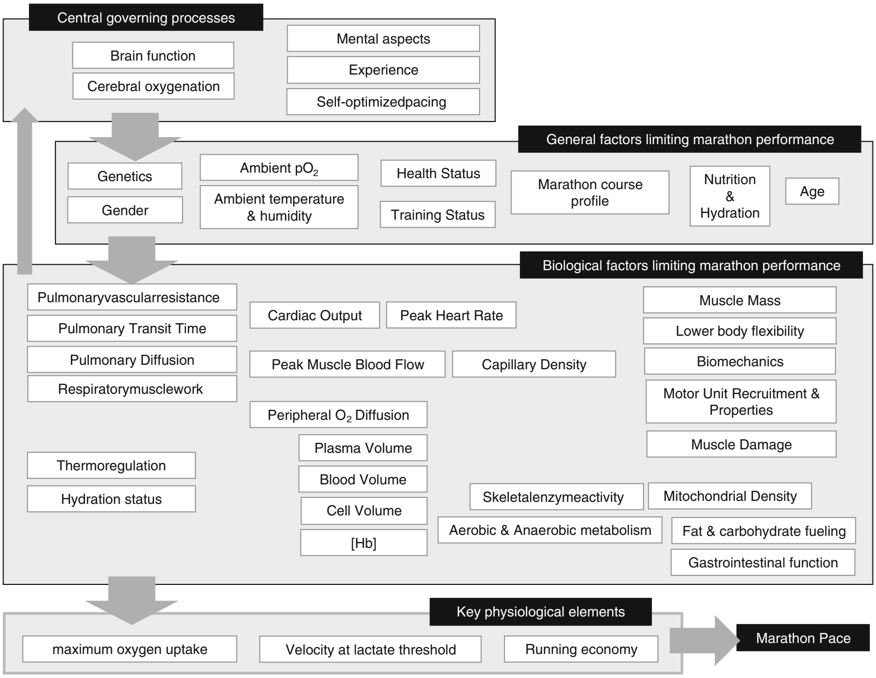


**Fig. 1.1** Physiological and mental components limiting the performance during marathon (please note the list may not be exhaustive)

## 1.2 Oxygen Uptake During Marathon Running

A runner's $\dot{V}O_{2peak}$ is defined as the maximum amount of oxygen taken up and consumed by all tissue during exhaustive exercise (Bassett and Howley 2000). The $\dot{V}O_{2peak}$ consists primarily—although not exclusively—of the ability

(i) to transport large amounts of blood (i.e. high cardiac output and total body hemoglobin),
(ii) to distribute blood (i.e. by muscle blood flow) and
(iii) to extract and utilize oxygen within the muscle cell.

(Bassett and Howley 2000; Joyner and Coyle 2008). The biological adaptation from long distance running allows an athlete to run a marathon at approximately 75–85 % of $\dot{V}O_{2peak}$ (Joyner and Coyle 2008; Bassett and Howley 2000). In contrast a 5 and 10-km run will be performed at 90–100 % $\dot{V}O_{2peak}$ explaining why marathon runners, when compared to middle-distance runners, possess a lower $\dot{V}O_{2peak}$. Male world-class marathon runners hold a $\dot{V}O_{2peak}$ of >80 ml/min/kg and female runners of >75 ml/min/kg.

## 1.3 Central Limitations to $\dot{V}O_{2peak}$

The primary limiting factors of $\dot{V}O_{2peak}$ are related to cardiac dimension, pulmonary diffusion and blood oxygen carrying capacity (Green et al. 1987, 1990).

### 1.3.1 Cardiac Dimensions

Endurance exercise provokes morphological, regulatory, and functional adaptation of the runner's heart (Pavlik et al. 2013). It is well known that endurance athletes' hearts adapt to training with a reduction in their rate at rest (resting bradycardia) resulting in heart rates <50 bpm (Underwood and Schwade 1977). Such a reduction is due to enhanced parasympathetic and reduced sympathetic activity. The reduction in resting heart rate following endurance training allows athletes' to perform at a lower heart rate with equal running velocity compared to pre-training.

Recreational endurance exercise produces a global cardiac enlargement, potentially increasing dimensions of all cardiac chambers but rarely produce left ventricular wall thickness greater than normal (Thompson 2007). However, in athletes performing extreme endurance disciplines such as ultra-runners, cardiac dimensions —especially chamber size and wall thickness (left ventricle internal dimensions, intraventricular septum thickness, posterior wall thickness)—may be significantly enlarged beyond normal (Nagashima et al. 2003; Thompson 2007).

The inter-individual difference in peak stroke volume (volume of blood expelled by the heart per beat) explains most of the variance in runners' $\dot{V}O_{2peak}$. It is noteworthy, that the peak values of heart rate are limited and decline with age, but stroke volume increases substantially especially with high-intensity exercise (Helgerud et al. 2007).

### 1.3.2 Pulmonary Diffusion

At sea level, pulmonary diffusion may limit performance, since in some cases, the ability of the pulmonary system to oxygenate blood may be insufficient (Dempsey et al. 1984; Powers et al. 1985). The runner's large cardiac output, that is, the volume of blood being pumped over time, permits the transportation of greater amounts of blood volume per heartbeat. The large blood transport however, may not allow the lungs to fully saturate hemoglobin with oxygen since the transit time of the blood within the lungs may be too short. Thus, well-trained athletes with large cardiac dimensions may show signs of "exercise-induced arterial hypoxemia" (Dempsey et al. 1984), especially when commencing heavy exercise.

### 1.3.3 Blood Oxygen Carrying Capacity

At the commencement of (endurance) exercise, the vascular system reallocates blood flow (within and between muscles) to metabolically active skeletal muscles, to ensure optimal $O_2$-extraction. Increased blood allocation to the muscles is primarily achieved by elevated blood volume and red blood cells. Low-intensity endurance exercise has been shown to improve plasma volume (Green et al. 1987) and muscle blood flow (Coyle 1999) within a relatively short time period (after approximately 3 days of training (Green et al. 1987)), however a greater amount of exercise is necessary (approximately 3–5 weeks with 3–5 sessions/week) to further increase $\dot{V}O_{2peak}$ (Hickson et al. 1981) and capillary- and mitochondrial density (Hoppeler and Weibel 2000).

Reduced blood volume due to dehydration may compromise heat loss and improve thermal strain in marathon runners (Cheuvront and Haymes 2001). Remaining well hydrated during marathon (especially when performing in the heat) is (i) essential for optimal temperature regulation and (ii) upholds blood pressure and cardiac output for proper oxygen transport.

Altogether, the oxygen delivery to the exercising muscles may be limited by the aforementioned central factors however, several peripheral factors may also minimize endurance performance.

## 1.4 Peripheral Limitations to $\dot{V}O_{2peak}$

It is well documented that mitochondria enzyme activity as well as capillary density limit peripheral $O_2$-utilization. Furthermore, the increase of enzymes as well capillaries improves peak oxygen uptake (Pringle et al. 2003; Kirkendall and Garrett 1998; Hoppeler and Weibel 2000; Tonkonogi et al. 2000; Bizeau et al. 1998) resulting in greater muscular oxygen extraction from the blood stream.

The trained, in contrast to untrained muscle, has three times greater capillary density, three to four times greater activity of aerobic enzymes, a larger content of slow twitch fibers (type I) (Henriksson 1992), and more efficient type I- (Linossier et al. 1993) and II-muscle fibers (Billat 2001). All aforementioned adaptations ultimately allow improved mitochondria ATP-synthesis leading to postponed onset of fatigue.

### 1.4.1 Muscle Adaptation and Lactate Threshold

The training goal of a marathon runner is to increase the velocity that can be maintained over 42.195 km by improving (i) the efficiency of bio-chemical process to transfer chemical into mechanical energy, (ii) biomechanics of locomotion, (iii) the ability to resist fatigue.

In endurance athletes, the velocity at the lactate threshold ($v_{LT}$) is closely linked to performance (Midgley et al. 2007; Bassett and Howley 2000). As a result, the

$v_{LT}$ and fractional utilization of $\dot{V}O_{2peak}$ at $v_{LT}$ (% $\dot{V}O_{2peak}$) are regarded as good indictors of endurance performance between individuals of different ages, genders, and disciplines (Zinner et al. 2015). In untrained individuals, there is typically no increase in blood lactate <60 % of peak oxygen uptake, although this value may vary individually (Scharhag-Rosenberger et al. 2010). In endurance-trained individuals, a rise in the concentration of blood lactate occurs at 75–90 % of peak oxygen uptake. It has long been suggested that the rise in blood lactate is the cause for muscle fatigue due to muscle hypoxia. However, as Cairns nicely summarized, lactate per se is not the reason for acidosis-induced muscle fatigue (Cairns 2006). As mentioned earlier, the relative contribution of anaerobic metabolism plays a minor role during marathon running; yet in 5 and 10 km events the contribution accounts for up to 20 % of the total energy turnover (Joyner and Coyle 2008).

### *1.4.2 Substrate Regulation During Marathon Running*

Depending on body size, gender, and age, the muscle mass of an endurance athlete totals approximately 15 kg (Hagerman 1984; Coyle et al. 1991). Examination of muscle biopsies have identified different muscle fiber types with different glycolytic and oxidative capacity (Saltin et al. 1977; Bassel-Duby and Olson 2006). Depending on the mode, frequency, intensity, duration of exercise, nutrition and environmental factors, the muscle has the potential to highly adapt to endurance training (Hawley et al. 1985; Zierath and Hawley 2004). Plasticity of adaptation however, seems (Holloszy 1967) genetically determined (Bouchard et al. 2011) and explains the large inter-individual variance in muscle distribution.

It is important to note, that for a marathon runner, fat oxidation during moderate or high intensity running is insufficient to satisfy the muscular ATP demands thereby favoring glycogen pathways. All marathon runners, independent of performance level, rely on carbohydrate fueling as evidenced by an average respiratory exchange ratio of >0.90 in the last half of the marathon (Spriet 2007).

With ongoing high-intensity running mitochondrial oxidation capacity is limited, consequently leading to the production of lactic acid (Holloszy et al. 1977; Robergs et al. 2004; Joyner and Coyle 2008). The oxidation system is highly adaptable to endurance training and explains why $\dot{V}O_{2peak}$ (Daussin et al. 2007, 2008; Gibala et al. 2006; Burgomaster et al. 2008; Akimoto et al. 2005; Kusuhara et al. 2007; Serpiello et al. 2011; Laursen and Jenkins 2002) increases and well trained marathon runners may perform close to their $\dot{V}O_{2peak}$ without reaching $V_{LT}$ (Holloszy et al. 1977).

The velocity during a marathon depends to a great extent on a high level of aerobic metabolism (Joyner and Coyle 2008). Depending on the analysis and modelling, aerobic metabolism will account for >86–93 % of energy production in distance running (Duffield et al. 2005a, b). With increased running duration, the capacity of fueling contributes to fatigue since glycogen stores deplete with prolonged exercise, thereby limiting oxidative ATP generation, and ultimately forcing the runner to reduce pace. In this case, special nutrition strategies before and during a marathon may counteract early depletion of glycogen stores by supplementing glycogen store and preventing hypoglycaemia (Coyle et al. 1983; Sherman and Costill 1984; Murray 1998).

Depending on the performance level, a marathon is usually run within 2–6 h. The main fuels for ATP production and muscle contraction derive from muscle and liver carbohydrates as well as muscle and adipose fat (van Loon et al. 2001; O'Brien et al. 1993). The depletion of muscle and liver glycogen inevitably lead to decreased performance (Green 1997; St Clair Gibson et al. 2001). For this reason, the intake of approximately 30–60 g CHO/h has been proposed during high-intensity exercise (Coyle and Montain 1992) to prevent muscle glycogen depletion (Stepto et al. 2001; Wojtaszewski and Richter 1998).

Prolonged muscle contraction, for example, during marathon running, requires sustained energy fueled by continuous generation of the universal energy compound ATP (adenosine triphosphate). ATP production during marathon running mainly relies on the breakdown of energy-rich molecules from glucose (also called as glycolysis) and mitochondrial respiration (ATP production by downbreak of carbohydrates and free fatty acids aerobic metabolism) (Romijn et al. 1993).

As a general rule, the use of carbohydrates for ATP production increases with intensity. Untrained runners generally use a higher relative amount of carbohydrates at a given intensity when compared to well-trained runners. With augmented fitness (i) the ability to take up free fatty acids from the plasma rises, (ii) the ability to store and oxidize intramuscular triacylglycerol increases and (iii) the maximal rates of carbohydrate and fat oxidation elevates (Hawley 2002). Collectively, such adaptations improve the reliance on fat oxidation at a given running velocity with a simultaneous sparing of carbohydrate fueling.

## 1.5 Running Economy

Recently, running economy has been deemed the "forgotten factor" in marathon running (Foster and Lucia 2007). Running economy [defined as the steady state $\dot{V}O_2$ expressed in ml/kg/min (Costill et al. 1973), or ml/min/m (di Prampero et al. 1986)] distinguishes between athletes of different performance levels (Conley and Krahenbuhl 1980). Runners with similar $\dot{V}O_{2peak}$ may perform differently during a marathon depending on their economy of running. Well trained runners display lower submaximal oxygen uptake at a given intensity when compared to less trained runners (Saunders et al. 2004; Barnes and Kilding 2015). Male world class runners have been shown to have a peak oxygen uptake of $\dot{V}O_{2max}$: 83 ml/min/kg need at 16 km/h ca. approximately 40 ml/min/km (Lucia et al. 2008), female runners with a $\dot{V}O_{2peak}$ of 75 ml/min/kg run 16 km/h with 44 ml/min/kg (Jones 2006). Recent reviews have nicely summarized which training strategies may be most promising for increasing running economy in the range of 1–8 %, including high-intensity (uphill) running, different forms of strength training, and high altitude training (Barnes and Kilding 2015).

Ultimately however, the amount of accumulated years of running seems to have the greatest influence on improvements in running economy (Nelson and Gregor 1976; Svedenhag and Sjödin 1985; Jones 2006; Conley and et al. 1984). For example, a former female world class runner improved her economy of running by 14 % within 5 years (Jones 2006). As experimentally proven, the doubling of training volume does not lead to further gains in performance (Costill et al. 1988, 1991; Londeree 1997; Lake and Cavanagh 1996). It appears that once a certain level of adaptation is reached, further adaptations seem to be more dependent on high-intensity rather than on high-volume training (Londeree 1997).

## References

Akimoto T, Pohnert SC, Li P, Zhang M, Gumbs C, Rosenberg PB, Williams RS, Yan Z (2005) Exercise stimulates Pgc-1alpha transcription in skeletal muscle through activation of the p38 MAPK pathway. J Biol Chem 280(20):19587–19593. doi:10.1074/jbc.M408862200

Barnes KR, Kilding AE (2015) Strategies to improve running economy. Sports Med 45(1):37–56. doi:10.1007/s40279-014-0246-y

Bassel-Duby R, Olson EN (2006) Signaling pathways in skeletal muscle remodeling. Annu Rev Biochem 75:19–37. doi:10.1146/annurev.biochem.75.103004.142622

Bassett DR Jr (2002) Scientific contributions of A. V. Hill: exercise physiology pioneer. J Appl Physiol (1985) 93(5):1567–1582. doi:10.1152/japplphysiol.01246.2001

Bassett DR Jr, Howley ET (2000) Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc 32(1):70–84

Billat LV (2001) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part II: anaerobic interval training. Sports Med 31(2):75–90

Bizeau ME, Willis WT, Hazel JR (1998) Differential responses to endurance training in subsarcolemmal and intermyofibrillar mitochondria. J Appl Physiol 85(4):1279–1284

Bouchard C, Lesage R, Lortie G, Simoneau JA, Hamel P, Boulay MR, Perusse L, Theriault G, Leblanc C (1986) Aerobic performance in brothers, dizygotic and monozygotic twins. Med Sci Sports Exerc 18(6):639–646

Bouchard C, Rankinen T, Timmons JA (2011) Genomics and genetics in the biology of adaptation to exercise. Compr Physiol 1(3):1603–1648. doi:10.1002/cphy.c100059

Burgomaster KA, Howarth KR, Phillips SM, Rakobowchuk M, Macdonald MJ, McGee SL, Gibala MJ (2008) Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. J Physiol 586(1):151–160. doi:10.1113/jphysiol.2007.142109

Cairns SP (2006) Lactic acid and exercise performance: culprit or friend? Sports Med 36(4):279–291

Cheuvront SN, Haymes EM (2001) Thermoregulation and marathon running: biological and environmental influences. Sports Med 31(10):743–762

Conley DL, Krahenbuhl GS (1980) Running economy and distance running performance of highly trained athletes. Med Sci Sports Exerc 12(5):357–360

Conley KGSBLE et al (1984) Following Steve Scott: physiological changes accompanying training. Phys Sports Med 12(1):103–106

Costill DL (1970) Metabolic responses during distance running. J Appl Physiol 28(3):251–255

Costill DL, Flynn MG, Kirwan JP, Houmard JA, Mitchell JB, Thomas R, Park SH (1988) Effects of repeated days of intensified training on muscle glycogen and swimming performance. Med Sci Sports Exerc 20(3):249–254

Costill DL, Thomas R, Robergs RA, Pascoe D, Lambert C, Barr S, Fink WJ (1991) Adaptations to swimming training: influence of training volume. Med Sci Sports Exerc 23(3):371–377

Costill DL, Thomason H, Roberts E (1973) Fractional utilization of the aerobic capacity during distance running. Med Sci Sports 5(4):248–252

Coyle EF (1999) Physiological determinants of endurance exercise performance. J Sci Med Sport 2(3):181–189

Coyle EF, Feltner ME, Kautz SA, Hamilton MT, Montain SJ, Baylor AM, Abraham LD, Petrek GW (1991) Physiological and biomechanical factors associated with elite endurance cycling performance. Med Sci Sports Exerc 23(1):93–107

Coyle EF, Hagberg JM, Hurley BF, Martin WH, Ehsani AA, Holloszy JO (1983) Carbohydrate feeding during prolonged strenuous exercise can delay fatigue. J Appl Physiol Respir Environ Exerc Physiol 55(1 Pt 1):230–235

Coyle EF, Montain SJ (1992) Carbohydrate and fluid ingestion during exercise: are there trade-offs? Med Sci Sports Exerc 24(6):671–678

Daussin FN, Ponsot E, Dufour SP, Lonsdorfer-Wolf E, Doutreleau S, Geny B, Piquard F, Richard R (2007) Improvement of VO2max by cardiac output and oxygen extraction adaptation during intermittent versus continuous endurance training. Eur J Appl Physiol 101 (3):377–383. doi:10.1007/s00421-007-0499-3

Daussin FN, Zoll J, Ponsot E, Dufour SP, Doutreleau S, Lonsdorfer E, Ventura-Clapier R, Mettauer B, Piquard F, Geny B, Richard R (2008) Training at high exercise intensity promotes qualitative adaptations of mitochondrial function in human skeletal muscle. J Appl Physiol 104 (5):1436–1441. doi:10.1152/japplphysiol.01135.2007 01135.2007[pii]

Dempsey JA, Hanson PG, Henderson KS (1984) Exercise-induced arterial hypoxaemia in healthy human subjects at sea level. J Physiol 355:161–175

di Prampero PE, Atchou G, Bruckner JC, Moia C (1986) The energetics of endurance running. Eur J Appl Physiol Occup Physiol 55(3):259–266

Duffield R, Dawson B, Goodman C (2005a) Energy system contribution to 400-metre and 800-metre track running. J Sports Sci 23(3):299–307. doi:10.1080/02640410410001730043

Duffield R, Dawson B, Goodman C (2005b) Energy system contribution to 1500- and 3000-metre track running. J Sports Sci 23(10):993–1002. doi:10.1080/02640410400021963

Foster C, Lucia A (2007) Running economy: the forgotten factor in elite performance. Sports Med (Auckland, NZ) 37 (4–5):316-319

Gibala MJ, Little JP, van Essen M, Wilkin GP, Burgomaster KA, Safdar A, Raha S, Tarnopolsky MA (2006) Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. J Physiol 575(Pt 3):901–911. doi:10.1113/jphysiol.2006.112094

Gibson AS, Lambert MI, Noakes TD (2001) Neural control of force output during maximal and submaximal exercise. Sports Med 31(9):637–650

Green HJ (1997) Mechanisms of muscle fatigue in intense exercise. J Sports Sci 15(3):247–256. doi:10.1080/026404197367254

Green HJ, Jones LL, Hughson RL, Painter DC, Farrance BW (1987) Training-induced hypervolemia: lack of an effect on oxygen utilization during exercise. Med Sci Sports Exerc 19(3):202–206

Green HJ, Jones LL, Painter DC (1990) Effects of short-term training on cardiac function during prolonged exercise. Med Sci Sports Exerc 22(4):488–493

Hagerman FC (1984) Applied physiology of rowing. Sports Med 1(4):303–326

Hampson DB, St Clair Gibson A, Lambert MI, Noakes TD (2001) The influence of sensory cues on the perception of exertion during exercise and central regulation of exercise performance. Sports Med 31(13):935–952

Hawley JA (2002) Adaptations of skeletal muscle to prolonged, intense endurance training. Clin Exp Pharmacol Physiol 29(3):218–222

Hawley JA, Burke LM, Phillips SM, Spriet LL (2011) Nutritional modulation of training-induced skeletal muscle adaptations. J Appl Physiol (1985) 110(3):834–845. doi:10.1152/japplphysiol.00949.2010

Helgerud J, Hoydal K, Wang E, Karlsen T, Berg P, Bjerkaas M, Simonsen T, Helgesen C, Hjorth N, Bach R, Hoff J (2007) Aerobic high-intensity intervals improve VO2max more than moderate training. Med Sci Sports Exerc 39(4):665–671. doi:10.1249/mss.0b013e3180304570

Henriksson J (1992) Effects of physical training on the metabolism of skeletal muscle. Diabetes Care 15(11):1701–1711

Hickson RC, Hagberg JM, Ehsani AA, Holloszy JO (1981) Time course of the adaptive responses of aerobic power and heart rate to training. Med Sci Sports Exerc 13(1):17–20

Holloszy JO (1967) Biochemical adaptations in muscle. Effects of exercise on mitochondrial oxygen uptake and respiratory enzyme activity in skeletal muscle. J Biol Chem 242(9):2278–2282

Holloszy JO, Rennie MJ, Hickson RC, Conlee RK, Hagberg JM (1977) Physiological consequences of the biochemical adaptations to endurance exercise. Ann N Y Acad Sci 301:440–450

Hoppeler H, Weibel ER (2000) Structural and functional limits for oxygen supply to muscle. Acta Physiol Scand 168(4):445–456

Hunter AM, St Clair Gibson A, Lambert MI, Nobbs L, Noakes TD (2003) Effects of supramaximal exercise on the electromyographic signal. Br J Sports Med 37(4):296–299

Jones AM (2006) The physiology of the women's world record holder for the women's marathon. Int J Sports Sci Coaching 1(2):101–116

Joyner MJ, Coyle EF (2008) Endurance exercise performance: the physiology of champions. J Physiol 586(1):35–44. doi:10.1113/jphysiol.2007.143834

Joyner MJ, Ruiz JR, Lucia A (2011) The two-hour marathon: who and when? J Appl Physiol (1985) 110(1):275–277. doi:10.1152/japplphysiol.00563.2010

Kay D, Marino FE (2000) Fluid ingestion and exercise hyperthermia: implications for performance, thermoregulation, metabolism and the development of fatigue. J Sports Sci 18 (2):71–82. doi:10.1080/026404100365135

Kay D, Marino FE, Cannon J, St Clair Gibson A, Lambert MI, Noakes TD (2001) Evidence for neuromuscular fatigue during high-intensity cycling in warm, humid conditions. Eur J Appl Physiol 84(1–2):115–121. doi:10.1007/s004210000340

Kirkendall DT, Garrett WE Jr (1998) The effects of aging and training on skeletal muscle. Am J Sports Med 26(4):598–602

Kusuhara K, Madsen K, Jensen L, Hellsten Y, Pilegaard H (2007) Calcium signalling in the regulation of PGC-1alpha, PDK4 and HKII mRNA expression. Biol Chem 388(5):481–488. doi:10.1515/BC.2007.052

Lake MJ, Cavanagh PR (1996) Six weeks of training does not change running mechanics or improve running economy. Med Sci Sports Exerc 28(7):860–869

Laursen PB, Jenkins DG (2002) The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. Sports Med 32(1):53–73

Linossier MT, Denis C, Dormois D, Geyssant A, Lacour JR (1993) Ergometric and metabolic adaptation to a 5-s sprint training programme. Eur J Appl Physiol 67(5):408–414

Londeree BR (1997) Effect of training on lactate/ventilatory thresholds: a meta-analysis. Med Sci Sports Exerc 29(6):837–843

Lucia A, Olivan J, Bravo J, Gonzalez-Freire M, Foster C (2008) The key to top-level endurance running performance: a unique example. British J Sports Med 42 (3):172–174; discussion 174. doi:10.1136/bjsm.2007.040725

Midgley AW, McNaughton LR, Jones AM (2007) Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? Sports Med 37(10):857–880 37103 [pii]

Millet G, Lepers R, Lattier G, Martin V, Babault N, Maffiuletti N (2000) Influence of ultra-long-term fatigue on the oxygen cost of two types of locomotion. Eur J Appl Physiol 83(4–5):376–380

Millet GY, Lepers R, Maffiuletti NA, Babault N, Martin V, Lattier G (2002) Alterations of neuromuscular function after an ultramarathon. J Appl Physiol 92(2):486–492. doi:10.1152/japplphysiol.00122.2001

Murray R (1998) Rehydration strategies–balancing substrate, fluid, and electrolyte provision. Int J Sports Med 19(Suppl 2):S133–S135. doi:10.1055/s-2007-971978

Nagashima J, Musha H, Takada H, Murayama M (2003) New upper limit of physiologic cardiac hypertrophy in Japanese participants in the 100-km ultramarathon. J Am Coll Cardiol 42 (9):1617–1623

Nelson RC, Gregor RJ (1976) Biomechanics of distance running: a longitudinal study. Res Quarterly 47(3):417–428

Noakes TD (2000) Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. Scand J Med Sci Sports 10(3):123–145

Noakes TD (2007) The central governor model of exercise regulation applied to the marathon. Sports Med 37(4–5):374–377

O'Brien MJ, Viguie CA, Mazzeo RS, Brooks GA (1993) Carbohydrate dependence during marathon running. Med Sci Sports Exerc 25(9):1009–1017

Pavlik G, Major Z, Csajagi E, Jeserich M, Kneffel Z (2013) The athlete's heart Part II Influencing factors on the athlete's heart: Types of sports and age (Review). Acta Physiol Hung 100(1):1–27 10.1556/APhysiol. 100.2013.1.1

Pinniger GJ, Steele JR, Groeller H (2000) Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? Med Sci Sport Exer 32(3):647–653. doi:10.1097/00005768-200003000-00015

Powers SK, Lawler J, Dempsey JA, Dodd S (1985) Landry G (1989) Effects of incomplete pulmonary gas exchange on VO2 max. J Appl Physiol 66(6):2491–2495

Pringle JS, Doust JH, Carter H, Tolfrey K, Campbell IT, Sakkas GK, Jones AM (2003) Oxygen uptake kinetics during moderate, heavy and severe intensity "submaximal" exercise in humans: the influence of muscle fibre type and capillarisation. Eur J Appl Physiol 89(3–4):289–300. doi:10.1007/s00421-003-0799-1

Robergs RA, Ghiasvand F, Parker D (2004) Biochemistry of exercise-induced metabolic acidosis. Am J Physiol Regul Integr Comp Physiol 287(3):R502–R516. doi:10.1152/ajpregu.00114.2004

Romijn JA, Coyle EF, Sidossis LS, Gastaldelli A, Horowitz JF, Endert E, Wolfe RR (1993) Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. Am J Physiol 265(3 Pt 1):E380–E391

Saltin B, Henriksson J, Nygaard E, Andersen P, Jansson E (1977) Fiber types and metabolic potentials of skeletal muscles in sedentary man and endurance runners. Ann N Y Acad Sci 301:3–29

Saunders PU, Pyne DB, Telford RD, Hawley JA (2004) Factors affecting running economy in trained distance runners. Sports Med (Auckland, NZ) 34 (7):465–485

Scharhag-Rosenberger F, Meyer T, Gassler N, Faude O, Kindermann W (2010) Exercise at given percentages of VO2max: heterogeneous metabolic responses between individuals. J Sci Med Sport/Sports Med Australia 13(1):74–79. doi:10.1016/j.jsams.2008.12.626

Serpiello FR, McKenna MJ, Bishop DJ, Aughey RJ, Caldow MK, Cameron-Smith D, Stepto NK (2011) Repeated sprints alter signalling related to mitochondrial biogenesis in humans. Med Sci Sports Exerc. doi:10.1249/MSS.0b013e318240067e

Sherman WM, Costill DL (1984) The marathon: dietary manipulation to optimize performance. Am J sports Med 12(1):44–51

Sjodin B, Svedenhag J (1985) Applied physiology of marathon running. Sports Med 2(2):83–99

Spriet LL (2007) Regulation of substrate use during the marathon. Sports Med 37(4–5):332–336

St Clair Gibson A, Schabort EJ, Noakes TD (2001) Reduced neuromuscular activity and force generation during prolonged cycling. Am J Physiol Regul Integr Comp Physiol 281(1):R187–R196

Stepto NK, Martin DT, Fallon KE, Hawley JA (2001) Metabolic demands of intense aerobic interval training in competitive cyclists. Med Sci Sports Exerc 33(2):303–310

Svedenhag J, Sjödin B (1985) Physiological characteristics of elite male runners in and off-season. Canadian journal of applied sport sciences Journal canadien des sciences appliquées au sport 10(3):127–133

Thompson PD (2007) Cardiovascular adaptations to marathon running: the marathoner's heart. Sports Med 37(4–5):444–447

Tonkonogi M, Walsh B, Svensson M, Sahlin K (2000) Mitochondrial function and antioxidative defence in human muscle: effects of endurance training and oxidative stress. J Physiol 528(Pt 2):379–388

Underwood RH, Schwade JL (1977) Noninvasive analysis of cardiac function of elite distance runners–echocardiography, vectorcardiography, and cardiac intervals. Ann N Y Acad Sci 301:297–309

van Loon LJ, Greenhaff PL, Constantin-Teodosiu D, Saris WH, Wagenmakers AJ (2001) The effects of increasing exercise intensity on muscle fuel utilisation in humans. J Physiol 536(Pt 1):295–304

Wilmore JH, Costill DL (1999) Physiology of sport and exercise, 2nd edn. Human Kinetics, Champaign, IL

Wojtaszewski JF, Richter EA (1998) Glucose utilization during exercise: influence of endurance training. Acta Physiol Scand 162(3):351–358. doi:10.1046/j.1365-201X.1998.0322e.x

Zierath JR, Hawley JA (2004) Skeletal muscle fiber type: influence on contractile and metabolic properties. PLoS Biol 2(10):e348. doi:10.1371/journal.pbio.0020348

Zinner C, Sperlich B, Wahl P, Mester J (2015) Classification of selected cardiopulmonary variables of elite athletes of different age, gender, and disciplines during incremental exercise testing. SpringerPlus 4:544. doi:10.1186/s40064-015-1341-8

# Chapter 2
# Biomechanics of Marathon Running

**Thomas Stöggl and Tobias Wunsch**

**Abstract** This book section starts with an introduction towards the historical development of modern marathon running with respect to number of participants, gender and age distribution and the world record marathon times. This encompasses the development of the mean running velocities, details about the applied stride characteristics (e.g. stride rate, stride length), the applied strike patterns (e.g. forefoot strike vs. heel strike), the prevalence and causes of running related injuries. The second part gives an overview about general biomechanical principles which are relevant in running. In particular, specific definitions (phase definition of the running cycle, strike patterns), force components and the mathematical basics with respect to running energetics, joint loading, leg stiffness etc. are presented. The final part gives an overview about the state of the art knowledge about performance and injury related aspects with respect to marathon running from a biomechanical perspective. Special attention is paid to anthropometrics, running technique related aspects, fatigue effects and footwear.

## 2.1 Statistics About Marathon Running

### *2.1.1 Historical Development of Marathon Running*

#### 2.1.1.1 General Data About Marathon Running

Marathon running, covering the distance of 42.195 km is part of the Olympics since 1896. Since the New York City Marathon 1976, the sport has exploded on a global basis. Over the last 40 years, millions of runners participate in marathons in the world-metropoles like Tokio, Bosten, London, Berlin, Chicago and New York with more than 40,000–50,000 finishers, per each. These races, which belong to the

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C. Zinner and B. Sperlich (eds.), *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*, DOI 10.1007/978-3-319-29728-6_2

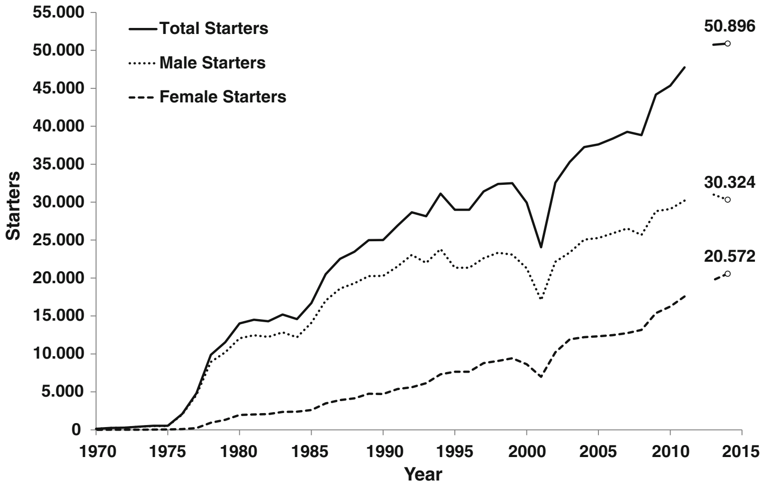


**Fig. 2.1** Development of the number of participants (starters) in the New York City Marathon

"World Marathon Majors Series", illustrate how the marathon evolved from an Olympic competition to a world-wide social and fitness phenomenon (Burfoot 2007). To note here that in 1976 only 2090 started in the New-York marathon, while during the first marathon in 1970 only 127 starters were registered with 55 passing the finish line (Fig. 2.1).

Violet Piercy was the first woman who took part in a marathon (1926, London); however, her time was not officially registered. Kathrine Switzer was the first woman who officially participated in a marathon (1967, Boston). Even though at the beginning women were rare and not very accepted in marathon races (1984 first Olympic marathon for women) the participation of women in the marathon has increased markedly from 11 to 34 %, from 1980 to 1998 and community based training programs vary in their gender makeup from 28 to 60 % female and 40 to 72 % male (Chorley et al. 2002; Dolgener et al. 1994; Hagan et al. 1987; Janssen and ten Hoor 1989; Johnson et al. 1982; Krebs 1992; Wen et al. 1997). Today, female make up to 40 % of all participants (see Fig. 2.1 for the New York City Marathon). As women have entered the marathon race in unprecedented numbers, the gender gap between male and female performances has narrowed dramatically. Indeed the marathon gender gap in 2003 was approximately 8 % (Fig. 2.2a), which is lower than the differences in many other running distances (Burfoot 2007). The rate of improvements in marathon performance of women has been much faster than of men. Thus, it is hypothesized that women marathon runners might finally close the gap and overtake men on the long run (Olson et al. 2011). However, in contrast to this hypothesis, since 2003 only the men's world records were improved leading to a gender difference of 10.1 % in 2015.

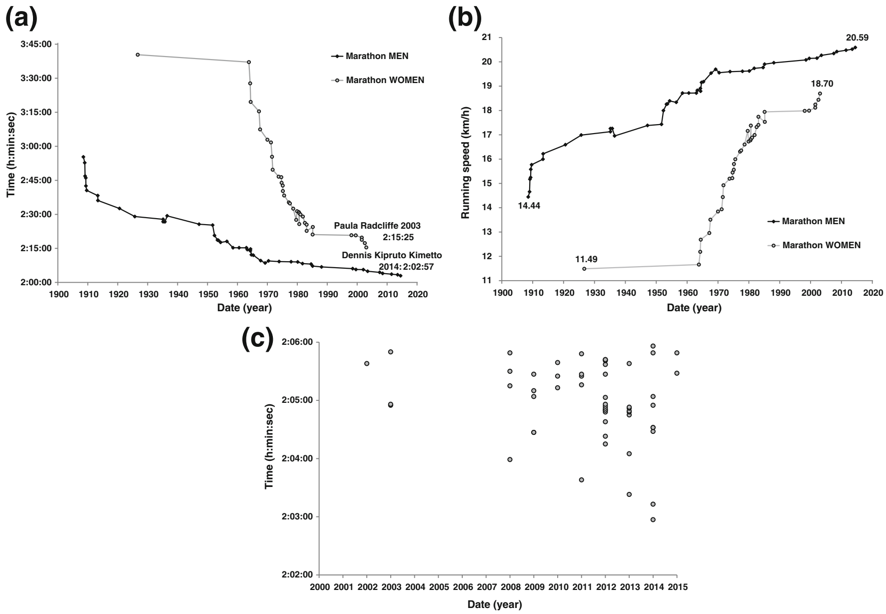


**Fig. 2.2** Development of the marathon world record time (**a**), and mean running velocity (**b**) across the years (*Note* not all world records presented were officially accepted). (**c**) Illustration of the amount of male marathon runners that were able to run below 2:06:00 over the marathon distance from the year 2000 to 2015 (*To note* no male runner was able to run below 2:06:00 before the year 2002)

From 1980 to 1998, the median age of marathon finishers in the United States increased for both males (34.0–38.0 years) and females (31.3–34.0 years) (Chorley et al. 2002). The percent of marathon finishers who are classified as junior (<20 years) has declined from 5 to 1 %, whereas the masters (>40 years) has climbed from 26 to 40 % (Chorley et al. 2002). Based on the explosive growth in the total number of finishers as described above, however the total number of finishers in the juniors has stayed relatively unchanged, while the number of masters has markedly increased representing the most rapidly growing age group (Chorley et al. 2002).

#### 2.1.1.2 Biomechanical Facts About Marathon Running

When analyzing the historical development of the marathon world record, a steady increase in performance can be observed in both female and male runners (Fig. 2.2a, b). Starting with a winning time of 2:55:18 in 1908 in men and 3:40:22 in 1926 in female, representing a mean running speed of 14.44 and 11.49 km/h, respectively, the to date world records are 2:02:57 [Dennis Kipruto Kimetto (KEN), 2014, Berlin] and 2:15:25 [Paula Radcilffe (GBR), 2003, London], resulting in an increase in the running speed of 43 % in male and 63 % in female up to mean

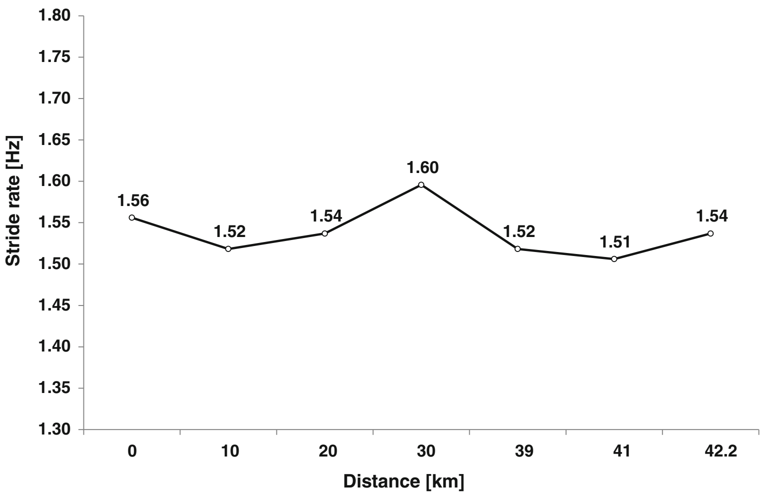


**Fig. 2.3** Stride rate across the marathon distance of the word-record holder Dennis Kimetto at the Berlin Marathon in 2014

running speeds of 20.59 and 18.70 km/h, respectively. To note, that these world record times represent impressive mean race paces of 2:55, respectively 3:12 min: sec per kilometer. The average marathon running velocity for the age group 20–34 (unpublished data of the New York Marathon 2015) is approximately 2.8 m/s (10 km/h). However, not only a steady improvement of the world record can be observed, but also the total amount of runners that are able to run very fast marathon times (i.e. below 2:06:00) has dramatically increased (Fig. 2.2c). While in the years 2002 and 2003 first time four runners were able to run below 2:06:00, up to present (2015) the number has increased to >55 different runners.

On average marathon runners need approximately 20,000 strides (Nigg 2010) with a range of 11,400–26,000 strides. Based on a video analysis of various sections of the marathon (unpublished data), the current world record holder demonstrated a quite stable mean stride rate of 1.54 Hz (1.51–1.60 Hz), representing a stride length of 3.71 m (3.57–3.79 m) resulting in approximately 11,400 strides (Fig. 2.3).

The question arises, about the factors that have contributed to this steady development in performance in both female and male marathon runners. The answer is multifactorial, with e.g. enhanced professionalization in combination with higher possibility to earn money with running (Salz and Steinkirchner 2010), optimized training regimes (Saunders et al. 2006), optimized performance diagnostics and control (Higginson 2009; Wunsch and Schwameder 2015), individual optimized running technique, improved regeneration strategies, improvements in running equipment such as footwear or functional clothing (Ali et al. 2011; Worobets et al. 2013), nutrition strategies during preparation phase but also during the marathon (Buell et al. 2013; Stellingwerff 2012), fast marathon courses, etc.

## 2.1.2 *Injury Related Aspects with Marathon Running*

### 2.1.2.1 Prevalence of Running Injuries

During the course of a year, approximately two-thirds of runners sustain at least one injury that causes an interruption in their normal training (Lysholm and Wiklander 1987). However, for runners training for marathons, the yearly incidence rate can be as high as 90 % (Satterthwaite et al. 1996). According to a review of Van Gent et al. (2007) the overall incidence of lower extremity injuries in long distance runners in preparation to or during a marathon varied from 19 to 79 %. In other studies in which non-lower-extremity injuries were also described and included, the reported incidence for injuries ranged from 26 to 92 % (Bennell et al. 1996; Bovens et al. 1989; Kretsch et al. 1984; Lun et al. 2004; Macera et al. 1989, 1991; Maughan and Miller 1983; Satterthwaite et al. 1999; Walter et al. 1989; Wen 2007). To note here, that older, more experienced runners were shown to be less affected by injury (Marti et al. 1988; Taunton et al. 2003).

### 2.1.2.2 Most Common Running Injuries

According to the review of Van Gent et al. (2007) the most common site of lower extremity injuries was the knee (7.2–50.0 % e.g. patellofemoral pain syndrome, Iliotibial band friction syndrome and meniscal injuries), followed by the lower leg (9.0–32.2 % e.g. shin, Achilles tendon, calf, and heel), the foot (5.7–39.3 %), and the upper leg (3.4–38.1 % e.g. hamstrings, thigh, and quadriceps). Less common sites of lower extremity injuries were the ankle (3.9–16.6 %) and the hip/pelvis (3.3–11.5 %) (Kretsch et al. 1984; Nicholl and Williams 1982a, b; Satterthwaite et al. 1999). For both sexes the knee was the most common site for injury, with 36 and 32 % for men and women (Taunton et al. 2003). While men were seen to have hamstring and calf problems more often than women, women tended to have hip problems more than men (Satterthwaite et al. 1999) (Fig. 2.4). Additional complaints for both sexes included tibial stress syndrome, plantar fasciitis, Achilles tendonitis (Maughan and Miller 1983), thigh muscle soreness, blistered feet, chaffing, abrasions, malaise, lateral ankle sprains, alimentary disorders and extreme exhaustion (Satterthwaite et al. 1996, 1999; Taunton et al. 2003).

## 2.1.3 *Epidemiology of Running Injuries*

Injuries in marathon runners can be multifactorial, but are often attributed to training errors (Lysholm and Wiklander 1987). In this context the importance to


**Fig. 2.4** Most common running injuries of the lower extremities for both female and male runners

identify modifiable risk factors—since these factors are under the control of the runner—are highlighted (Cameron 2010). The three most commonly cited independent factors for injury are (1) an increase in weekly mileage too quickly; (2) previous injury; and (3) level of experience (Fredericson and Misra 2007; Marti et al. 1988).

The running distance is one of the strongest risk factors associated with injury, as well as any sudden increase in running mileage or change in training volume or intensity (Macera et al. 1991; Taunton et al. 2003; Van Gent et al. 2007; Walter et al. 1989; Warren and Jones 1987). In addition, Nielsen et al. (2012) suggests that marathon runners should, continually increase their weekly volume before the marathon and runners may be advised to run a minimum of 30 km/week before a marathon to reduce their risk of injury (Fredericson and Misra 2007; Rasmussen et al. 2013). However, from an injury perspective, it remains unclear whether a maximum in the training kilometers per week exist and if an increase in weekly mileage is associated with specific types of running injuries. While Rasmussen et al. (2013) found no differences in running related injuries between runners with 30–60 km/week and more than 60 km/week, Macera et al. (1989) and Walter et al. (1989) reported that an absolute running volume greater than 64 km/week was a significant risk factor for male runners to sustain a running related injury. For knee injuries, strong evidence was found that increasing the training distance progressively per week is a protective factor. However, the relation between distance and injury is not simple and there may be a fine balance between overuse and underconditioning among long distance runners (Olson et al. 2011).

A very strong second predictor is previous injury (Taunton et al. 2003; Walter et al. 1989) with those that had previous musculoskeletal problems, the associated odds ratio was very high (Macera et al. 1991). It is essential that injured runners fully recover before participating in running events to prevent re-injury (Macera et al. 1991; Marti et al. 1988).

Experienced runners were found to be at a decreased risk of injury because they are able to listen to the "language of their body" (Taunton et al. 2003) to avoid overuse injuries and develop musculoskeletal adoptions to running (Satterthwaite et al. 1999) and are more likely to have better baseline training techniques, which may lower the injury rate during the marathon training program (Chorley et al. 2002). In terms of recovery time after a running injury, Satterthwaite et al. (1999) found that injuries of experienced runners heal slower. In contrast Van Middelkoop et al. (2007) reported that runners with a running experience of more than 10 years were more likely to recover faster.

## 2.2 Biomechanics of Running

### *2.2.1 Kinematics*

Kinematics is the branch of mechanics that deals with pure motion, without reference to the masses or forces involved in it. Kinematical analysis in running can be used to determine (1) **Times** e.g. step time (from foot strike to the foot strike of the contralateral foot), stride time (from foot strike to the consecutive set-down of the same foot), step or stride rate (amount of steps/strides per second), ground contact time (the duration from foot strike to toe-off), flight, float or air time (from foot strike to the foot strike of the contralateral foot), swing time (from toe-off to the consecutive foot strike of the same foot); (2) **Distances** e.g. step or stride length (distance covered within one step or stride), oscillation amplitude of the center of mass (COM) in vertical distance, distance of the COM to the heel at foot strike, etc.; and (3) **Angles** e.g. joint angles, foot ground angle, etc.

#### 2.2.1.1 Running Cycle—Definition of Single Phases

According to kinematical analysis the running cycle can be divided into single phases (Fig. 2.5):

**Stance phase** (40 % of the stride cycle): The stance phase can be divided into initial contact (foot contacts the ground), mid stance (at about 50 % of stance, the foot has full contact to the ground) and toe-off (foot leaves the ground). The first phase between initial contact and mid stance is characterized by eccentric work of the lower limb muscles (in particular the quadriceps muscle group) to attenuate the load acting on the runner (Hamner et al. 2010). The COM shows a downward motion, which is related to the flexion of the ankle, hip and in particular the knee joint (Mann and Hagy 1980). At mid stance, when the stance leg has to attenuate the

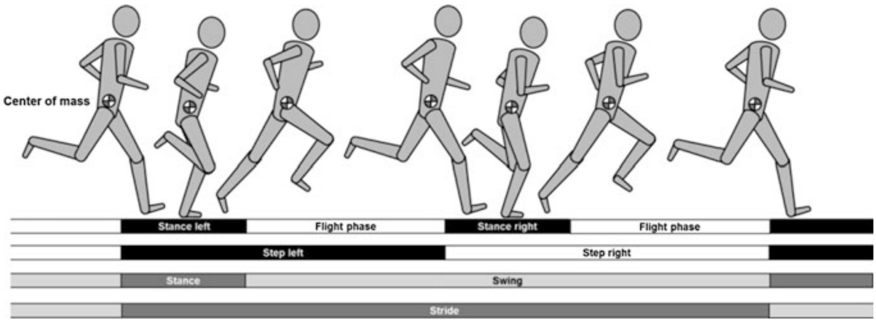


**Fig. 2.5** Phase definitions of the running cycle

entire body mass of the runner, the knee is maximally flexed (30–50° knee flexion) (Malinzak et al. 2001). From this position to toe-off, the lower limb muscles act concentrically to extend the ankle, knee and hip joint to generate an active push-off from the ground. During this phase the M. soleus and M. gastrocnemius are the main contributors to forward and vertical acceleration of the COM (Hamner et al. 2010). Toe-off defines the end of stance and the beginning of the swing phase and flight phase in the running cycle.

**Swing phase** (60 % of the stride cycle): After toe-off the swing leg shows a flexion in the knee and hip joints to form a compact unit, which can be easily moved forward by concentric action of the hip flexors. Thus the knee reaches an optimal height related to the running speed. From this position the swinging limb is preparing for the next ground contact (Dugan and Bhat 2005).

#### 2.2.1.2 Strike Patterns

Foot strikes during running are typically classified as either (1) **rearfoot strike** (heel strike, heel-toe running), in which initial contact is made somewhere on the heel or rear one-third of the foot (foot ground angle >0°, Fig. 2.6a); (2) **midfoot strike**, in which the heel and the region below the fifth metatarsal contact simultaneously (foot ground angle approximately 0°, Fig. 2.6b); or (3) **forefoot strike** (ball running), in which initial contact is made on the front third of the foot, after which heel contact typically follows shortly thereafter (foot ground angle <0°, Fig. 2.6c) (Bertelsen et al. 2012; Hasegawa et al. 2007; Larson et al. 2011). In case of differences in the strike pattern between left and right foot the term **split strike** is used (Kasmer et al. 2013).

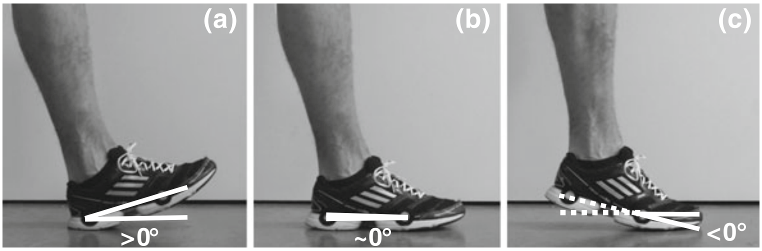


**Fig. 2.6** Definition of strike patterns according to the foot ground angle: (**a**) rearfoot strike, (**b**) midfoot strike and (**c**) forefoot strike (modified from Wunsch and Schwameder 2015)

## *2.2.2 Dynamics/Ground Reaction Forces*

Dynamics is the branch of mechanics that deals with the motion and equilibrium of systems under the action of forces, usually from outside the system. Analyzing the ground reaction force in running, the vertical, the anterior-posterior, and the medio-lateral force component have to be considered (Fig. 2.7).

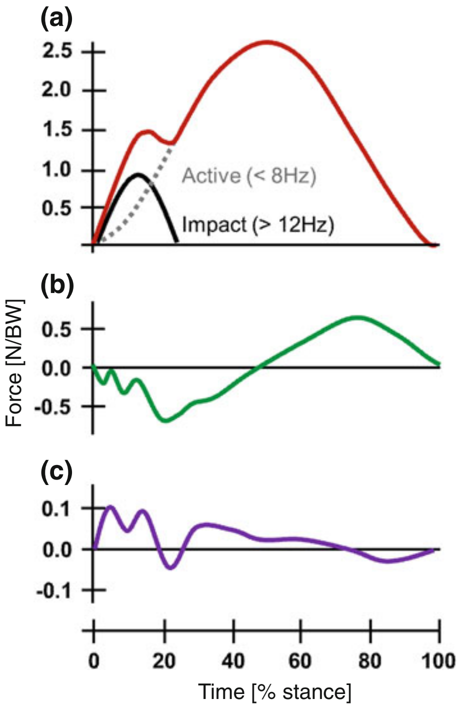


**Fig. 2.7** Illustration of the three force-time curves in (**a**) vertical, (**b**) anterior-posterior (*horizontal*) and (**c**) medio-later direction of one ground contact during running at a running velocity of 3.5 m/s

#### 2.2.2.1 Vertical and Impact Forces During Running

The vertical force is the highest force component in running and reaches peak values of up to three times body weight (Munro et al. 1987). The vertical force component can be divided into two types (1) high frequency (>12 Hz) "impact" forces and (2) low frequency (<8 Hz) "active" forces (Fig. 2.7a). "Impact forces" are forces resulting from a collision between two objects and occur during the first 20–30 ms of stance within the eccentric phase. The expression "active force" is used to indicate that the whole movement is controlled through muscle activity (Nigg 2010).

In heel-toe running, the magnitude of the impact peak of the ground reaction force depends on the deceleration of the foot and part of the leg ("effective mass") and the deceleration of the rest of the body (Nigg 2010). The effective mass in heel-toe running is estimated between 5 and 15 kg (Denoth et al. 1984) and is higher when the knee is more extended at initial contact and smaller when the knee is more bent (Nigg 2010). During forefoot running, the effective mass consists of the forefoot and part of the foot, and is much smaller (1–2 kg) than for heel strikers (Karamers-de Quervarin et al. 2009). This might explain why the impact peak during forefoot running was found to be smaller compared with other strike patterns (Nigg 2010).

In running the vertical force is required to vertically decelerate the body during the first part of stance and thereafter to upward accelerate the COM to provide sufficient flight time to reposition the limbs (Weyand et al. 2010, 2000).

#### 2.2.2.2 Anterior-Posterior Force (Braking and Propulsion)

The horizontal forces can be divided into braking and propulsive forces. The braking forces during running occur during the first half of stance from initial contact to mid stance, while the propulsive forces occur during the second half of stance from mid stance to toe-off. The braking force and braking time should be very small to avoid loss of speed during the braking phase of ground contact (Nummela et al. 2007). Chang and Kram (1999) suggest that in running at constant speed a reduced braking of the COM also requires reduced propulsion to fulfill the running task, which is beneficial in terms of running economy. Furthermore, they reported that the horizontal propulsive forces make up more than one-third of the total metabolic cost required for running at a constant speed.

#### 2.2.2.3 Medio-Lateral Force

Medio-lateral forces are the shear forces during stance phase in running, with a relatively small magnitude compared with the vertical and anterior-posterior forces (Morley et al. 2010). Cavanagh and Lafortune (1980) reported that medio-lateral ground reaction forces show a high variability within and between subjects. The presented course of the medio-lateral force during stance (Fig. 2.7c) consequently is just one individual characteristic of a runner and not a general mean of this ground reaction force component.

## 2.2.3 *Joint Moments, Joint Power and Joint Energy*

### 2.2.3.1 Joint Moments

A joint moment is defined as the product of the force and the perpendicular distance between the point of force application and the axis of rotation (moment arm) (Rodgers and Cavanagh 1984). Joint moments can be divided into external ($M_{external}$) and internal ($M_{internal}$) moments. The external moment is defined by the acting force ($F_{external}$) and the moment arm of a joint ($d_{external}$), defined as the distance between point of force application and joint center. The internal moment is defined by the muscle force ($F_{internal}$) and the moment arm ($d_{internal}$) of the muscle to the joint (Fig. 2.8). In case of that the external moment is equal to the internal moment no joint movement will occur. If the external moment is not equal to the internal moment a joint extension or flexion motion will occur.

As shown in Fig. 2.8 $d_{external}$ is much larger than $d_{internal}$. To realize an active push-off from the ground a high amount of muscle force is required. E.g. when $F_{external}$ = 500 N (i.e. the last part of push-off), $d_{external}$ = 0.25 m and $d_{internal} = 0.04$ m, $F_{internal}$ can be calculated as follows:

$$
\begin{aligned}
& M_{internal} > M_{external} \\
& \rightarrow F_{internal} \cdot d_{internal} > F_{external} \cdot d_{external} \\
& \rightarrow F_{internal} > 500\,\mathrm{N} \cdot 0.25\,\mathrm{m}/0.04\,\mathrm{m} \\
& \rightarrow F_{internal} > 3125\,\mathrm{N}
\end{aligned}
$$

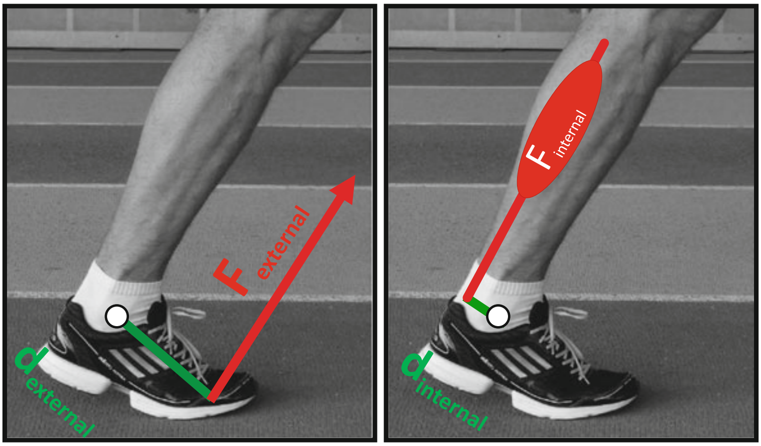


**Fig. 2.8** Illustration of internal and external forces ($F_{internal}$ and $F_{external}$) and the moment arms of the muscle ($d_{internal}$) and the moment arm of a joint with respect to the acting ground reaction force ($d_{external}$ and $F_{external}$)

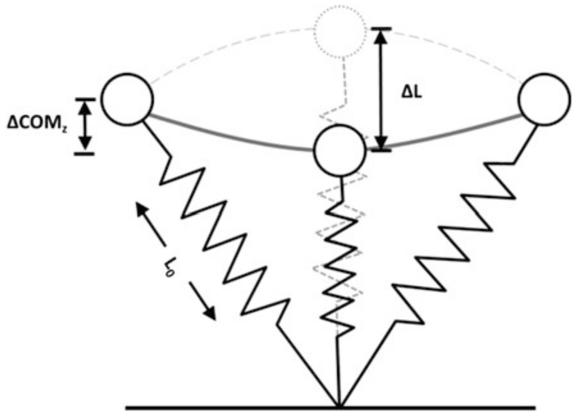


**Fig. 2.9** Illustration of *1* vertical stiffness, based on the maximal vertical displacement of the COM ($\Delta COM_Z$) and *2* leg stiffness based on the peak displacement ($\Delta L$) of the initial leg length $L_0$

#### 2.2.3.2 Stiffness

In literature mainly between three types of stiffness is distinguished (to mention that within these three methods variations in the calculation procedures as regards the determination of leg length, direction of the force, etc. exist). The underlying model for these considerations is a spring-mass model, that considers the entire body as a mass and a spring (Butler et al. 2003) (Fig. 2.9).

**Vertical stiffness ($k_{vert}$)**, is calculated from the maximum ground reaction force ($F_{max}$) during contact divided by the vertical displacement of the COM ($\Delta COM_z$) (McMahon and Cheng 1990b): $k_{vert} = F_{max}/\Delta COM_z$.

**Leg stiffness ($k_{leg}$)**, is calculated as $F_{max}$ divided by the peak displacement ($\Delta L$) of the initial leg length ($L_0$) (Morin et al. 2005): $k_{leg} = F_{max}/\Delta L$.

**Joint stiffness ($k_{joint}$)**, is a measure that can be used to indirectly measure factors related to lower extremity injuries, related mechanically to the attenuation of loads transmitted through the body. Joint stiffness is calculated as the change in the joint moment ($\Delta M$) divided by the change in the joint angle ($\Delta\theta$) in the braking phase: $k_{joint} = \Delta M/\Delta\theta$ (Ferris et al. 1998; Hamill et al. 2014; Stefanyshyn and Nigg 1998b).

#### 2.2.3.3 Joint Power and Joint Energy (Work)

The instantaneous joint power ($P_j$) for the joint j is defined by the joint moment ($M_j$) times the angular velocity of the respective joint ($\omega_j$): $P_j = M_j * \omega_j$.

When integrating the joint power-time curve, the amount of positive (energy generated) and negative (energy absorbed) work done by the referring joint can be calculated.

In running, joint power analysis during stance phase indicates that for each joint there are phases where energy is either absorbed (decrease in joint energy; $E_{abs}$) or generated (increase in joint energy; $E_{gen}$) (Fig. 2.10). The absorption of energy is referred to eccentric muscle contraction, whereas the generation of energy is

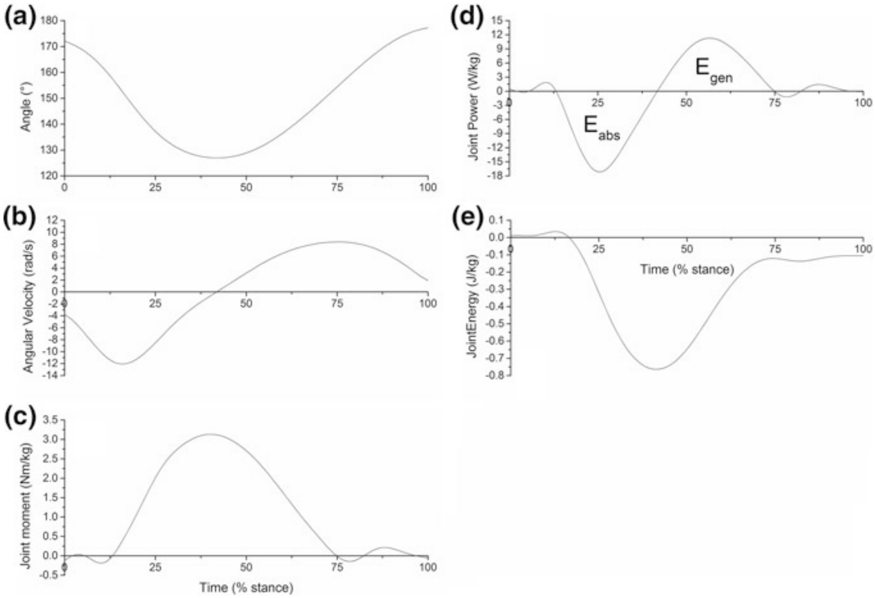


**Fig. 2.10** Example of time courses of the (**a**) knee joint angle, (**b**) angular velocity (differentiation of joint angle) , (**c**) joint moment , (**d**) joint power (joint moment times angular velocity) with $E_{abs}$ indicating energy absorption and $E_{gen}$ indicating energy generation, and (**e**) joint energy (integration of the joint power curve over time) during the stance phase running at a speed of 3 m/s

referred to concentric muscle contraction. Since athletic performance is largely dependent on the mechanical energy which is produced at the joints, understanding the contributions of each of the various lower extremity joints may provide further insight into athletic performance of these activities (Stefanyshyn and Nigg 1998a). In this context, training induced differences (e.g. in the muscle-tendon unit) or running shoes could affect the energy absorbed or generated at the joints. In case of that the absorbed energy is dissipated and not stored for later re-use, it seems beneficial that a reduction of such energy absorption might lead to an increase in performance (Stefanyshyn and Nigg 1998a).

## *2.2.4 Running Economy*

Running economy is typically defined as the metabolic cost required to run sub-maximally at a given velocity and can be determined by measuring the steady-state oxygen consumption ($\dot{V}O_2$) (Anderson 1996; Conley and Krahenbuhl 1980; Saunders et al. 2004). In running, a strong relation between distance running performance and running economy can be observed (Anderson 1996; Conley and Krahenbuhl 1980; Fletcher et al. 2009).

In the classic study of Pollock (1977) it was demonstrated that elite runners with a focus on marathon had lower $\dot{V}O_{2max}$ values but better running economy when compared with those who focused on shorter running distances. From a biomechanical point of view running economy is affected by a number of variables such as stride length and stride rate (Cavanagh and Williams 1982), ground contact time (Nummela et al. 2007), ground reaction forces (Nummela et al. 2007), muscular activity (Kyrolainen et al. 2001; Tartaruga et al. 2012b) vertical oscillation of the COM (Heise et al. 2011; Tartaruga et al. 2012a; Williams and Cavanagh 1987) or the capacity of elements to store and return elastic energy (Gleim et al. 1990). However, descriptive kinematic and kinetic parameters alone cannot explain the complexity of running economy (Kyrolainen et al. 2001; Martin and Morgan 1992; Williams and Cavanagh 1987). It has been suggested that further variables that describe muscle force production (i.e. force-length-velocity relationship and activation) are probably more suitable for explaining running economy (Martin and Morgan 1992).

## 2.3 Predictors of Marathon Performance and Injury

In this chapter selected aspects related to marathon performance and injury are presented.

### *2.3.1 Anthropometrics*

Distance runners come in many sizes and shapes, from tall to short, from stout to lean (Frederick 1990; Frederick and Clarke 1982; Kleindienst et al. 2003). Their anthropometric data show that the average marathoner is 176.5 cm tall and has a body mass of 65.8 kg, with a high range in both parameters (152–197 cm and 40–100 kg) (Kleindienst et al. 2003).

#### 2.3.1.1 Related to Performance

Top-class Kenyan marathon runners (n = 14) with a marathon personal best of <02:07:16 and a training volume of 180–220 km per week were 171.2 ± 6.1 cm tall and had a body mass of 57.7 ± 4.0 kg. Furthermore, this group of elite athletes were characterized by the following anthropometric profile (Vernillo et al. 2013): (1) body density 1.13 ± 0.02; (2) percentage of body fat 8.87 ± 0.07 %; (3) somatotype dispersion mean 4.58 ± 3.62; (4) somatotype attitudinal mean 0.51 ± 0.09; (5) height to weight ratio 44.32 ± 1.06; (6) skinfolds extremity to trunk ratio 0.36 ± 0.11; (7) endomorphy 1.53 ± 0.32; (8) mesomorphy 1.61 ± 1.81 and (9) ectomorphy 3.86 ± 0.78 (Fig. 2.11).

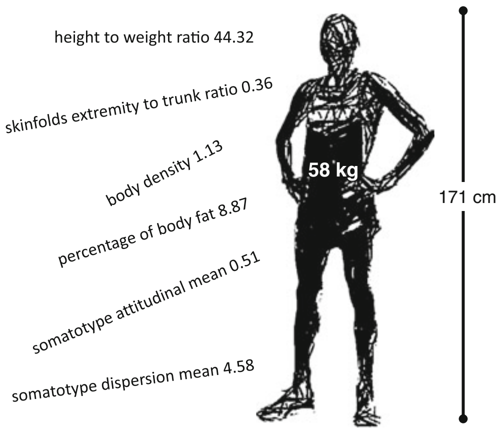


**Fig. 2.11** Anthropometrical characteristics of world elite marathon runners (Vernillo et al. 2013)

In the few studies that compared elite and non-elite marathon runners it was indicated that the anthropometrics of a runner can have a substantial impact on the running performance. Studies comparing elite and non-elite runners showed that a reduced body mass (53 vs. 64 kg in female) (Hagan et al. 1987); (58 vs. 66 kg in male) (Kleindienst et al. 2003; Vernillo et al. 2013) was associated with race times in both genders. Elite versus non-elite females showed a body mass index of 19.6 versus 20.3 and body fat of 14.8 versus 16.4 % (Hagan et al. 1987). With respect to running performance, body mass index (r = 0.52) and body fat (r = 0.52) were positively related to marathon race time in females (Hagan et al. 1987). These findings are in line with Knechtle et al. (2011) who found that body mass index (r = 0.48), body fat (r = 0.56) but also body mass (r = 0.60), skin-fold at pectoral (r = 0.61), mid-axilla (r = 0.69), triceps (r = 0.49), subscapular (r = 0.61), abdominal (r = 0.59), suprailiac (r = 0.55) and medial calf (r = 0.53) site correlated to half-marathon race time of recreational female runners. Elite runners were also less endomorphic but more ectomorphic than the average runners. No significant differences between elite and non-elite runners were found for either bone widths or circumferences (Bale et al. 1986).

Scholz et al. (2008) identified a strong correlation between the moment arm of the Achilles tendon and running economy in highly trained male runners. Smaller moment arms of the Achilles tendon correlated with lower rates of metabolic energy consumption ($r^2 = 0.75$, $P < 0.001$). In contrast to that, Kunimasa et al. (2014) found that the Achilles tendon moment arm was significantly longer and the foot lever ratio was significantly lower in Kenyans than in Japanese distance runners. Furthermore, running performance was positively related to the Achilles tendon moment arm (r = 0.55, $P < 0.001$) and negatively to the foot lever arm (r = −0.45, $P = 0.002$).

Kenyan elite distance runners were shown to have a lower BMI and a more slender body shape compared to Caucasian elite distance runners (Saltin et al. 1995). Furthermore, Kenyan boys' circumference of the lower leg was found to be smaller when compared with Caucasian boys. Therefore the long, slender legs of Kenyans could be advantageous as the energy cost when running is a function of leg mass (Larsen 2003).

Thus, knowledge about the anthropometrics of marathon runners could be useful to practitioners and researchers, providing information for talent identification and development for the assessment of training progression to enhance performance (Vernillo et al. 2013).

#### 2.3.1.2 Related to Injury

A number of authors (McKenzie et al. 1985; Messier and Pittala 1988; Warren and Jones 1987) have reported that runners with high longitudinal arches (pes cavus) are at an increased risk of injury during running, whereas others (Montgomery et al. 1989; Rudzki 1997a; Wen et al. 1997) did not find arch height to be a risk factor in running injuries.

Another anatomical factor that has been suggested to be related to running injuries is the range of motion in plantar and dorsiflexion. Some studies (James and Jones 1990; Messier and Pittala 1988; Warren and Jones 1987) have found that runners with a greater range of motion in plantar flexion have more injuries than runners with less mobility in plantar flexion. On the other hand, van Mechelen et al. (1993) reported no difference in ankle range of motion between a group of runners with lower extremity injuries and a group of controls, and Montgomery et al. (1989) suggested that military recruits who sustained stress fractures during training tended to have less ankle flexibility than recruits who did not sustain these injuries.

Anatomical variables such as tibia varum, rearfoot varus, and leg length discrepancies could be grouped together as lower extremity alignment abnormalities. These factors, and other problems related to alignment of the body have been reported to be associated with overuse running injuries by some authors (James and Jones 1990; Lysholm and Wiklander 1987; Stanish 1984), although others (Montgomery et al. 1989; Rudzki 1997b; Walter et al. 1989; Wen et al. 1997) did not find these associations.

Due to these conflicting reports in the literature we can overall conclude that injury mechanisms in running are highly individual. Further research in this field is desired to identify different types of runners with specific anatomical risk factor profiles.

### *2.3.2 Running Stride Characteristics*

Running speed is defined as the product of stride length and stride rate (Hay 2002): $v(m/s) = strides/sec(Hz) \cdot cycle\ length\ (m)$. Submaximal running speed up to a level of 90 % is primarily regulated by an increase in stride length, while maximal running speed is achieved by an increase in stride rate (Cavanagh and Kram 1989; Mero and Komi 1986; Nummela et al. 2007). The stride cycle splits up into ground contact and swing phase with the former being the only phase during the running cycle in which a runner can produce force and influence stride length and running speed. The increase in stride length results from increasing both vertical and horizontal ground reaction forces affecting the COM motion during stance (Nummela et al. 2007). The primarily task of the swing phase is to reposition the leg and to prepare the consecutive ground contact.

#### 2.3.2.1 Related to Performance

Oxygen uptake increases curvilinear as stride length is either lengthened or shortened compared to the individual preferred condition (Cavanagh and Williams 1982). For a given speed most runners typically choose a stride length/stride rate relation close to the most economic one, determined by $VO_2$ (Cavanagh and Williams 1982; Högberg 1952). To enhance running economy, interventions for altering stride length and stride rate are often approached from a practitioner's perspective. However, most reports in the literature do not support a correlation between running economy and stride length/stride rate. There is evidence that: (1) the level of performance has no influence on the stride length/stride rate relation (Williams and Cavanagh 1987), (2) training interventions with the objective of altering stride length and stride rate have no general effect on running economy (Franch et al. 1998) and (3) seem only be effective for a small group of runners (Morgan et al. 1994).

In terms of ground contact time, short contact times were shown to be beneficial for both running economy and maximal running speed (Nummela et al. 2007). Furthermore, the braking force and braking time should be very small to avoid loss of speed during the braking phase of ground contact, which can be reached by a small horizontal distance between the COM and first contact point of the leg (Nummela et al. 2007).

According to the motion of the COM, most reports in the literature stated that excessive vertical oscillation of the COM is linked to poor running economy (Anderson 1996; Heise and Martin 2001; Saunders et al. 2004; Williams and Cavanagh 1987). The vertical oscillation of the COM requires potentially a wasteful vertical motion in running (Anderson 1996) with an increase in vertical impulse shown to be negatively related to running economy (Heise and Martin 2001).

#### 2.3.2.2 Related to Injury

Heiderscheit et al. (2011) found that subtle increases in step rate can substantially reduce the loading of the hip and knee joints during running and might be beneficial in the prevention and treatment of common running-related injuries. However, it has to be considered that despite the clear reduction in the magnitude of knee joint loading when step rate is increased, the corresponding increase in the number of steps required for a given distance (i.e. loading cycles) may offset any potential benefit to injury reduction. That is, the cumulative loading incurred by the lower extremity may be the same for a given running distance (Heiderscheit et al. 2011). However, running with shorter stride lengths has been suggested to reduce the risk of a tibial stress fracture, despite the greater number of loading cycles (Edwards et al. 2009). Thus, it appears that the benefits of reducing the magnitude of loading outweigh the detriments of increased loading cycles. Whether this same injury-reducing benefit is realized for other common running-related injuries (e.g., anterior knee pain, iliotibial band syndrome) has yet to be determined (Heiderscheit et al. 2011).

## *2.3.3 Strike Pattern*

Runners can be categorized according to their strike pattern (Fig. 2.6). In long distance running the percentages of heel, midfoot, forefoot and split strike among elite runners were 75–89, 3–24, 1–2 and 6 % (Hasegawa et al. 2007; Larson et al. 2011). Novice runners (inactive persons taking up running) showed almost exclusively the heel strike pattern (97–99 %) (Bertelsen et al. 2012). Why runners prefer a certain strike pattern is unclear and seem to be dependent by a sum of influencing factors as e.g. running speed, training, fatigue, presence of shoes, shoe design and surface characteristics such as stiffness, slipperiness, unevenness and roughness (Breine et al. 2014; Lieberman et al. 2015). Thus it was proposed that one's footfall pattern is an intrinsic dynamic which is difficult to alter (Hamill 2012).

### 2.3.3.1 Related to Performance

Differences in strike patterns have led to numerous hypotheses about their advantages and disadvantages (Lieberman et al. 2015). Especially the forefoot running pattern has gained popularity for its claimed benefits of performance enhancement and prevention of injuries (Lieberman et al. 2010; Romanov and Fletcher 2007). It was hypothesized that forefoot running would functionally improve the spring-mass mechanics of running (Lieberman et al. 2010). Forefoot runners activate their plantar flexor muscles 11 % earlier and 10 % longer than heel strikers. This earlier and longer relative activation of the plantar flexors likely enhances the capacity for the passive structures of the foot and ankle to store elastic energy, which could enhance the performance of the active muscle by increasing the storage of elastic strain energy in the cross-bridges and activated titin (Ahn et al. 2014).

However, numerous studies showed that no differences between heel and forefoot strike in terms of running economy could be detected (Ardigo et al. 1995;

Cunningham et al. 2010; Gruber et al. 2013; Larson et al. 2011; Perl et al. 2012). Gruber et al. (2013) e.g. found no differences in $\dot{V}O_2$ or carbohydrate contribution to total energy expenditure (%CHO) between heel and forefoot strikers and Larson et al. (2011) found no significant differences between marathon race times and foot strike patterns both in runners of recreational and sub-elite level. These results suggest that the forefoot pattern is not more economical than the heel strike pattern (Gruber et al. 2013). The strike patterns of the current and previous world record holder furthermore support these inconclusive results. While Dennis Kimetto (WR 2014) could be identified as heel striker the previous world record holder Wilson Kipsang (WR 2013) and Haile Gebrselassie (WR 2007) were mid- and forefoot striker (unpublished data).

#### 2.3.3.2 Related to Injury

Within the last years training programs e.g. the "pose running method" and minimalistic shoe concepts (see Sect. 2.3.5) have been developed to alter the heel strike pattern towards a mid- or forefoot running style (Arendse et al. 2004; Diebal et al. 2012). It was demonstrated that in forefoot running no discernible impact peak in the vertical ground reaction force occurs which was suggested to prevent injuries (Lieberman et al. 2010). However, there is conflicting evidence that the amount of impact is related to injury. Some studies found a relationship between vertical ground reaction forces and injury (Hreljac et al. 2000; Milner et al. 2006) while others did not (Bredeweg and Buist 2011; Hamill et al. 2014; Scott and Winter 1990). According to Hamill et al. (2014) limited evidence exists regarding the mechanical changes that occur with the initial adoption of the forefoot pattern.

An abrupt change of an intrinsic dynamic strike pattern could rather lead to overuse injuries. Perl et al. (2012) reported that running with a non-heel strike pattern increases Achilles tendon impulse by 24 % for each step compared to running with a heel strike pattern. Injury to the Achilles tendon may result from repetitive submaximal loading, creating microscopic tears to collagen fibers which experience high tensile forces during running (Kirkendall and Garrett 1997; Micheli 1986). Furthermore, changing a strike pattern towards a forefoot running style could also lead to an increase in the contact pressure on the metatarsals (Goss and Goss 2012) which increases the risk of osteoarthritis in these joints.

### *2.3.4 Fatigue Effects*

In general fatigue can be divided into peripheral fatigue, occurring within the motor units of muscles, and into central fatigue, in the brain and the spinal cord (Weir et al. 2006). Thus fatigue in running is a multi-dimensional response of the human body which influences the physiological and biomechanical movement pattern to change away from the baseline condition (Hunter and Smith 2007; Maclaren et al. 1989). The internal changes with fatigue could therefore ultimately lead to external kinematic and kinetic changes during a marathon which affect the stride characteristics and contribute to a reduction in running economy up to 15 % (Hunter and Smith 2007; Kyrolainen et al. 2000).

#### 2.3.4.1 Related to Performance

As response to fatigue, athletes slightly change their running kinematics within a stride cycle. According to the spatio-temporal variables a fatigued runner demonstrates a decrease in stride rate (Avogadro et al. 2003; Candau et al. 1998; Dutto and Smith 2002; Garcia-Perez et al. 2013; Gerlach et al. 2005; Hunter and Smith 2007), an increase in stride length (Garcia-Perez et al. 2013) and increase in contact time (Avogadro et al. 2003) or no changes in these parameters (Finni et al. 2003; Morgan et al. 1990). These kinematical changes seem to be necessary to minimize metabolic cost during fatigue (Hunter and Smith 2007). Furthermore, fatigued runners show a minor reduction in the foot ground angle (Christina et al. 2001), an increase in maximal knee flexion and extension (Mizrahi et al. 2000) and an increase in the hip vertical excursion between the highest position to peak acceleration position (Mizrahi et al. 2000).

In terms of stiffness, the relationship between mechanical stiffness and athletic performance is of great interest to the sport and research communities (Brughelli and Cronin 2008). According to the literature, running economy has been shown to be related to stiffness (Dutto and Smith 2002; Heise and Martin 2001; Kerdok et al. 2002; Mcmahon and Cheng 1990a). Kerdok et al. (2002) reported that an increase in lower extremity stiffness induced by running on softer surfaces is associated with greater running economy. In addition Dutto and Smith (2002) reported that as runners become fatigued both stiffness and running economy decreased. Thus, it could be speculated that increased stiffness in a runner is beneficial in order to utilize the stored elastic energy that occurs during the loading portion of stance (Latash and Zatsiorsky 1993) and positively affect running economy.

#### 2.3.4.2 Related to Injury

Fatigue can be hypothesized to be a primarily contributor for running related injuries (Willems et al. 2012). However, a number of different factors seem to affect fatigue induced injuries. Willems et al. (2012) analyzed prior to and after a 20 km run the force distribution underneath the feet via a foot scan. The results showed an increased loading under the whole and medial arch which was in line with other research on this topic (Garcia-Perez et al. 2013; Weist et al. 2004). These findings indicate that the natural damping of the foot is reduced with fatigue in running leading to an increased risk of stress fractures (Weist et al. 2004).

Another risk factor for running related injuries with fatigue might be the vertical ground reaction force (Zadpoor and Nikooyan 2011). However, there are conflicting reports in the literature about the amount of increase or decrease in the vertical ground reaction force with fatigue (Christina et al. 2001; Gerlach et al. 2005; Rabita et al. 2011). In a mathematical modeling study Nikooyan and Zadpoor (2012) showed that actually no changes in the vertical ground reaction force peaks (impact and active) occurred. Yet the soft tissue vibration increased with fatigue. Soft tissue vibrations occur in response to the impact force and are normally heavily damped through the musculoskeletal system (Nigg and Wakeling 2001). The increase in vibration therefore could indicate that the capacity of the human body's protective mechanism decreases with muscle fatigue (Zadpoor and Nikooyan 2010).

In terms of running related injuries also the vertical and leg stiffness should be considered. Dutto and Smith (2002) showed that both vertical and leg stiffness decreased with fatigue. These changes are primarily caused by the reductions in stride rate and can be related to muscle activation of the lower limb (Dutto and Smith 2002). According to the literature there is evidence that increased stiffness would be beneficial in terms of injury prevention, whereas reduced stiffness could enhance the risk of lower limb injuries (Grimston et al. 1991; Hamill et al. 2011; Hennig and Lafortune 1991).

## *2.3.5 Footwear*

In general a running shoe consists of: (1) **The outsole**: Rubber sole to provide enough traction between the shoe and the running surface; (2) **The midsole**: The classic midsole is built of EVA (Ethylene-vinyl acetate) foam and should guarantee sufficient cushioning. Sometimes further cushioning and torsion elements of different material e.g. plastic, gel, air pocket are integrated. The midsole of a running shoe shows a positive drop defined as the difference between heel and forefoot height, and (3) **The insole and the upper**: Both are in contact with the foot and should cope with the foot anatomy and runners needs in comfort (Fig. 2.12).

### 2.3.5.1 Related to Performance

#### Shoe Mass

According to Frederick (1986) a reduction of 100 g shoe mass causes a 1 % reduction in $\dot{V}O_2$. It is estimated that a 1 % decrease in $\dot{V}O_2$ can permit a runner to increase his or her speed per unit cost by approximately 0.049 m/s (Hanson et al. 2011). During a marathon this could save a runner approximately 3 min.


**Fig. 2.12** Components of a running shoe

**Energy Consideration**

An athlete has three major strategies available to improve the work-energy balance during locomotion (1) to store and return energy, (2) to optimize muscle functions and (3) to minimize the loss of energy (Nigg and Segesser 1992). These three factors have to be considered to provide an optimal energy condition in shoe soles.

However, running shoe designs had limited success following the concept of energy return due to the capability of cushioning materials to energy return (Nigg 2010; Shorten 1993). Also the concept of optimizing the musculoskeletal system by optimizing the force-length and force-velocity relationship of specific muscles lacked from scientific support in running (Roy and Stefanyshyn 2006). It is much more known from cycling, where the position of the athlete on the bicycle could be adjusted in order to optimize the length-ranges and velocities in which muscles work (Nigg 2010). Therefore, Nigg and Segesser (1992) suggested that novel running shoe designs should focus on strategies to minimize the energy loss. To follow this concept next to material changes (e.g. adidas Boost) (Nigg et al. 2003; Worobets et al. 2013) also structural changes of running shoe midsoles (e.g. adidas Springblade, On running shoe) were considered. According to Roy and Stefanyshyn (2006) increased midsole longitudinal bending stiffness could lead to improvements in running economy by 1 % and also structural changes of the midsole were identified to improve running economy up to 2 % (Wunsch et al. 2015).

Another strategy of minimizing energy loss relates to the extra energy cost through muscle activity to damp soft tissue vibrations especially at impact during locomotion. The strategy should, therefore, consist in minimizing the negative effects of resonance between the input signal (impact force) and the oscillation frequencies of the soft-tissue vibration (Nigg 2010). However, to the best of our knowledge no shoe-concept was yet designed that addresses this strategy.

**Midsole Thickness, Minimalistic Running Shoes and Barefoot Running**
Minimalistic running shoes (with a very thin and flexible midsole e.g. Vibram FiveFingers, etc.) have been in the focus of attention during the last years especially because of the assumed benefits on performance enhancement and injury prevention (see Sect. 2.3.3). In this context minimalistic running is often associated with running barefoot. At the 1960 Olympic Games in Rome, Abebe Bikila won the marathon with a new world record time of 2:15:16 running the entire race barefoot (Nigg 2010). In terms of running performance it is assumed that the oxygen consumption for running barefoot compared to running with running shoes typically shows a differences of about 4–5 % in favor of running barefoot (e.g. Freychat et al. 1996; Nigg 2010). These benefits in running barefoot might belong to the additional mechanical work an athlete must perform against the gravity as well as to accelerate the additional mass of the shoe during a marathon. The lack of difference found in most of the studies suggests that factors other than shoe mass play important roles in determining the metabolic costs of barefoot versus shod running (Burkett et al. 1985; Divert et al. 2008; Franz et al. 2012; Frederick 1984; Squadrone and Gallozzi 2009). Furthermore, barefoot running is different to running in barefoot or minimalistic shoe concepts. Athletes and their coaches should not expect to instantly replicate barefoot running while running in a minimalist shoe (Bonacci et al. 2013). Thus Nigg (2010) suggests that the performance advantage of barefoot running is small and that barefoot running may only be beneficial for a small group of runners.

**The Preferred Movement Path**
The traditional thinking in the sport shoe and orthotics community is that shoes and orthotics align the skeleton. However, experimental results do not provide conclusive support for this expectation (Nigg 2010). The skeleton of an individual athlete much more attempts for a given task (e.g. heel-toe running) to stay with minimal adjustments in the same movement path, ‘the preferred movement path’ (Nigg 2001; Nigg et al. 2015). The changes (if any) are typically subject specific, small, and often inconsistent (Nigg 2010). Muscle activity is used to ensure that the skeleton stays in this path (Nigg et al. 2015). If this paradigm is correct a good running shoe with the potential to increase running performance would be a shoe that allows or support the skeleton to move in the ‘preferred movement path’. A good shoe would consequently demand less muscle activity for the movement task (Nigg et al. 2015). Furthermore, from a training perspective the paradigm of the ‘preferred movement path’ could also be used to develop running shoes that clearly focus on disturbance of the ‘preferred movement path’ of a joint leading to an increased muscle activity of selected muscles (Nigg 2010).

Furthermore the theory of the ‘preferred movement path’ seems not only be effective regarding performance but also in term of preventing running related injuries (Nigg et al. 2015).

#### 2.3.5.2 Related to Injury

**Midsole Thickness, Minimalistic Running Shoes and Barefoot Running**
Based on current knowledge it is not known whether people running barefoot or in minimalistic shoes have more, equal, or fewer injuries than people running in conventional running shoes (Nigg 2010). From an injury perspective barefoot and minimalistic running could much more be used as a training tool to strengthen the foot muscles (Bruggemann et al. 2005). Barefoot training has been used by coaches for a long time with the suggestion that barefoot training improves the strength of the overall muscular system and that barefoot training strengthens all the muscles, including both the large muscles like the M.biceps femoris and the M.gastrocnemius, as well as small muscles like the M.soleus and the M.peroneus longus leading to a well-balanced development of the muscles crossing the joint (Nigg 2009). Experimental evidence for such training could be provided by studies using wobble board training (Emery et al. 2005; Emery and Meeuwisse 2010). The relationship between wobble board training and barefoot training is that both training forms strengthen the small and large muscles crossing a joint improving motion and control strategies of the athlete (Nigg 2009). However, also different barefoot shoe concepts which can be classified into shoes that try to (a) mimic the shape of the human foot (e.g. adidas 'Feet You Wear' concept), (b) mimic the kinematics of barefoot running (e.g. Nike free concept), and (c) mimic the feeling of barefoot movement (e.g. MBT Masai Barefoot Technology concept) were effective in terms of injury prevention. It has been shown that (a) the 'Feet You Wear' Basketball shoe could reduce the risk of injuries (Meeuwisse et al. 2003), (b) the Nike free running shoe increase the flexor strength of the Metatarsophalangeal (MTP) joint (Potthast et al. 2005) and reduces the rate of injuries (Brüggemann et al. 2008) and (c) MBT shoes were able to reduce low back pain in golfers (Nigg et al. 2006). These findings illustrate the potential of barefoot running or running with barefoot shoe concepts as a suitable trainings tool to prevent injuries. However, translations of these findings into marathon running are not yet available.

**Comfort**
Runners can quickly identify comfortable running shoe. Maybe comfort it is one of the key aspect when buying a certain running shoe. Even though it is very difficult to provide a highly reliable measurement for comfort (Miller et al. 2000; Mundermann et al. 2001) studies assessing comfort of shoe and insert conditions have shown that the choice for a certain shoe concept is highly individual and different functional groups of runners need different shoe designs to feel comfortable (e.g. some participants like a medial support while others not) (Mundermann et al. 2001; Nigg et al. 2015). Furthermore, there is evidence that shoe designs that are more comfortable for a runner are associated with lower movement-related injury frequency than shoe conditions that are less comfortable (Nigg et al. 2015).

## 2.4 Conclusion

Sports Biomechanics has the potential to evaluate aspects of performance and injury in marathon running. The current book chapter illustrates in many sections that there is still discrepancy regarding the performance and injury related factors in marathon running. E.g. questions about the optimal spatio-temporal parameters, the distribution of force components along stance in combination with whole body posture, the optimal strike pattern etc. is still open to debate. In this context it should be considered that each marathon runner is an individual, with specific anthropometrics, training history and stress tolerance. Thus, an optimization of an individual running technique in terms of performance and injury prevention is highly subjective. The same is true for the choice of an optimal running shoe. Future shoe concepts could use novel midsole materials and designs to improve the energy conditions in running, to support the 'preferred movement path' and be comfortable and therefore be individually tailored and custom fit. Within this process a fine balance between performance orientation and injury prevention is desired.

The big open questions in marathon running who will break the 2-h marathon barrier and when this might happen is still open for discussion (Joyner et al. 2011). In 2008, after the race where Haile Gebrselassie won the Berlin Marathon with the world record time of 2:03:59, he told the reporters that he was too old to break the 2-h barrier (Delliaux et al. 2011). It is suggested that a world-class marathon runner from East Africa, aged around 25 or less, could break the 2 h barrier if specifically trained early enough (Olson et al. 2011). Whoever breaks the 2 h will likely have an outstanding running economy combined with an optimal running technique and ideal anthropometrics for marathon running. Modeling using the progression data of the world record times since the late 1920s demonstrates that the time under 2-h will possibly occur by the years 2021–2022 or using a less optimistic model by the year 2035 (Joyner et al. 2011).

## References


Ahn AN, Brayton C, Bhatia T, Martin P (2014) Muscle activity and kinematics of forefoot and rearfoot strike runners. J Sport Health Sci 3(2):102–112. doi:10.1016/j.jshs.2014.03.007

Ali A, Creasy RH, Edge JA (2011) The effect of graduated compression stockings on running performance. J Strength Conditioning Res 25(5):1385–1392. doi:10.1519/JSC.0b013e3181d6848e

Anderson T (1996) Biomechanics and running economy. Am J Sports Med 22(2):76–89

Ardigo LP, Lafortuna C, Minetti AE, Mognoni P, Saibene F (1995) Metabolic and mechanical aspects of foot landing type, forefoot and rearfoot strike, in human running. Acta Physiol Scand 155(1):17–22. doi:10.1111/j.1748-1716.1995.tb09943.x

Arendse RE, Noakes TD, Azevedo LB, Romanov N, Schwellnus MP, Fletcher G (2004) Reduced eccentric loading of the knee with the pose running method. Med Sci Sports Excercise 36 (2):272–277. doi:10.1249/01.MSS.0000113684.61351.B0

Avogadro P, Dolenec A, Belli A (2003) Changes in mechanical work during severe exhausting running. Eur J Appl Physiol 90(1–2):165–170. doi:10.1007/s00421-003-0846-y
Bale P, Bradbury D, Colley E (1986) Anthropometric and training variables related to 10 km running performance. Br J Sports Med 20(4):170–173
Bennell KL, Malcolm SA, Thomas SA, Wark JD, Brukner PD (1996) The incidence and distribution of stress fractures in competitive track and field athletes. A twelve-month prospective study. Am J Sports Med 24(2):211–217
Bertelsen ML, Jensen JF, Nielsen MH, Nielsen RO, Rasmussen S (2012) Footstrike patterns among novice runners wearing a conventional, neutral running shoe. Gait Posture 38(2):354–356. doi:10.1016/j.gaitpost.2012.11.022
Bonacci J, Saunders PU, Hicks A, Rantalainen T, Vicenzino BT, Spratford W (2013) Running in a minimalist and lightweight shoe is not the same as running barefoot: a biomechanical study. Brit J Sport Med 47(6):387–392. doi:10.1136/bjsports-2012-091837
Bovens AM, Janssen GM, Vermeer HG, Hoeberigs JH, Janssen MP, Verstappen FT (1989) Occurrence of running injuries in adults following a supervised training program. Int J Sports Med 10(Suppl 3):S186–S190. doi:10.1055/s-2007-1024970
Bredeweg S, Buist I (2011) No relationship between running related injuries and kinetic variables. Br J Sports Med 45(4):328. doi:10.1136/bjsm.2011.084038.52
Breine B, Malcolm P, Frederick EC, De Clercq D (2014) Relationship between running speed and initial foot contact patterns. Med Sci Sports Exerc 46(8):1595–1603. doi:10.1249/MSS.0000000000000267
Brüggemann GP, Goldmann J, Potthast W (2008) Effects and evaluation of functional footwear. In: Proceedings Orthopaedie und Reha Technik (pp.). Leipzig, Germany
Bruggemann GP, Potthast W, Braunstein B, Niehoff A (2005) Effect of increased mechanical stimuli on foot muscles functional capacity. In: Book of abstracts of the ISB XXth congress-ASB 29th annual meeting, Cleveland
Brughelli M, Cronin J (2008) A review of research on the mechanical stiffness in running and jumping: methodology and implications. Scand J Med Sci Sports 18(4):417–426. doi:10.1111/j.1600-0838.2008.00769.x
Buell JL, Franks R, Ransone J, Powers ME, Laquale KM, Carlson-Phillips A, National Athletic Trainers A (2013) National athletic trainers' association position statement: evaluation of dietary supplements for performance nutrition. J Athletic Training 48(1):124–136. doi:10.4085/1062-6050-48.1.16
Burfoot A (2007) The history of the marathon. Sports Med 37(4–5):284–287
Burkett LN, Kohrt WM, Buchbinder R (1985) Effects of shoes and foot orthotics on VO2 and selected frontal plane knee kinematics 17(1):158–163
Butler RJ, Crowell HP 3rd, Davis IM (2003) Lower extremity stiffness: implications for performance and injury. Clin Biomech 18(6):511–517
Cameron KL (2010) Commentary: time for a paradigm shift in conceptualizing risk factors in sports injury research. J Athletic Training 45(1):58–60. doi:10.4085/1062-6050-45.1.58
Candau R, Belli A, Millet GY, Georges D, Barbier B, Rouillon JD (1998) Energy cost and running mechanics during a treadmill run to voluntary exhaustion in humans. Eur J Appl Physiol 77(6):479–485
Cavanagh PR, Kram R (1989) Stride length in distance running: velocity, body dimensions, and added mass effects. Med Sci Sports Exerc 21(4):467–479
Cavanagh PR, Lafortune MA (1980) Ground reaction forces in distance running. J Biomech 13(5):397–406
Cavanagh PR, Williams KR (1982) The effect of stride length variation on oxygen uptake during distance running. Med Sci Sports Exerc 14(1):30–35. doi:10.1249/00005768-198214010-00006
Chang YH, Kram R (1999) Metabolic cost of generating horizontal forces during human running. J Appl Physiol 86(5):1657–1662
Chorley JN, Cianca JC, Divine JG, Hew TD (2002) Baseline injury risk factors for runners starting a marathon training program. Clin J Sports Med 12(1):18–23

Christina KA, White SC, Gilchrist LA (2001) Effect of localized muscle fatigue on vertical ground reaction forces and ankle joint motion during running. Hum Mov Sci 20(3):257–276. doi:10.1016/S0167-9457(01)00048-3

Conley DL, Krahenbuhl GS (1980) Running economy and distance running performance of highly trained athletes. Med Sci Sports Exerc 12(5):357–360. doi:10.1249/00005768-198012050-00010

Cunningham CB, Schilling N, Anders C, Carrier DR (2010) The influence of foot posture on the cost of transport in humans. J Exp Biol 213(5):790–797. doi:10.1242/Jeb.038984

Delliaux S, Boussuges A, Rossi P (2011) The two-hour marathon, who and when? Haile Gebrselassie in 2000. J Appl Physiol 110(1):288

Denoth J, Gruber K, Keppler M, Riuder H (1984) Forces and torques during sport activities with high acceleration. In SM Perren, E Schneider (eds) Biomechanics current interdisciplinary research, pp 102–106

Diebal AR, Gregory R, Alitz C, Gerber JP (2012) Forefoot running improves pain and disability associated with chronic exertional compartment syndrome. Am J Sports Med 40(5):1060–1067. doi:10.1177/0363546512439182

Divert C, Mornieux G, Freychat P, Baly L, Mayer F, Belli A (2008) Barefoot-shod running differences: shoe or mass effect? Int J Sports Med 29(6):512–518. doi:10.1055/s-2007-989233

Dolgener FA, Kolkhorst FW, Whitsett DA (1994) Long slow distance training in novice marathoners. Res Q Exerc Sport 65(4):339–346. doi:10.1080/02701367.1994.10607638

Dugan SA, Bhat KP (2005) Biomechanics and analysis of running gait. Phys Med Rehabil Clinics N Am 16(3):603–621. doi:10.1016/j.pmr.2005.02.007

Dutto DJ, Smith GA (2002) Changes in spring-mass characteristics during treadmill running to exhaustion. Med Sci Sports Exerc 34(8):1324–1331

Edwards WB, Taylor D, Rudolphi TJ, Gillette JC, Derrick TR (2009) Effects of stride length and running mileage on a probabilistic stress fracture model. Med Sci Sports Excercise 41 (12):2177–2184. doi:10.1249/MSS.0b013e3181a984c4

Emery CA, Cassidy JD, Klassen TP, Rosychuk RJ, Rowe BH (2005) Effectiveness of a home-based balance-training program in reducing sports-related injuries among healthy adolescents: a cluster randomized controlled trial. Can Med Assoc J 172(6):749–754. doi:10.1503/cmaj.1040805

Emery CA, Meeuwisse WH (2010) The effectiveness of a neuromuscular prevention strategy to reduce injuries in youth soccer: a cluster-randomised controlled trial. Br J Sports Med 44 (8):555–562. doi:10.1136/bjsm.2010.074377

Ferris DP, Louie M, Farley CT (1998) Running in the real world: adjusting leg stiffness for different surfaces. 265(1400):989–994. doi:10.1098/rspb.1998.0388

Finni T, Kyröläinen H, Avela J, Komi PV (2003) Maximal but not submaximal performance is reduced by constant-speed 10-km run. J Sports Med Phys Fitness 43(4):411–417

Fletcher JR, Esau SP, Macintosh BR (2009) Economy of running: beyond the measurement of oxygen uptake. J Appl Physiol 107(6):1918–1922. doi:10.1152/japplphysiol.00307.2009

Franch J, Madsen K, Djurhuus MS, Pedersen PK (1998) Improved running economy following intensified training correlates with reduced ventilatory demands. Med Sci Sports Exerc 30(8):1250–1256

Franz JR, Wierzbinski CM, Kram R (2012) Metabolic cost of running barefoot versus shod: is lighter better? Med Sci Sports Exerc 44(8):1519–1525. doi:10.1249/MSS.0b013e3182514a88

Frederick EC (1984) Physiological and ergonomics factors in running shoe design. Appl Ergonomics 15(4):281–287. doi:10.1016/0003-6870(84)90199-6

Frederick EC (1986) Kinematically mediated effects of sport shoe design: a review. J Sports Sci 4(3):169–184. doi:10.1080/02640418608732116

Frederick EC (1990) Biomechanics of distance running. In PR Cavanagh (ed) Human Kinetics, Champaign, IL, pp 307–320

Frederick EC, Clarke J (1982) Sports medicine, sports science. In: Cantsu and Gillespie (eds) Collamore Press, pp 47–57

Fredericson M, Misra AK (2007) Epidemiology and aetiology of marathon running injuries. Sports Med 37(4–5):437–439
Freychat P, Belli A, Carret JP, Lacour JR (1996) Relationship between rearfoot and forefoot orientation and ground reaction forces during running. Med Sci Sports Exerc 28(2):225–232. doi:10.1097/00005768-199602000-00011
Garcia-Perez JA, Perez-Soriano P, Llana S, Martinez-Nova A, Sanchez-Zuriaga D (2013) Effect of overground vs treadmill running on plantar pressure: influence of fatigue. Gait Posture 38(4):929–933. doi:10.1016/j.gaitpost.2013.04.026
Gerlach KE, White SC, Burton HW, Dorn JM, Leddy JJ, Horvath PJ (2005) Kinetic changes with fatigue and relationship to injury in female runners. Med Sci Sports Excerc 37(4):657–663
Gleim GW, Stachenfeld NS, Nicholas JA (1990) The influence of flexibility on the economy of walking and jogging. J Orthop Res 8(6):814–823. doi:10.1002/jor.1100080606
Goss DL, Goss MT (2012) A review of mechanics and injury trends among various running styles. Army Med Depart J
Grimston SK, Engsberg JR, Kloiber R, Hanley DA (1991) Bone mass, external loads, and stress-fracture in female runners. Int J Sport Biomech 7(3):293–302
Gruber AH, Umberger BR, Braun B, Hamill J (2013) Economy and rate of carbohydrate oxidation during running with rearfoot and forefoot strike patterns. J Appl Physiol 115(2):194–201. doi:10.1152/japplphysiol.01437.2012
Hagan RD, Upton SJ, Duncan JJ, Gettman LR (1987) Marathon performance in relation to maximal aerobic power and training indices in female distance runners. Br J Sports Med 21(1):3–7
Hamill J (2012) Rearfoot and forefoot footfall patterns: implications for barefoot running. J Foot Ankle Res 5(1). doi:10.1186/1757-1146-5-S1-K1
Hamill J, Gruber AH, Derrick TR (2014) Lower extremity joint stiffness characteristics during running with different footfall patterns. Eu J Sport Sci 14(2):130–136. doi:10.1080/17461391.2012.728249
Hamill J, Russell EM, Gruber AH, Miller R (2011) Impact characteristics in shod and barefoot running. Footwear Sci 3(1):33–40
Hamner SR, Seth A, Delp SL (2010) Muscle contributions to propulsion and support during running. J Biomech 43(14):2709–2716. doi:10.1016/j.jbiomech.2010.06.025
Hanson NJ, Berg K, Deka P, Meendering JR, Ryan C (2011) Oxygen cost of running barefoot vs. running shod. Int J Sports Med 32(6):401–406. doi:10.1055/s-0030-1265203
Hasegawa H, Yamauchi T, Kraemer WJ (2007) Foot strike patterns of runners at the 15-km point during an elite-level half marathon. J Strength Conditioning Res 21(3):888–893. doi:10.1519/R-22096.1
Hay JG (2002) Cycle rate, length, and speed of progression in human locomotion. J Appl Biomech 18(3):257–270
Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB (2011) Effects of step rate manipulation on joint mechanics during running. Med Sci Sports Exerc 43(2):296–302. doi:10.1249/MSS.0b013e3181ebedf4
Heise GD, Martin PE (2001) Are variations in running economy in humans associated with ground reaction force characteristics? Eur J Appl Physiol 84(5):438–442
Heise GD, Smith JD, Martin PE (2011) Lower extremity mechanical work during stance phase of running partially explains interindividual variability of metabolic power. Eur J Appl Physiol 111(8):1777–1785. doi:10.1007/s00421-010-1793-z
Hennig EM, Lafortune M (1991) Relationships between ground reaction force and tibial bone acceleration parameters. Int J Sport Biomech 7:303–309
Higginson BK (2009) Methods of running gait analysis. Curr Sports Med Rep 8(3):136–141
Högberg P (1952) How do stride length and stride frequency influence the energy-output during running? Arbeitsphysiologie 14:437–441
Hreljac A, Marshall RN, Hume PA (2000) Evaluation of lower extremity overuse injury potential in runners. Med Sci Sports Excerc 32(9):1635–1641

Hunter I, Smith GA (2007) Preferred and optimal stride frequency, stiffness and economy: changes with fatigue during a 1-h high-intensity run. Eu J Appl Pyhsiol 100(6):653–661. doi:10.1007/s00421-007-0456-1

James SL, Jones DC (1990) Biomechanics of distance running. In Cavanagh PR (ed) Human Kinetics, Champaign, IL, pp 249–269

Janssen GM, ten Hoor F (1989) Marathon running: functional changes in male and female subjects during training and contests. Introduction. Int J Sports Med 10(Suppl 3):S118–S123. doi:10.1055/s-2007-1024958

Johnson GO, Thorland WG, Crabbe JM, Dienstbier R, Fagot T (1982) Effects of a 16-week marathon training program on normal college males. J Sports Med Phys Fitness 22(2):224–230

Joyner MJ, Ruiz JR, Lucia A (2011) The two-hour marathon: who and when? J Appl Physiol (1985) 110:275–277 (United States)

Karamers-de Quervarin I, Stacoff A, Stüssi E (2009) Gehen und Laufen. In: Gollhofer A, Müller E (eds) Handbuch Sportbiomechanik. Hofmann-Verlag, Schorndorf, pp 192–213

Kasmer ME, Liu XC, Roberts KG, Valadao JM (2013) Foot-strike pattern and performance in a marathon. Int J Sports Physiol Perform 8(3):286–292. doi:10.23006790

Kerdok AE, Biewener AA, McMahon TA, Weyand PG, Herr HM (2002) Energetics and mechanics of human running on surfaces of different stiffnesses. J Appl Physiol 92(2):469–478. doi:10.1152/japplphysiol.01164.2000

Kirkendall DT, Garrett WE (1997) Function and biomechanics of tendons. Scand J Med Sci Sports 7(2):62–66

Kleindienst F, Brüggemann GP, Krabbe B, Walther M (2003) Functional grading of cushioning and forefoot felxibility characteristics in running shoes. In: Book of abstracts of the footwear biomechanics symposium, Queenstown, New Zealand

Knechtle B, Knechtle P, Barandun U, Rosemann T, Lepers R (2011) Predictor variables for half marathon race time in recreational female runners. Clin Sci 66(2):287–291. doi:10.1590/s1807-59322011000200018

Krebs PS (1992) The effects of cycling and marathon training on eighteen blood parameters. J Sports Med Phys Fitness 32(1):64–69

Kretsch A, Grogan R, Duras P, Allen F, Sumner J, Gillam I (1984) 1980 Melbourne marathon study. Med J Aust 141(12–13):809–814

Kunimasa Y, Sano K, Oda T, Nicol C, Komi PV, Locatelli E, Ito A, Ishikawa M (2014) Specific muscle-tendon architecture in elite Kenyan distance runners. Scand J Med Sci Sports 24(4): e269–e274

Kyrolainen H, Belli A, Komi PV (2001) Biomechanical factors affecting running economy. Med Sci Sports Exerc 33(8):1330–1337. doi:10.1097/00005768-200108000-00014

Kyrolainen H, Pullinen T, Candau R, Avela J, Huttunen P, Komi PV (2000) Effects of marathon running on running economy and kinematics. Eur J Appl Physiol 82(4):297–304. doi:10.1007/s004210000219

Larsen HB (2003) Kenyan dominance in distance running. Comparative biochemistry and physiology Part A 136(1):161–170. doi:10.1016/s1095-6433(03)00227-7

Larson P, Higgins E, Kaminski J, Decker T, Preble J, Lyons D, McIntyre K, Normile A (2011) Foot strike patterns of recreational and sub-elite runners in a long-distance road race. J Sports Sci 29(15):1665–1673. doi:10.1080/02640414.2011.610347

Latash ML, Zatsiorsky VM (1993) Joint Stiffness—Myth or Reality. Hum Mov Sci 12(6):653–692. doi:10.1016/0167-9457(93)90010-M

Lieberman DE, Castillo ER, Otarola-Castillo E, Sang MK, Sigei TK, Ojiambo R, Okutoyi P, Pitsiladis Y (2015) Variation in foot strike patterns among habitually barefoot and shod runners in kenya. Plos One 10(7). doi:10.1371/journal.pone.0131354

Lieberman DE, Venkadesan M, Werbel WA, Daoud AI, D'Andrea S, Davis IS, Mang'Eni RO, Pitsiladis Y (2010) Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature 463(7280):531–535. doi:10.1038/Nature08723

Lun V, Meeuwisse WH, Stergiou P, Stefanyshyn DJ (2004) Relation between running injury and static lower limb alignment in recreational runners. Br J Sports Med 38(5):576–580. doi:10.1136/bjsm.2003.005488

Lysholm J, Wiklander J (1987) Injuries in runners. Am J Sports Med 15(2):168–171

Macera CA, Pate RR, Powell KE, Jackson KL, Kendrick JS, Craven TE (1989) Predicting lower-extremity injuries among habitual runners. Arch Intern Med 149(11):2565–2568. doi:10.1001/archinte.149.11.2565

Macera CA, Pate RR, Woods J, Davis DR, Jackson KL (1991) Postrace morbidity among runners. Am J Prev Med 7(4):194–198

Maclaren DPM, Gibson H, Parry-Billings M, Edwards RHT (1989) A review of metabolic and physiological factors in fatigue. In: Pandolf KB (ed) Exercise and sport sciences reviews. Williams & Wilkins, Baltimore, pp 29–66

Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE (2001) A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clin Biomech 16(5):438–445. doi:10.1016/S0268-0033(01)00019-5

Mann RA, Hagy J (1980) Biomechanics of walking, running, and sprinting. Am J Sports Med 8(5):345–350

Marti B, Vader JP, Minder CE, Abelin T (1988) On the epidemiology of running injuries. The 1984 Bern Grand-Prix study. Am J Sports Med 16(3):285–294

Martin PE, Morgan DW (1992) Biomechanical considerations for economical walking and running. Med Sci Sports Exerc 24(4):467–474

Maughan RJ, Miller JD (1983) Incidence of training-related injuries among marathon runners. Br J Sports Med 17(3):162–165

McKenzie DC, Clement DB, Taunton JE (1985) Running shoes, orthotics, and injuries. Sports Med 2(5):334–347

Mcmahon TA, Cheng GC (1990a) The mechanics of running—how does stiffness couple with speed. J Biomech 23:65–78. doi:10.1016/0021-9290(90)90042-2

McMahon TA, Cheng GC (1990b) The mechanics of running: how does stiffness couple with speed? J Biomech 23(Suppl 1):65–78

Meeuwisse WH, Sellmer R, Hagel BE (2003) Rates and risks of injury during intercollegiate basketball. Am J Sports Med 31(3):379–385

Mero A, Komi PV (1986) Force-, EMG-, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. Eur J Appl Physiol 55(5):553–561

Messier SP, Pittala KA (1988) Etiologic factors associated with selected running injuries. Med Sci Sports Exerc 20(5):501–505

Micheli LJ (1986) Lower extremity overuse injuries. Acta Medica Scandinavica Supplementum 711:171–177

Miller JE, Nigg BM, Liu W, Stefanyshyn DJ, Nurse MA (2000) Influence of foot, leg and shoe characteristics on subjective comfort. Foot Ankle Int 21(9):759–767

Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS (2006) Biomechanical factors associated with tibial stress fracture in female runners. Med Sci Sports Exerc 38(2):323–328. doi:10.1249/01.mss.0000183477.75808.92

Mizrahi J, Verbitsky O, Isakov E, Daily D (2000) Effect of fatigue on leg kinematics and impact acceleration in long distance running. Hum Mov Sci 19(2):139–151. doi:10.1016/S0167-9457(00)00013-0

Montgomery LC, Nelson FR, Norton JP, Deuster PA (1989) Orthopedic history and examination in the etiology of overuse injuries. Med Sci Sport Excerc 21(3):237–243

Morgan D, Martin P, Craib M, Caruso C, Clifton R, Hopewell R (1994) Effect of step length optimization on the aerobic demand of running. J Appl Physiol 77(1):245–251

Morgan DW, Martin PE, Baldini FD, Krahenbuhl GS (1990) Effects of a prolonged maximal run on running economy and running mechanics. Med Sci Sport Exer 22(6):834–840

Morin JB, Dalleau G, Kyrolainen H, Jeannin T, Belli A (2005) A simple method for measuring stiffness during running. J Appl Biomech 21(2):167–180

Morley JB, Decker LM, Dierks T, Blanke D, French JA, Stergiou N (2010) Effects of varying amounts of pronation on the mediolateral ground reaction forces during barefoot versus shod running. J Biomech 26(2):205–214

Mundermann A, Stefanyshyn DJ, Nigg BM (2001) Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors. Med Sci Sports Exerc 33(11):1939–1945

Munro CF, Miller DI, Fuglevand AJ (1987) Ground reaction forces in running: a reexamination. J Biomech 20(2):147–155

Nicholl JP, Williams BT (1982a) Medical problems before and after a popular marathon. Br Med J 285(6353):1465–1466

Nicholl JP, Williams BT (1982b) Popular marathons—forecasting casualties. Br Med J 285(6353):1464–1465

Nielsen RO, Buist I, Sorensen H, Lind M, Rasmussen S (2012) Training errors and running related injuries: a systematic review. Int J Sports Pysical Ther 7(1):58–75

Nigg BM (2001) The role of impact forces and foot pronation: a new paradigm. Clin J Sport Med 11(1):2–9

Nigg BM (2009) Biomechanical considerations on barefoot movement and barefoot shoe concepts. Footwear Sci 1(2):73–79

Nigg BM (2010) Biomechanic of sport shoes, vol 1. University of Calgary, Calgary

Nigg BM, Baltich J, Hoerzer S, Enders H (2015) Running shoes and running injuries: mythbusting and a proposal for two new paradigms: 'preferred movement path' and 'comfort filter'. Br J Sports Med 49(20):1290–1294. doi:10.1136/bjsports-2015-095054

Nigg BM, Emery C, Hiemstra LA (2006) Unstable shoe construction and reduction of pain in osteoarthritis patients. Med Sci Sports Exerc 38(10):1701–1708 00005768-200610000-00003 [pii]

Nigg BM, Segesser B (1992) Biomechanical and orthopedic concepts in sport shoe construction. Med Sci Sports Exerc 24(5):595–602

Nigg BM, Stefanyshyn DJ, Cole G, Stergiou P, Miller J (2003) The effect of material characteristics of shoe soles on muscle activation and energy aspects during running. J Biomech 36(4):569–575. doi:10.1016/S0021-9290(02)00428-1

Nigg BM, Wakeling JM (2001) Impact forces and muscle tuning: a new paradigm. Exerc Sport Sci Rev 29(1):37–41

Nikooyan AA, Zadpoor AA (2012) Effects of muscle fatigue on the ground reaction force and soft-tissue vibrations during running: a model study. IEEE Trans Biomed Eng 59(3):797–804. doi:10.1109/TBME.2011.2179803

Nummela A, Keranen T, Mikkelsson LO (2007) Factors related to top running speed and economy. Int J Sports Med 28(8):655–661. doi:10.1055/s-2007-964896

Olson TP, Taylor BJ, Johnson BD (2011) The two-hour marathon: the importance of breathing economy. J Appl Physiol 110(1):291

Perl DP, Daoud AI, Lieberman DE (2012) Effects of footwear and strike type on running economy. Med Sci Sports Exerc 44(7):1335–1343. doi:10.1249/Mss.0b013e318247989e

Pollock ML (1977) Submaximal and maximal working capacity of elite distance runners. Part I Cardiorespirat Aspects 301:310–322

Potthast W, Niehoff A, Braunstein B, Goldmann JP, Heinrich K, Brüggemann GP (2005) Changes in morphology and function of toe flexor muscles are related to training footwear. In: Book of abstracts of the proceedings of the 7th symposium on footwear biomechanics, pp 118–119

Rabita G, Slawinski J, Girard O, Bignet F, Hausswirth C (2011) Spring-mass behavior during exhaustive run at constant velocity in elite triathletes. Med Sci Sports Excerc 43(4):685–692. doi:10.1249/MSS.0b013e3181fb3793

Rasmussen CH, Nielsen RO, Juul MS, Rasmussen S (2013) Weekly running volume and risk of running-related injuries among marathon runners. Int J Sports Phys Ther 8(2):111–120

Rodgers MM, Cavanagh PR (1984) Glossary of biomechanical terms, concepts, and units. Phys Ther 64(12):1886–1902

Romanov N, Fletcher G (2007) Runners do not push off the ground but fall forwards via a gravitational torque. Sports Biomech 6(3):434–452. doi:10.1080/14763140701491625

Roy JP, Stefanyshyn DJ (2006) Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. Med Sci Sports Exerc 38(3):562–569. doi:10.1249/01.mss.0000193562.22001.e8

Rudzki SJ (1997a) Injuries in Australian Army recruits. Part II: location and cause of injuries seen in recruits. Mil Med 162(7):477–480

Rudzki SJ (1997b) Injuries in Australian Army recruits. Part III: the accuracy of a pretraining orthopedic screen in predicting ultimate injury outcome. Mil Med 162(7):481–483

Saltin B, Larsen H, Terrados N, Bangsbo J, Bak T, Kim CK, Svedenhag J, Rolf CJ (1995) Aerobic exercise capacity at sea level and at altitude in Kenyan boys, junior and senior runners compared with Scandinavian runners. Scand J Med Sci Sports 5(4):209–221

Salz J, Steinkirchner P (2010) Millionenmarkt Marathon. Wer an den Marathon-Läufern verdient. Accessed on 28 Nov 2015. http://www.wiwo.de/unternehmen/millionenmarkt-marathon-wer-an-den-marathon-laeufern-verdient/5693202.html

Satterthwaite P, Larmer P, Gardiner J, Norton R (1996) Incidence of injuries and other health problems in the Auckland Citibank marathon, 1993. Br J Sports Med 30(4):324–326

Satterthwaite P, Norton R, Larmer P, Robinson E (1999) Risk factors for injuries and other health problems sustained in a marathon. Br J Sports Med 33(1):22–26

Saunders PU, Pyne DB, Telford RD, Hawley JA (2004) Factors affecting running economy in trained distance runners. Sports Med 34(7):465–485. doi:10.2165/00007256-200434070-00005

Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, Hawley JA (2006) Short-term plyometric training improves running economy in highly trained middle and long distance runners. J Strength Conditioning Res 20(4):947–954. doi:10.1519/R-18235.1

Scholz MN, Bobbert MF, van Soest AJ, Clark JR, van Heerden J (2008) Running biomechanics: shorter heels, better economy. J Exp Biol 211(Pt 20):3266–3271. doi:10.1242/jeb.018812

Scott SH, Winter DA (1990) Internal forces of chronic running injury sites. Med Sci Sports Exerc 22(3):357–369

Shorten MR (1993) The energetics of running and running shoes. J Biomech 26(Suppl 1):41–51. doi:10.1016/0021-9290(93)90078-S

Squadrone R, Gallozzi C (2009) Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. J Sports Med Phys Fitness 49(1):6–13. doi:10.1016/j.jshs.2014.03.003

Stanish WD (1984) Overuse injuries in athletes: a perspective. Med Sci Sports Exerc 16(1):1–7

Stefanyshyn DJ, Nigg BM (1998a) Contribution of the lower extremity joints to mechanical energy in running vertical jumps and running long jumps. J Sports Sci 16(2):177–186. doi:10.1080/026404198366885

Stefanyshyn DJ, Nigg BM (1998b) Dynamic angular stiffness of the ankle joint during running and sprinting. J Appl Biomech 14:292–299

Stellingwerff T (2012) Case study: nutrition and training periodization in three Elite marathon runners. Int J Sport Nutr Exerc Metab 22:392–400

Tartaruga MP, Brisswalter J, Peyre-Tartaruga LA, Avila AO, Alberton CL, Coertjens M, Cadore EL, Tiggemann CL, Silva EM, Kruel LF (2012a) The relationship between running economy and biomechanical variables in distance runners. Res Q Exerc Sport 83(3):367–375. doi:10.1080/02701367.2012.10599870

Tartaruga MP, Brisswalter J, Peyre-Tartaruga LA, Avila AOV, Alberton CL, Coertjens M, Cadore EL, Tiggemann CL, Silva EM, Kruel LFM (2012b) The relationship between running economy and biomechanical variables in distance runners. Res Q Exerc Sport 83(3):367–375. doi:10.1080/02701367.2012.10599870

Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD (2003) A prospective study of running injuries: the Vancouver Sun Run “In Training” clinics. Br J Sports Med 37(3):239–244

Van Gent RN, Siem D, van Middelkoop M, van Os AG, Bierma-Zeinstra SM, Koes BW (2007) Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. Br J Sports Med 41(8):469–480. doi:10.1136/bjsm.2006.033548 (discussion 480)

van Mechelen W, Hlobil H, Kemper HC, Voorn WJ, de Jongh HR (1993) Prevention of running injuries by warm-up, cool-down, and stretching exercises. Am J Sports Med 21(5):711–719

Van Middelkoop M, Kolkman J, van Ochten J, Bierma-Zeinstra SM, Koes BW (2007) Course and predicting factors of lower-extremity injuries after running a marathon. Clin J Sports Med 17(1):25–30. doi:10.1097/JSM.0b013e3180305e4d

Vernillo G, Schena F, Berardelli C, Rosa G, Galvani C, Maggioni M, Agnello L, La Torre A (2013) Anthropometric characteristics of top-class Kenyan marathon runners. J Sports Med Phys Fitness 53(4):403–408

Walter SD, Hart LE, McIntosh JM, Sutton JR (1989) The Ontario cohort study of running-related injuries. Arch Intern Med 149(11):2561–2564

Warren BL, Jones CJ (1987) Predicting plantar fasciitis in runners. Med Sci Sports Excer 19(1):71–73

Weir JP, Beck TW, Cramer JT, Housh TJ (2006) Is fatigue all in your head? A critical review of the central governor model. Br J Sports Med 40(7):573–586. doi:10.1136/bjsm.2005.023028 (discussion 586)

Weist R, Eils E, Rosenbaum D (2004) The influence of muscle fatigue on electromyogram and plantar pressure patterns as an explanation for the incidence of metatarsal stress fractures. Am J Sports Med 32(8):1893–1898. doi:10.1177/0363546504265191

Wen DY (2007) Risk factors for overuse injuries in runners. Curr Sports Med Reports 6(5):307–313

Wen DY, Puffer JC, Schmalzried TP (1997) Lower extremity alignment and risk of overuse injuries in runners. Med Sci Sports Excer 29(10):1291–1298

Weyand PG, Sandell RF, Prime DN, Bundle MW (2010) The biological limits to running speed are imposed from the ground up. J Appl Physiol 108(4):950–961. doi:10.1152/japplphysiol.00947.2009

Weyand PG, Sternlight DB, Bellizzi MJ, Wright S (2000) Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J Appl Physiol 89(5):1991–1999

Willems TM, Ridder RD, Rosen R (2012) The effect of fatigue on plantar pressure distribution during running in view of running injuries. J Foot Ankle Res 5(Suppl 1). doi:10.1186/1757-1146-5-S1-P33

Williams KR, Cavanagh PR (1987) Relationship between distance running mechanics, running economy, and performance. J Appl Physiol 63(3):1236–1245

Worobets J, Tomaras E, Wannop JW, Stefanyshyn DJ (2013) Running shoe cushioning properties can influence oxygen consumtion. Footwear Sci 5(sup1):S75–S76. doi:10.1080/19424280.2013.799566

Wunsch T, Kröll J, Strutzenberger G, Schwameder H (2015) Biomechanical and metabolic effects of a leaf spring structured midsole in heel-toe running. Footwear Sci. doi:10.1080/19424280.2015.1018342

Wunsch T, Schwameder H (2015) Lauftechniken sportbiomechanisch analysieren. Sportphysio 3. doi:10.1055/s-005-29905

Zadpoor AA, Nikooyan AA (2010) Modeling muscle activity to study the effects of footwear on the impact forces and vibrations of the human body during running. J Biomech 43(2):186–193. doi:10.1016/j.jbiomech.2009.09.028

Zadpoor AA, Nikooyan AA (2011) The relationship between lower-extremity stress fractures and the ground reaction force: a systematic review. Clin Biomech 26(1):23–28. doi:10.1016/j.clinbiomech.2010.08.005

# Chapter 3
# Nutrition for Marathon Running

**Karsten Koehler**

**Abstract** Marathon runners can uniquely benefit from nutritional strategies that support their training responses and/or maximize their performance during the actual race. Promising strategies during marathon training include the adequate provision of dietary energy, macronutrients (carbohydrates, protein), and selected micronutrients (e.g., iron) to meet the increased requirements of prolonged distance running. Nutritional and training approaches aimed at increasing fat oxidation rates or facilitating weight loss may be associated with negative effects and should therefore be conducted with care. During the actual marathon race, runners can benefit from carbohydrate loading strategies that serve to maximize pre-race muscle glycogen storage capacity. Consumption of carbohydrates, fluid, and sodium can prevent preemptive fatigue due to nutrient depletion, and caffeine supplementation can provide ergogenic effects during prolonged running. Because the responses to these nutritional interventions can vary substantially among individuals and require fine tuning depending on factors such as performance level, environmental conditions, designated running pace, propensity for gastrointestinal discomfort, and availability of aid stations during the race, marathon runners are highly encouraged to familiarize themselves with these strategies prior to utilizing them in a competitive setting.

**Keywords** Aerobic performance · Sports nutrition · Muscle glycogen · Iron · Fat adaptation · Caffeine · Hydration

## 3.1 Introduction

Nutrition is a factor of paramount importance for marathon running. Adequate nutritional strategies can support the marathon runner in achieving their goals when training for marathon running as well as in maximizing their performance during

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C. Zinner and B. Sperlich (eds.), *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*, DOI 10.1007/978-3-319-29728-6_3

the actual race (Burke et al. 2007). It is beyond the scope of this chapter to address general nutritional guidelines for individuals who exercise, which are covered in detail elsewhere (Rodriguez et al. 2009). The purpose of this chapter is to discuss and define specific nutritional requirements of the marathon runner and to identify nutritional strategies that have the potential to improve marathon performance. These include strategies to optimize the storage and utilization of energy substrates, the prevention of fatigue secondary to nutrient depletion, and minimization of gastrointestinal distress during prolonged running.

Due to the high load of marathon training, runners uniquely benefit from strategies that allow them to sustain prolonged exercise at a vigorous pace and from interventions that maximize marathon-specific training adaptations (Stellingwerff 2013). Nutritional strategies should be aligned with the goals, requirements, and characteristics of specific training periods and consequently may vary between general training, race-specific training, pre-race preparation periods, and specific training interventions practiced only by a few (elite) runners, such as altitude training or heat acclimatization (Stellingwerff 2012; Burke et al. 2007).

Energy production during prolonged running is almost exclusively aerobic. The primary energy substrates utilized during marathon running are carbohydrates (CHO) originating from intramuscular glycogen stores and plasma glucose, which is maintained by liver glycogen as well ingested dietary CHO, and fatty acids originating from intramuscular triglycerides and plasma free fatty acids, which are mainly derived from adipose tissue (Spriet 2007). However, the relative contribution of these metabolic fuels is largely dependent the relative exercise intensity, which is defined by the actual running pace as well as the runner's training status: Recreational runners who complete the marathon distance in the range of 3.5 h or more exercise at intensities of 60–65 % of maximal oxygen uptake ($VO_2$max), where fat oxidation can account for as much as 60 % of total energy production (Romijn et al. 1993). The relative contribution of fatty acid oxidation is considerable lower in faster recreational runners who exercise at intensities 70–75 % of $VO_2$max, and elite marathon runners who finish a marathon in 2:20 (h:min) or less rely almost exclusively on CHO, as their intensity is between 80 and 90 % of $VO_2$max (Spriet 2007; Stellingwerff 2013). Because CHO storage is limited, the depletion of muscle glycogen and plasma glucose can occur after as little as 90 min of running, which is associated with the onset of fatigue and the need to reduce the running pace (Rapoport 2010; Jeukendrup 2011). Therefore, various nutritional and training strategies that serve to maximize the muscle glycogen storage and minimize the utilization of muscle glycogen and liver-derived plasma glucose during marathon running are associated with performance benefits (Jeukendrup 2011; Stellingwerff 2013).

Another nutritional factor that can limit prolonged running performance during marathon training and competition is adequate hydration, particularly in environmental conditions that facilitate excessive fluid losses (Maughan et al. 2007). This chapter will provide a general overview of hydration strategies and discuss how these can be integrated with other nutritional goals.

The cumulative mechanical impact of prolonged running on the gastrointestinal tract as well as the consumption of beverages and food while exercising is associated with an increased risk of gastrointestinal complications (Pfeiffer et al. 2012). Nutritional strategies will be addressed that can help minimizing these complications and consequently directly impact the well-being and performance of runners.

## 3.2 Nutrition for Marathon Training

During general marathon training, the optimal diet provides nutrients to ensure good overall health of the runner and to maximize the effects of marathon training. Appropriate nutrient timing before, during, or after a workout can help to reduce fatigue, enhance training adaptations and performance, and maximize recovery (Rodriguez et al. 2009). Nutrients that are of particular relevance for general marathon training include overall dietary energy, macronutrients, iron, vitamin C and other dietary antioxidants, and nutrients that modulate immune function. Recommendations for other nutrients, for which there is currently not sufficient scientific evidence that they are specific to marathon running, can be found elsewhere (Rodriguez et al. 2009).

### *3.2.1 Energy, Body Weight, and Body Composition*

Endurance exercise, and particularly long distance running, is associated with a high energy cost (Loucks 2007). The energy cost of distance running can be estimated at approximately 1 kcal (4.2 kJ) per km per kg body weight (1 kcal/kg/km or 4.2 kJ/kg/km), or 1.6 kcal/kg/mile (6.7 kJ/kg/mile) (Maughan and Burke 2002), so that even in recreational runners, energy requirements may be substantially higher than in the general populations. Considering that elite marathon runners may train as much as 150–280 km/week on 2–3 sessions per day (Burke et al. 2007; Stellingwerff 2013), it is not surprising that energy requirements of marathon runners are significantly elevated when compared to their sedentary counterparts. For example, total energy expenditure increased on average by 30 % in sedentary individuals who underwent a 40-week training program while preparing for a half-marathon. As such, their physical activity level, which is defined as the ratio of total energy expenditure to resting energy expenditure, increased from sedentary 1.6 to 2.1 (Westerterp et al. 1992). Even greater physical activity levels of 2.3 and higher have been measured in elite distance runners (Fudge et al. 2006). It is generally recommended that athletes increase their caloric intake to account for the increased energy expenditure of exercise (Rodriguez et al. 2009), but it should be considered that energy balance is not necessarily the goal of marathon training (Loucks 2004, 2007). A low body weight and/or a low body fat percentage are beneficial for marathon running, as they assist fast and economic running and facilitate heat dissipation

(O’Connor et al. 2007). Therefore, many marathon runners may intentionally limit their caloric intake to attain or maintain a low body weight and/or a low body fat percentage (Burke 2007). In fact, issues surrounding inadequate dietary energy intakes are particularly prevalent in marathon running and other endurance sports (Loucks 2004, 2007). Considerations specific for the female marathon runner, who is at an even greater risk of not meeting her energy requirements (Loucks 2007), will be addressed elsewhere in this book, but there is increasing evidence that male endurance athletes are also at risk of energy deficiency (Hagmar et al. 2013). Negative health effects of chronic energy deficiency can include disrupted reproductive function, reduced bone strength and quality, and impaired cardiovascular health (Loucks et al. 2011), and there is preliminary evidence that chronic energy deficiency may also be associated with suboptimal endurance exercise performance (Vanheest et al. 2013). Therefore, marathon runners are advised to define realistic goals for their body weight and body composition, which should not interfere with other nutritional targets. Because appetite and voluntary food intake are not reliable markers of energy requirements, athletes may need to determine the increased energy cost of marathon training to adequately adjust their overall dietary energy intake (Loucks 2007). Observational as well as experimental data suggests that athletes should maintain their energy availability in the range of 30–45 kcal per kg fat-free mass (FFM) even when attempting to lose weight in order to prevent the suppression of metabolic and reproductive functions and to conserve bone health (Loucks 2007). Energy availability, which is defined as the difference between daily caloric intake and the energy expended during exercise and describes the amount of dietary energy that is available for other metabolic functions after deducting the energy cost of exercise training, can be easily monitored by athletes and/or their coaches, as it requires only the assessment of total dietary energy intake, exercise expenditure, and the size of fat-free mass (Loucks 2007).

## *3.2.2 Substrate and Macronutrient Metabolism*

### 3.2.2.1 Carbohydrates

Because of their high training load, it is a crucial ability for the marathon runner to quickly recover between subsequent training bouts. It is undisputed that a high dietary CHO intake can facilitate the restoration of muscle glycogen stores between repeated bouts of prolonged exercise as well as improve performance during subsequent exercise bouts (Costill and Miller 1980; Fallowfield and Williams 1993). Current recommendations acknowledge that CHO requirements are increased during periods of high training load, even though most studies have failed to demonstrate that a high CHO intake during endurance training is associated with improved aerobic performance (Sherman et al. 1993; Achten et al. 2004). Nevertheless, current recommendations for long-distance running suggest a CHO intake of 5–7 g per kg body weight during periods of moderate training loads and a CHO intake of 7–12 g/kg during high-volume periods (Burke et al. 2006; Jeukendrup 2011). Because dietary energy intake may vary depending on energy balance and body weight goals, some athletes may need to increase their CHO intake substantially to reach these recommendations (Burke et al. 2006; Loucks 2007). This is particularly true for female athletes, whose habitual energy and CHO intakes are often lower when compared to their male counterparts (Tarnopolsky and Ruby 2001). For athletes who attempt to lose weight, it may be beneficial to periodize CHO and energy intakes over the course of a competitive season such that CHO and energy intakes are reduced during periods that emphasize body weight and body composition goals and, conversely, CHO and energy intakes are increased during training period that emphasize performance and recovery (Burke et al. 2004).

#### 3.2.2.2 Fat Adaptation

Strategies that are associated with an increased oxidation of fatty acids originating from plasma free fatty and/or intramuscular triglyceride stores will allow athletes to conserve crucial CHO stores during long-distance running (Spriet 2007). Well-controlled laboratory studies have shown that overall fat oxidation can increase by as much as 30 % after several days of endurance training on an iso-caloric diet with a low CHO (2.5 g/kg/d) and high fat content (4.6 g/kg/d) (Burke et al. 2000). This drastic increase in fat oxidation is likely due to the upregulation of beta-oxidative pathways and muscle fatty acid transporters as well as elevated whole body-fat oxidation (Burke and Hawley 2002). The increase in fat oxidation following several days of such a high-fat/low-CHO diet can be maintain even when athletes restore their muscle glycogen stores by consuming a high-CHO diet for 24 h (Burke et al. 2002). However, studies have failed to demonstrate a clear performance benefit of this strategy for trained individuals (Burke and Hawley 2002). High-intensity performance capacity, which can be crucial during surges or sprints, appears to be compromised during high-fat/low-CHO diets secondary to a downregulation of glycolytic pathways during fat adaptation (Havemann et al. 2006), and a low CHO intake has also been linked to an increased risk of injury or disease (Nimmo et al. 2007), reduced well-being, and an impaired capacity to train (Burke et al. 2004). Therefore, fat-adaptation strategies that involve multiple days of training on a high-fat/low-CHO diet are currently not recommended. However, many elite marathon runners periodically conduct single training sessions in a state of low CHO availability, which they achieve by exercising following an overnight fast or after deliberately not restoring CHO stores after workout earlier in the day (Stellingwerff 2013). These single training bouts on low CHO availability are considered physiologically and psychologically challenging and likely results in an improved capacity to oxidize fat without increasing the risk of side effects of prolonged fat adaptation strategies, such as delayed recovery, decreased training quality, immune stress, and impaired high-intensity exercise capacity. Elite marathon runners incorporate 1–5 training sessions with low CHO availability per week into their training regular training schedule, but it is recommended to gradually reduce the frequency of these low CHO availability training bouts during the preparatory training and taper periods prior to the marathon race (Stellingwerff 2013).

### 3.2.3 Protein Requirements

For male endurance athletes, protein requirements can be as high as 1.6 g/kg, which is twice as high as requirements for the sedentary population. Protein requirements for female endurance athletes are about 10–20 % lower than in male athletes, i.e. 1.3–1.45 g/kg (Tarnopolsky 2004). The increased protein requirements in endurance athletes reflect increased levels of amino acid oxidation during prolonged aerobic exercise, which can account for as much as 5 % of the energy expenditure of exercise (Rennie et al. 2006). Protein oxidation and requirements are particularly increased in the CHO-deficient state, during high-intensity exercise, and in the calorie-restricted state (Tarnopolsky 2004). In fact, increased protein during periods of calorie-restricted weight loss may be associated with a preservation of lean mass (Pasiakos et al. 2013). In most endurance athletes, habitual dietary protein intake is in the range or exceeds these requirements, but some athletes may consume inadequate protein from their diet, particularly those who chronically restrict caloric intake (Tarnopolsky 2004).

The co-ingestion of protein and CHO following endurance exercise (<8 h) can enhance muscle resynthesis and stimulate muscle protein synthesis (Moore 2015), and post-exercise consumption of a supplement providing both CHO and protein has been shown to result in improved endurance performance when compared to placebo (Roy et al. 2002). There is no evidence that the ingestion of protein in addition to CHO during endurance exercise is beneficial (Colombani et al. 1999).

### 3.2.4 Micronutrients

#### 3.2.4.1 Iron

Iron is an integral component of the oxygen-carrying molecules hemoglobin and myoglobin and many cellular mechanisms. Reduced iron status is associated with impaired exercise capacity and performance (Zourdos et al. 2015), and adequate iron stores may be particularly critical for adaptations to altitude training (Hawley and Spargo 2007). Due to potentially low dietary iron intake as well as increased iron requirements of endurance training, marathon runners and other endurance athletes are a group that is particular prone to suffer from suboptimal iron status (Zourdos et al. 2015). In many endurance athletes, and particularly in female athletes, dietary iron intake is below the recommendations, and dietary iron intake may further be compromised by diets that provide only few sources of highly bioavailable heme iron, such as meat products, but include large amounts of nutrients that reduce intestinal iron absorption, such as tannins (e.g., in coffee or tea) or phytates (e.g., in legumes or grains).

In addition, prolonged running is associated with increased iron requirements secondary to increased erythrocyte turnover and increased hemolysis and hemoglobinuiria, which can be caused by the destruction of erythrocytes in capillaries in the foot due to the prolonged repeated impacts of running ("foot strike hemolysis"). Other factors for increased iron requirements in endurance athletes include increased iron losses through gastrointestinal bleeding and sweating, as well as altered iron metabolism secondary to the exercise-induced upregulation of hepcidin, a protein involved in iron sequestration (Peeling et al. 2008). The relative contribution of these factors in the pathophysiology of iron status abnormalities in endurance athletes remains poorly understood, but it is well documented that athletes are at increased risk of low iron status when compared to their sedentary counterparts. Whereas the prevalence of iron deficiency anemia, which presents the most severe form of iron status abnormalities characterized by hemoglobin concentrations below the clinical range of 130 g/L in males and 120 g/L in female, is similar among athletes and general population, the prevalence of iron depletion, characterized by low iron storage, is significantly increased in athletes. Among women the risk of low iron status is further elevated due to the iron loss of menstrual bleeding, and the prevalence of iron depletion in female athletes can be as high as 37 %, which is approximately 1.5 times greater than in sedentary women (Fogelholm 1995).

For endurance athletes, it is typically recommended to monitor iron status at regular intervals of 1–2 times per year (Rodriguez et al. 2009). Clinical measures of iron status (Table 3.1) include makers of iron storage, such as ferritin, markers of cellular iron demand, such as soluble transferrin receptor (sTfR), and measures of oxygen transport capacity (hemoglobin, hematocrit). In athletes with iron-deficiency anemia, supplementation with 50–100 mg iron per day is typically associated with improvements in aerobic capacity (Zourdos et al. 2015). In athletes with iron deficiency without anemia, which is typically defined by serum ferritin concentrations below 12–15 μg/L, or iron depletion, defined by ferritin concentrations below 20–35 μg/L, iron supplementation may improve metabolic efficiency, endurance capacity, and endurance performance (Zourdos et al. 2015); whereas, iron supplementation is not associated with performance benefits in athletes with adequate iron status, as indicated by serum ferritin above >35 μg/L. A study among participants of the Zurich marathon revealed that 15 % of male runners demonstrated serum ferritin concentrations that were indicative of iron overload (Mettler and Zimmermann 2010). Because iron supplementation in individuals with adequate iron status can increase the risk of side effects, such as hematochromatosis and iron toxicity, it is critical to monitor iron status prior to supplementation (Zourdos et al. 2015). It is further noteworthy that nutritional interventions that increase dietary iron intake and enhance bioavailability of dietary iron appear at least equally effective in preventing exercise-induced reductions in iron status when compared to iron supplementation (Lyle et al. 1992).

**Table 3.1** Stages of Iron status abnormalities, their effects on marathon-related performance, and their prevalence in marathon runners

| Stage | Clinical marker | Performance and health effects[c] | Prevalence in marathon runners[d] |
|---|---|---|---|
| Low iron storage (iron depletion) | Serum ferritin <20–35 μg/L[c] | Unclear, but supplementation recommended | |
| Iron deficiency | Serum ferritin <15 μg/L[b] sTfR: log (serum ferritin) ≥4.5[b] | Impaired marathon performance, immunosuppression, reduced bone strength; reversible by supplementation | Women: 28 % Men: 1.6 % |
| Iron-deficiency anemia | Hemoglobin <120 g/L (women)[a] Hemoglobin <130 g/L (men)[a] | Impaired oxygen transport capacity, reduced aerobic capacity; reversible by supplementation | Women: 14 % Men: <1 % |
| Iron overload | Serum ferritin >150 μg/L (women)[a] Serum ferritin >200 μg/L (men)[a] | Hemochromatosis, iron toxicity | Women: 4.7 % Men: 15 % |

[a]World Health Organization (2007)
[b]Sinclair and Hinton (2005)
[c]Zourdos et al. (2015)
[d]Mettler and Zimmermann (2010)

#### 3.2.4.2 Antioxidants

The role of dietary antioxidants for marathon runners and other endurance athletes remains only poorly understood. It is well documented that due to their increased oxygen turnover, endurance athletes are exposed to greater levels of oxidative stress, and that supplementation of dietary antioxidants, primarily vitamin C and vitamin E, can attenuate measures of oxidative stress (Gomez-Cabrera et al. 2015). However, recent evidence suggests that the generation of oxidative stress per se is not critical and in fact may trigger cellular mechanism that are required for optimal training responses to aerobic exercise training. Because supplementation of high doses of dietary antioxidants may have the capacity to attenuate the beneficial effects of chronic exercise training (Gomez-Cabrera et al. 2015; Braakhuis 2012), antioxidant supplementation is not recommended for marathon runners and other endurance athletes. However, consumption of antioxidants in the range of the recommended daily allowance from food sources should provide health benefits without impairing training responses, and should be highly encouraged in athletes (Pingitore et al. 2015; Braakhuis 2012).

### 3.2.5 *Training of Race Strategies*

Particularly during later stages of marathon training, athletes are encouraged to incorporate race-specific strategies into their training regimen. Strategies that may warrant familiarization include CHO loading strategies as well as the consumption of CHO and fluid under race-like conditions. These strategies will be discussed in detail in the next section (Table 3.2).

**Table 3.2** Recommended nutritional strategies during marathon training

| Nutrient/strategy | Goal | Recommended intake | Comment |
|---|---|---|---|
| Energy | Weight stability: meet energy requirements<br>Weight loss: energy deficit, but prevent negative metabolic and health effects | Energy Availability[f]:<br>45 kcal/kg FFM/d[a]<br>Energy Availability:<br>>30 kcal/kg FFM/d[a] | Energy expenditure of running: ~1 kcal/kg/km (1.6 kcal/kg/mile) |
| Carbohydrates | Meet CHO requirements | Moderate training loads: 5–7 g/kg/d[b]<br>High training loads: 7–12 g/kg[b] | |
| Protein | Meet protein requirements | Men: 1.6 g/kg[c]<br>Women: 1.3–1.45 g/kg[c] | Sufficient in most athletes<br>Elevated during periods of energy deficit |
| Iron | Prevent iron depletion and deficiency | Men: 8 mg/d[d]<br>Women (age ≤50): 18 mg/d[d]<br>Women (age >51): 8 mg/d[d] | Highly bioavailable iron (heme iron); facilitate iron absorption (vitamin C)<br>Monitor iron status 1–2 times/year |
| Fat adaptation | Single training sessions in low glycogen state | 1. Overnight fasted, exercise directly after waking, no food<br>2. Limited CHO intake after first session of the day<br>Consume normal CHO following session[e] | 1–5 times per week, reduce frequency closer to race |

[a]Loucks et al. (2011)
[b]Burke (2007)
[c]Tarnopolsky (2004)
[d]Food and Nutrition Board (2015)
[e]Stellingwerff (2012)
[f]Energy Availability = Dietary Energy Intake − Exercise Energy Expenditure

## 3.3 Nutrition for the Marathon Race

Nutritional strategies before and during the race that provide nutrients at the right time can help to delay the onset of fatigue. Because of the paramount importance of CHO as metabolic fuel for marathon running (Spriet 2007), interventions that maximize muscle glycogen stores prior to the race and approaches during the race that minimize the breakdown of muscle glycogen and liver-derived plasma glucose are the most promising strategies to improve marathon performance. Well-being and marathon performance can further be improve through the consumption of fluid and minerals for the prevention of dehydration and the use of supplements with ergogenic effects.

### *3.3.1 Carbohydrate Loading*

During running events with a distance of 30 km and greater, fatigue is typically caused by the depletion of muscle glycogen stores and/or hypoglycemia (Burke 2007; Jeukendrup 2011), and is well established that fatigue can be delayed substantially when muscle glycogen stores are increased (Rapoport 2010). Even though to this date no field studies have explicitly been conducted over the full marathon distance, it is unequivocally accepted that marathon runners uniquely benefit from maximized muscle glycogen storage (Burke 2007). Studies conducted in the 1960s and 1970s established a classical model of muscle glycogen supercompensation, according to which a 3- or 4-day phase of prolonged exercise with a very low dietary CHO intake (≤15 % of dietary energy from CHO), which served to fully deplete muscle glycogen stores, followed by a 3–4 day loading phase with minimal exercise and very a high CHO intake (≥70 % of dietary energy from CHO), doubled muscle glycogen stores (Karlsson and Saltin 1971). As such, this strategy allowed runners to maintain their designated pace for a longer duration and improved 30-km running performance (Karlsson and Saltin 1971; Williams et al. 1992). However, these early studies also revealed potential side effects associated with glycogen supercompensation strategies, which included fatigue and difficulties to maintain the high training load required to fully deplete muscle glycogen as well as gastrointestinal distress secondary to the drastic change in dietary CHO intake between the depletion and loading phase (Burke 2007). Follow-up studies showed that a similar increase in muscle glycogen could be attained when the CHO intake during the initial depletion phase was maintained at normal levels (50 %) while runners exercised to deplete their muscle glycogen stores (Sherman et al. 1981). Recent experiments have shown that as little as 24 h of carbohydrate loading are sufficient to maximize muscle glycogen storage when athletes consume a diet with very high CHO content of 10 g/kg or more (Sedlock 2008). Most but not all data further suggest that slightly higher muscle glycogen levels can be attained when CHO loading occurs after the depletion of glycogen stores through prolonged low-intensity or short, high-intensity exercise due to increased rates of glucose transport and glycogen synthesis in the glycogen-depleted state. Elevated muscle glycogen levels can be maintained for 3–5 days when refraining from prolonged exercise (Sedlock 2008).

Even though several carbohydrate loading strategies exist, all seem to result in a similar increase in muscle glycogen storage, which is unarguably effective in improving the ability to sustain prolonged endurance exercise (Jeukendrup 2011). For endurance events lasting 90 min or longer, successful CHO loading can improve performance by as much as 2–3 % (Jeukendrup 2011), even though individual performance effects may vary substantially among individuals (Sedlock 2008).

The amount of CHO consumed during CHO loading is crucial for the success of CHO loading and should be in the range of 10–12 g/kg/day; whereas the type and source of dietary CHO do not seem to impact the capacity to store muscle glycogen (Sedlock 2008). Nevertheless, foods with a high CHO content may be required for athletes to consume the recommended amounts of CHO, and foods with a high glycemic index have been utilized in situations when the time for CHO loading is limited (Sedlock 2008). Despite earlier reports, it has been shown that female athletes exhibit a similar capacity to increase their muscle glycogen stores when compared to their male counterparts. However dietary intake must be adjusted to meet the CHO and energy needs of CHO loading, which may require female athletes, whose energy and CHO intake is habitually lower than that of male athletes, to drastically increase their dietary intake (Tarnopolsky and Ruby 2001). Studies of dietary practices of marathon runners suggest that even though most athletes self-report the consumption of a high CHO diet prior to a race, actual pre-race CHO intake may be substantially lower than recommended. This finding has been attributed to nutritional naivety as well as conscious attempts to avoid CHO-rich foods (Burke and Read 1987).

Because glycogen storage is associated with water retention, maximized CHO storage is typically associated with a weight gain of typically 1–2 kg (Jeukendrup 2011). For most athletes, the benefits of increased muscle glycogen storage will outweigh side effects, but some athletes may be opposed to gaining weight. Because most CHO loading strategies require substantial changes in the diet and as such can be associated with gastrointestinal distress, athletes should be encouraged to include their preferred CHO loading strategies into their training regimen as to test them prior to the actual marathon race.

#### 3.3.1.1 Pre-race Diet

During the final hours before a marathon, athletes should consume primarily easily digestible foods in order to minimize the stress on the digestive system. Theories that the ingestion of CHO shortly before exercise could be associated with performance detriments secondary to insulin-induced hypoglycemia and subsequent performance detriments are not only unfounded (Jeukendrup 2011). In fact, CHO ingestion as close as 5–15 min prior to exercising has been shown to evoke similar beneficial metabolic effects as the ingestion of CHO during exercise (Jeukendrup 2011).

### 3.3.2 Maintaining High Rates of CHO Oxidation During the Marathon

The beneficial effects of CHO ingestion during prolonged running have been known since the 1920s. CHO can improve performance during prolonged running through central effects as well as metabolic effects, which include the preservation of muscle glycogen, the provision of additional fuels, and the prevention of hypoglycemia (Tsintzas and Williams 1998; Carter et al. 2004; Millard-Stafford et al. 1997; Tsintzas et al. 1996). The effects of CHO ingestion on aerobic performance are dose-dependent, and performance benefits are maximized at CHO intake rates of 60–80 g/h (Stellingwerff 2013; Jeukendrup 2011). However, the utilization of exogenous CHO as metabolic fuel is limited by the ability to absorb CHO in the small intestine, and marathon runners should carefully choose CHO sources that allow them to maximize the potential of CHO ingestion. When CHO are consumed from a single source, such as glucose or glucose polymers (e.g. maltodextrin), exogenous CHO oxidation is limited by the saturation of intestinal glucose transporters (SGLT-1), which occurs at around 60 g/h during exercise (Baker and Jeukendrup 2014). However, the addition of fructose, which is absorbed using alternate intestinal transporters (GLUT-1), can increase exogenous CHO oxidation to approximately 90 g/h (Baker and Jeukendrup 2014). Because high CHO oxidation rates have been reported following the administration of fluids, bars, and gels (Jeukendrup 2011), it seems likely that exogenous CHO oxidation is independent of the form of CHO administration. Limitations in intestinal CHO absorption and oxidation appear to be independent of body size. Consequently, the benefits of CHO supplementation may be even greater in smaller and lighter marathon runners, who are may be able to oxidize similar amounts of exogenous CHO when compared bigger and heavier athletes (Stellingwerff 2013). On the other hand, slower runners, in whom CHO oxidation is lower due to the lower rate of energy expenditure as well as a lower contribution of CHO oxidation to total energy expenditure, may not require as much as 60–90 g/h of exogenous CHO while running a marathon. Athletes are strongly encouraged to adjust their CHO intake strategies to match CHO oxidation rates at their designated race pace.

### 3.3.3 Hydration

Depending on environmental conditions, hydration can become a performance-limiting factor during marathon running. Documented fluid loss during marathon running and similar distance running events is typically in the range of 0.7–1.8 L/h, but may be as high as 3.7 L/h in some individuals (Cheuvront and Haymes 2001). Athletes are generally advised to start exercising in a euhydrated state, which can be achieved through ingesting sufficient fluid (5–7 mL/kg) approximately 4 h before competition and subsequent monitoring of the urinary response (Sawka et al. 2007). While exercising, it is recommended to consume adequate fluid in order to maintain the level of dehydration below 2 % of body weight (Sawka et al. 2007; Maughan and Shirreffs 2008). If dehydration is expected to be greater due to severe environmental conditions and/or limited fluid availability during the race, hyperhydration strategies may be warranted. Hyperhydration can be achieved through consumption of excess fluid and the addition of sodium to retain fluid and prevent increased urination (Shirreffs et al. 2004). Athletes are strongly advised to refrain from prohibited hyperhydrating substances, such as glycerol (World Anti-Doping Agency 2015). Even though endurance performance capacity can be negatively impacted by dehydration by as little as 2 % of body weight, it has been repeatedly reported that faster marathon runners tend to consume less fluid and attain greater levels of dehydration when compared to slower runners (Zouhal et al. 2011). However, it remains unclear if these findings suggest that mild dehydration is associated with a performance benefit or that faster and better-trained runners have a greater tolerance for dehydration. Because fluid losses can vary considerable among individuals and are strongly dependent on both individual and environmental factors, athletes are advised to determine their individual fluid loss, and consequently their requirements, under race-like conditions. Exercise-associated fluid losses can easily be determined by assessing changes in body weight over the course of an exercise bout (Sawka et al. 2007).

Over-consumption of fluid may result in dilutional hyponatremia, which is associated with moderate side effects, such as confusion, weakness, and fainting (plasma $Na^+$ <130 mmol/L), and severe side effects, including seizures, coma, and death (plasma $Na^+$ <126 mmol/L). In most marathon runners, hyponatremia is asymptomatic, but it can become severe in a small proportion of athletes (Kipps et al. 2011), and has been linked to several fatalities during marathon races. Hyponatremia can be prevented by avoiding excessive fluid intake and by attenuating sodium depletion in runners who excrete salty sweat (Montain et al. 2006), which can be reached through sodium consumption of approximately 450 mg/h from sports beverages or the addition of salt to water and other beverages (Murray 2007).

### *3.3.4 Gastrointestinal Distress*

Between 10 and 95 % of marathon runners experience gastrointestinal distress during prolonged running (Jeukendrup 2011). Most runners report only mild symptoms, such as nausea and dizziness, but more severe complications such as stomach and intestinal cramps, vomiting, and diarrhea, may occur in a small proportion of runners and can impair marathon performance substantially (Pfeiffer et al. 2012). Gastrointestinal distress occurs more frequently during running when compared to other endurance exercise modes and its incidence increases with exercise duration (Peters et al. 1999). Dietary factors that have been linked to gastrointestinal distress include the consumption of highly concentrated sports drinks and particularly highly concentrated CHO and/or large amounts of CHO that may exceed the intestinal CHO absorption capacity (Sareban et al. 2015; Pfeiffer et al. 2009; Rehrer et al. 1992). Because the gastrointestinal CHO tolerance varies considerably among individuals and may adapt to chronically high CHO exposure, marathon runners are encouraged to determine their individual tolerable rate of CHO consumption (Jeukendrup 2011). Other dietary risk factors associated with gastrointestinal distress include the consumption of fat, fiber, or protein while exercising (Peters et al. 1999). Because none of these nutrients are essential for marathon running, athletes should be discouraged from products that contain significant amounts of fat, fibers, or protein during the race. There is limited evidence that gastrointestinal distress could be linked to insufficient fluid consumption and dehydration during prolonged running (Stuempfle et al. 2013), so that fluid consumption, particularly early during the race, may reduce the risk of gastrointestinal distress. Vitamin E has been linked to the prevention of intestinal ischemia during prolonged exercise (Buchman et al. 1999), but there is no evidence that vitamin E supplementation could reduce gastrointestinal distress during marathon running.

### *3.3.5 Supplements*

Despite an ever-growing market for sport supplements, compelling scientific evidence for an ergogenic effect exists for only a few substances. Caffeine, when consumed at doses of 3–6 mg/kg, improves aerobic endurance performance (Burke 2008) so that caffeine can have ergogenic effects for marathon runners. Caffeine has a half-life of 3–5 h and should be consumed approximately 1 h prior to the race. Slower runners may benefit from additional caffeine consumption (1 mg/kg) after approximately 2 h into the race. Even when caffeine is consumed at later stages during the race, performance benefits are still likely to occur (Burke 2008). Side effects of caffeine exist and include insomnia, tachycardia, headache, and nausea. The effects of caffeine on exercise performance are not altered by habituation or withdrawal (Van Soeren and Graham 1998), and the use of caffeine is currently not banned by the World Anti-Doping Agency (2015).

A novel group of supplements that may be of interest for marathon runners are dietary sources of nitrates, which can increase metabolic efficiency during submaximal exercise via generation of nitric oxide. As such, acute supplementation of nitrate or consumption of nitrate-rich beetroot juice of can reduce oxygen demand and increase running economy during prolonged exercise (Barnes and Kilding 2015). However, it remains to be determined whether these effects translated into meaningful improvements in aerobic performance, and consequently, in marathon performance (Table 3.3).

**Table 3.3** Recommended nutritional strategies for race preparation and during the marathon race

| Nutrient/Strategy | Goal | Recommended intake | Comment |
|---|---|---|---|
| *Race preparation* | | | |
| Carbohydrate loading | Maximize intramuscular glycogen stores | 10–12 g/kg/d, 1–3 d prior to race[a]<br>High glycemic index if limited to 1 d[b] | Exercise to deplete glycogen stores prior to loading may increase effects; Little or no exercise during loading |
| Hydration | Begin race in euhydrated state | 5–7 mL/kg, 4 h prior to exercise[c] | Test urine response |
| Caffeine | Ergogenic effects | 3–6 mg/kg, 1 h prior to race[d] | Side effects possible |
| *During the race* | | | |
| Carbohydrates | Maximize exogenous CHO oxidation | 60–90 g/h[e] | For >60 g/h: multiple CHO sources (e.g. glucose + fructose (2:1)) |
| Hydration | Maintain dehydration <2 % | Fluid intake should match sweat loss | Considerable individual variation, dependent on environmental conditions |
| Sodium | Prevent hyponatremia | 450 mg/h[f] | |

[a]Burke et al. (2007)
[b]Sedlock (2008)
[c]Sawka et al. (2007)
[d]Burke (2008)
[e]Baker and Jeukendrup (2014)
[f]Murray (2007)

### *3.3.6 Practical Recommendations*

During the marathon race, athletes typically have access to aid stations, where fluid (e.g., water and sports drinks) and food (e.g. bars, gels, and bananas) are provided. Based on availability, preference, and needs, some athletes may consider carrying small amounts of food and/or fluid in pockets or attached to belts. Elite runners typically have access to reserved aid stations so that they can consume customized drinks and foods during the race without having to carry these items.

The use of sport drinks is beneficial because they provide fluid as well as CHO and electrolytes, which both facilitate fluid uptake. The CHO concentration of a drink can be tailored such that both fluid and CHO requirements are met. CHO concentrations should be in the range of 4–8 % (40–80 g per L) in order to avoid delayed gastric emptying as well as gastrointestinal complications, both factors that are more likely to occur when CHO concentrations exceed 8 % (80 g per L) (Baker and Jeukendrup 2014). If needed, additional CHO can be supplied through sport gels, sport bars, or confectionary. Athletes are highly encouraged to incorporate their individual race strategies in their marathon training in order to familiarize themselves with the strategies and refine and adjust them based on individual needs and preference.

It is well documented that most athletes consume notably less CHO and fluid than recommended while competing in long-distance running events. Further, habitual CHO intake is typically lower during running when compared to other endurance events (Pfeiffer et al. 2012). Factors that may be associated with the limited ad libitum intake of CHO and fluid include individual habits, nutritional beliefs and practices, difficulties to consume large amounts of fluid while running, the need to slow down at aid stations, and the emergence of sport gels, which allow runners to consume CHO with less fluid.

## 3.4 Nutrition After the Marathon

Only very limited research is available how nutritional strategies may affect the recovery from marathon running. The main nutritional goals after marathon completion involve facilitation of the recovery of fluid and glycogen stores and providing nutrients to support recovery and repair mechanisms and immune function.

Depending on the level of dehydration attained during the race, adequate rehydration may be the most significant nutritional strategy following marathon running. The goal of rehydration is to regain fluid balance, and the effectiveness of rehydration is dependent on the amount of fluid consumed as well as the electrolyte content, primarily that of sodium. Effective rehydration can only be attained if the amount of fluid consumed covers both the fluid loss that occurred during the race (mainly in form of sweat) and additional fluid losses that occur in response to ingesting fluid (primarily in form of urine). As such, it is recommended to consume at least 1.5 times the fluid volume that was lost during exercise (Maughan et al. 1997). A higher sodium concentration will replace sodium sweat losses and retain fluid by reducing urinary output. Therefore, a sodium concentration of 50–60 mmol/L (1.1–1.4 g/L) is considered beneficial with regards to the effectiveness of rehydration when compared to a lower sodium concentration (20–25 mmol/L; 0.5–0.6 g/L) (Maughan et al. 1997).

Repletion of muscle glycogen stores typically occurs within 24–48 h when adequate CHO (7–10 g/kg) are consumed (Burke et al. 2004). Because glycogen synthesis is impaired in damaged muscle fibers (Costill et al. 1988), more CHO may be needed to restore muscle glycogen levels. However, in contrast to other events where athletes may have to compete again shortly after the race, fast glycogen repletion recovery should not be a high priority for marathon runners (Burke et al. 2004). Co-ingestion of protein along with may be beneficial for glycogen resynthesis and may provide additional amino acids for post-exercise protein synthesis. However, it remains unknown if these strategies actually translate into improved recovery and/or improved performance during subsequent marathon races.

Marathon running and other prolonged endurance exercise is associated with an increased risk of upper respiratory tract infections (URTI). Even though the pathophysiology of URTI is not fully understood, it has been hypothesized that prolonged heavy exertion is associated with an acute suppression of immune function (Akerström and Pedersen 2007). Whereas results from a meta-analysis suggest that supplementation of vitamin C may be associated with a reduction in infection rates in populations who are exposed to severe exercise (Akerström and Pedersen 2007), prospective studies have failed to demonstrate the capacity of vitamin C supplementation to attenuate the immune response to prolonged running (Peters et al. 2001). Supplementation of glutamine, an amino acid that is essential for lymphocyte proliferation, has been associated with reduced infection rates following marathon and ultramarathon running in one study (Castell and Newsholme 1997). However, subsequent trials have failed to confirm these effects. For other supplements, including colostrum, which contains bovine immunoglobulins, there is no scientific evidence the infection risk following prolonged exerting exercise such as marathon running can be reduced by supplementation (Akerström and Pedersen 2007).

Alcohol consumption following strenuous exercise may impair muscle glycogen synthesis and can negatively impact the post-exercise inflammatory response. More importantly, alcohol consumption may interfere with other recovery strategies (Vella and Cameron-Smith 2010). Therefore, athletes are encouraged to refrain from excessive alcohol consumption following the race and focus their attention on nutritional and hydration strategies that are effective in supporting post-marathon recovery.

## 3.5 Summary

Promising nutritional strategies that can be beneficial for marathon runners include provision of adequate energy, carbohydrates, and protein, to address the increased nutrient requirements of marathon training. Prolonged training in a state of low carbohydrate or energy availability can be associated with negative health and performance effects and should therefore be avoided by marathon runners. Both nutritional and exercise-related factors explain why marathon runners are at particular risk of inadequate iron status. The importance of carbohydrates for marathon performance is highlighted by the fact that pre-race strategies aimed at maximizing muscle glycogen storage as well as the administration of additional carbohydrates during the race are highly likely to improve marathon performance. Adequate provision of fluid and sodium is particularly important in conditions when dehydration and/or sodium losses may limit performance or impact health negatively. Among the many supplements available for marathon runners, clear scientific evidence for a performance benefit is only available for caffeine. Incorporating these strategies into their training routine will allow marathon runners to become familiarized with these strategies and test their individual responsiveness prior to the actual race.

## References

Achten J, Halson SL, Moseley L, Rayson MP, Casey A, Jeukendrup AE (2004) Higher dietary carbohydrate content during intensified running training results in better maintenance of performance and mood state. J Appl Physiol 96:1331–1340 (1985)

Akerström TC, Pedersen BK (2007) Strategies to enhance immune function for marathon runners: what can be done? Sports Med 37:416–419

Baker LB, Jeukendrup AE (2014) Optimal composition of fluid-replacement beverages. Compr Physiol 4:575–620

Barnes KR, Kilding AE (2015) Strategies to improve running economy. Sports Med 45:37–56

Braakhuis AJ (2012) Effect of vitamin C supplements on physical performance. Curr Sports Med Rep 11:180–184

Buchman AL, Killip D, Ou CN, Rognerud CL, Pownall H, Dennis K, Dunn JK (1999) Short-term vitamin E supplementation before marathon running: a placebo-controlled trial. Nutrition 15:278–283

Burke LM (2007) Nutrition strategies for the marathon: fuel for training and racing. Sports Med 37:344–347

Burke LM (2008) Caffeine and sports performance. Appl Physiol Nutr Metab 33:1319–1334

Burke LM, Angus DJ, Cox GR, Cummings NK, Febbraio MA, Gawthorn K, Hawley JA, Minehan M, Martin DT, Hargreaves M (2000) Effect of fat adaptation and carbohydrate restoration on metabolism and performance during prolonged cycling. J Appl Physiol 89:2413–2421 (1985)

Burke LM, Hawley JA (2002) Effects of short-term fat adaptation on metabolism and performance of prolonged exercise. Med Sci Sports Exerc 34:1492–1498

Burke LM, Hawley JA, Angus DJ, Cox GR, Clark SA, Cummings NK, Desbrow B, Hargreaves M (2002) Adaptations to short-term high-fat diet persist during exercise despite high carbohydrate availability. Med Sci Sports Exerc 34:83–91

Burke LM, Kiens B, Ivy JL (2004) Carbohydrates and fat for training and recovery. J Sports Sci 22:15–30

Burke LM, Loucks AB, Broad N (2006) Energy and carbohydrate for training and recovery. J Sports Sci 24:675–685

Burke LM, Millet G, Tarnopolsky MA, International Association of Athletics Federations (2007) Nutrition for distance events. J Sports Sci 25(Suppl 1):S29–S38

Burke LM, Read RS (1987) A study of carbohydrate loading techniques used by marathon runners. Can J Sport Sci 12:6–10

Carter JM, Jeukendrup AE, Jones DA (2004) The effect of carbohydrate mouth rinse on 1-h cycle time trial performance. Med Sci Sports Exerc 36:2107–2111

Castell LM, Newsholme EA (1997) The effects of oral glutamine supplementation on athletes after prolonged, exhaustive exercise. Nutrition 13:738–742

Cheuvront SN, Haymes EM (2001) Thermoregulation and marathon running: biological and environmental influences. Sports Med 31:743–762

Colombani PC, Kovacs E, Frey-Rindova P, Frey W, Langhans W, Arnold M, Wenk C (1999) Metabolic effects of a protein-supplemented carbohydrate drink in marathon runners. Int J Sport Nutr 9:181–201

Costill DL, Miller J (1980) Nutrition for endurance sport: carbohydrate and fluid balance. Int J Sports Med 1:2–14

Costill DL, Pearson DR, Fink WJ (1988) Impaired muscle glycogen storage after muscle biopsy. J Appl Physiol 64:2245–2248 (1985)

Fallowfield JL, Williams C (1993) Carbohydrate intake and recovery from prolonged exercise. Int J Sport Nutr 3:150–164

Fogelholm M (1995) Indicators of vitamin and mineral status in athletes' blood: a review. Int J Sport Nutr 5:267–284

Food and Nutrition Board, IOM, National Academies (2015) Dietary reference intakes (DRIs): recommended dietary allowances and adequate intakes, elements (Online). Available: http://www.nal.usda.gov/fnic/DRI/DRI_Tables/recommended_intakes_individuals.pdf. Accessed November 2015

Fudge BW, Westerterp KR, Kiplamai FK, Onywera VO, Boit MK, Kayser B, Pitsiladis YP (2006) Evidence of negative energy balance using doubly labelled water in elite Kenyan endurance runners prior to competition. Br J Nutr 95:59–66

Gomez-Cabrera MC, Salvador-Pascual A, Cabo H, Ferrando B, Viña J (2015) Redox modulation of mitochondriogenesis in exercise. Does antioxidant supplementation blunt the benefits of exercise training? Free Radic Biol Med 86:37–46

Hagmar M, Berglund B, Brismar K, Hirschberg AL (2013) Body composition and endocrine profile of male olympic athletes striving for leanness. Clin J Sport Med: Official J Can Acad Sport Med 23:197–201

Havemann L, West SJ, Goedecke JH, Macdonald IA, St Clair Gibson A, Noakes TD, Lambert EV (2006) Fat adaptation followed by carbohydrate loading compromises high-intensity sprint performance. J Appl Physiol 100:194–202 (1985)

Hawley JA, Spargo FJ (2007) Metabolic adaptations to marathon training and racing. Sports Med 37:328–331

Jeukendrup AE (2011) Nutrition for endurance sports: marathon, triathlon, and road cycling. J Sports Sci 29(Suppl 1):S91–S99

Karlsson J, Saltin B (1971) Diet, muscle glycogen, and endurance performance. J Appl Physiol 31:203–206

Kipps C, Sharma S, Pedoe DT (2011) The incidence of exercise-associated hyponatraemia in the London marathon. Br J Sports Med 45:14–19

Loucks AB (2004) Energy balance and body composition in sports and exercise. J Sports Sci 22:1–14

Loucks AB (2007) Low energy availability in the marathon and other endurance sports. Sports Med 37:348–352

Loucks AB, Kiens B, Wright HH (2011) Energy availability in athletes. J Sports Sci 29(Suppl 1): S7–S15

Lyle RM, Weaver CM, Sedlock DA, Rajaram S, Martin B, Melby CL (1992) Iron status in exercising women: the effect of oral iron therapy vs increased consumption of muscle foods. Am J Clin Nutr 56:1049–1055

Maughan RJ, Burke L (2002) Sports nutrition. Blackwell Science, Malden

Maughan RJ, Leiper JB, Shirreffs SM (1997) Factors influencing the restoration of fluid and electrolyte balance after exercise in the heat. Br J Sports Med 31:175–182

Maughan RJ, Shirreffs SM (2008) Development of individual hydration strategies for athletes. Int J Sport Nutr Exerc Metab 18:457–472

Maughan RJ, Watson P, Shirreffs SM (2007) Heat and cold: what does the environment do to the marathon runner? Sports Med 37:396–399

Mettler S, Zimmermann MB (2010) Iron excess in recreational marathon runners. Eur J Clin Nutr 64:490–494

Millard-Stafford M, Rosskopf LB, Snow TK, Hinson BT (1997) Water versus carbohydrate-electrolyte ingestion before and during a 15-km run in the heat. Int J Sport Nutr 7:26–38

Montain SJ, Cheuvront SN, Sawka MN (2006) Exercise associated hyponatraemia: quantitative analysis to understand the aetiology. Br J Sports Med 40:98–105 (discussion 98–105)

Moore DR (2015) Nutrition to support recovery from endurance exercise: optimal carbohydrate and protein replacement. Curr Sports Med Rep 14:294–300

Murray B (2007) The role of salt and glucose replacement drinks in the marathon. Sports Med 37:358–360

Nimmo MA, Ekblom B (2007) Fatigue and illness in athletes. J Sports Sci 25(Suppl 1):S93–S102

O'Connor H, Olds T, Maughan RJ (2007) Physique and performance for track and field events. J Sports Sci 25(Suppl 1):S49–S60

Pasiakos SM, Cao JJ, Margolis LM, Sauter ER, Whigham LD, McClung JP, Rood JC, Carbone JW, Combs GF, Young AJ (2013) Effects of high-protein diets on fat-free mass and muscle protein synthesis following weight loss: a randomized controlled trial. FASEB J 27:3837–3847

Peeling P, Dawson B, Goodman C, Landers G, Trinder D (2008) Athletic induced iron deficiency: new insights into the role of inflammation, cytokines and hormones. Eur J Appl Physiol 103:381–391

Peters EM, Anderson R, Nieman DC, Fickl H, Jogessar V (2001) Vitamin C supplementation attenuates the increases in circulating cortisol, adrenaline and anti-inflammatory polypeptides following ultramarathon running. Int J Sports Med 22:537–543

Peters HP, Bos M, Seebregts L, Akkermans LM, Van Berge Henegouwen GP, BOL E, Mosterd WL, De Vries WR (1999) Gastrointestinal symptoms in long-distance runners, cyclists, and triathletes: prevalence, medication, and etiology. Am J Gastroenterol 94:1570–1581

Pfeiffer B, Cotterill A, Grathwohl D, Stellingwerff T, Jeukendrup AE (2009) The effect of carbohydrate gels on gastrointestinal tolerance during a 16-km run. Int J Sport Nutr Exerc Metab 19:485–503

Pfeiffer B, Stellingwerff T, Hodgson AB, Randell R, Pöttgen K, Res P, Jeukendrup AE (2012) Nutritional intake and gastrointestinal problems during competitive endurance events. Med Sci Sports Exerc 44:344–351

Pingitore A, Lima GP, Mastorci F, Quinones A, Iervasi G, Vassalle C (2015) Exercise and oxidative stress: potential effects of antioxidant dietary strategies in sports. Nutrition 31:916–922

Rapoport BI (2010) Metabolic factors limiting performance in marathon runners. PLoS Comput Biol 6:e1000960

Rehrer NJ, van Kemenade M, Meester W, Brouns F, Saris WH (1992) Gastrointestinal complaints in relation to dietary intake in triathletes. Int J Sport Nutr 2:48–59

Rennie MJ, Bohé J, Smith K, Wackerhage H, Greenhaff P (2006) Branched-chain amino acids as fuels and anabolic signals in human muscle. J Nutr 136:264S–268S

Rodriguez NR, di Marco NM, Langley S (2009) American college of sports medicine position stand. Nutrition and athletic performance. Med Sci Sports Exerc 41:709–731

Romijn JA, Coyle EF, Sidossis LS, Gastaldelli A, Horowitz JF, Endert E, Wolfe RR (1993) Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. Am J Physiol 265:E380–E391

Roy BD, Luttmer K, Bosman MJ, Tarnopolsky MA (2002) The influence of post-exercise macronutrient intake on energy balance and protein metabolism in active females participating in endurance training. Int J Sport Nutr Exerc Metab 12:172–188

Sareban M, Zügel D, Koehler K, Hartveg P, Zügel M, Schumann U, Steinacker JM, Treff G (2015) Carbohydrate Intake in form of gel is associated with increased gastrointestinal distress but not with performance differences when compared to liquid carbohydrate ingestion during simulated long-distance triathlon. Int J Sport Nutr Exerc Metab

Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ, Stachenfeld NS (2007) American College of Sports Medicine position stand. Exercise and fluid replacement. Med Sci Sports Exerc 39:377–390

Sedlock DA (2008) The latest on carbohydrate loading: a practical approach. Curr Sports Med Rep 7:209–213

Sherman WM, Costill DL, Fink WJ, Miller JM (1981) Effect of exercise-diet manipulation on muscle glycogen and its subsequent utilization during performance. Int J Sports Med 2:114–118

Sherman WM, Doyle JA, Lamb DR, Strauss RH (1993) Dietary carbohydrate, muscle glycogen, and exercise performance during 7 d of training. Am J Clin Nutr 57:27–31

Shirreffs SM, Armstrong LE, Cheuvront SN (2004) Fluid and electrolyte needs for preparation and recovery from training and competition. J Sports Sci 22:57–63

Sinclair LM, Hinton PS (2005) Prevalence of iron deficiency with and without anemia in recreationally active men and women. J Am Diet Assoc 105:975–978
Spriet LL (2007) Regulation of substrate use during the marathon. Sports Med 37:332–336
Stellingwerff T (2012) Case study: nutrition and training periodization in three elite marathon runners. Int J Sport Nutr Exerc Metab 22:392–400
Stellingwerff T (2013) Contemporary nutrition approaches to optimize elite marathon performance. Int J Sports Physiol Perform 8:573–578
Stuempfle KJ, Hoffman MD, Hew-Butler T (2013) Association of gastrointestinal distress in ultramarathoners with race diet. Int J Sport Nutr Exerc Metab 23:103–109
Tarnopolsky M (2004) Protein requirements for endurance athletes. Nutrition 20:662–668
Tarnopolsky MA, Ruby BC (2001) Sex differences in carbohydrate metabolism. Curr Opin Clin Nutr Metab Care 4:521–526
Tsintzas K, Williams C (1998) Human muscle glycogen metabolism during exercise. Effect of carbohydrate supplementation. Sports Med 25:7–23
Tsintzas OK, Williams C, Wilson W, Burrin J (1996) Influence of carbohydrate supplementation early in exercise on endurance running capacity. Med Sci Sports Exerc 28:1373–1379
van Soeren MH, Graham TE (1998) Effect of caffeine on metabolism, exercise endurance, and catecholamine responses after withdrawal. J Appl Physiol 85:1493–1501 (1985)
Vanheest JL, Rodgers CD, Mahoney CE, De Souza MJ (2013) Ovarian suppression impairs sport performance in junior elite female swimmers. Med Sci Sports Exerc
Vella LD, Cameron-Smith D (2010) Alcohol, athletic performance and recovery. Nutrients 2:781–789
Westerterp KR, Meijer GA, Janssen EM, Saris WH, ten Hoor F (1992) Long-term effect of physical activity on energy balance and body composition. Br J Nutr 68:21–30
Williams C, Brewer J, Walker M (1992) The effect of a high carbohydrate diet on running performance during a 30-km treadmill time trial. Eur J Appl Physiol Occup Physiol 65:18–24
World Anti-Doping Agency (2015) The 2015 prohibited list. International Standard (Online). Available: https://wada-main-prod.s3.amazonaws.com/resources/files/wada-2015-prohibited-list-en.pdf. Accessed Nov 2015
World Health Organization (2007) Assessing the iron status of populations (Online). Available: http://www.who.int/nutrition/publications/micronutrients/anaemia_iron_deficiency/9789241596107.pdf. Accessed Nov 2015
Zouhal H, Groussard C, Minter G, Vincent S, Cretual A, Gratas-Delamarche A, Delamarche P, Noakes TD (2011) Inverse relationship between percentage body weight change and finishing time in 643 forty-two-kilometre marathon runners. Br J Sports Med 45:1101–1105
Zourdos MC, Sanchez-Gonzalez MA, Mahoney SE (2015) A brief review: the implications of iron supplementation for marathon runners on health and performance. J Strength Cond Res 29:559–565

# Chapter 4
# Thermoregulation During Marathon Running

**Oliver Faude and Lars Donath**

**Abstract** Marathon running is a popular psycho-physiologically demanding endurance event. As the majority of the energy produced during a marathon is converted to heat, marathon running is considered a particular challenge for the thermoregulatory system. Marathon race pace is mainly determined by the oxygen uptake ($VO_2$) which can be maintained during the run and running economy. Marathons are run at an exercise intensity ranging from 60 to 85 % of maximal oxygen uptake, depending on the performance level of the athlete. The main factors affecting thermoregulation are environmental conditions and dehydration. Changes in body temperature during long-distance endurance events are the result of heat production and heat loss. Premature hyperthermia negatively affects the cardio-vascular, central nervous and muscular systems. Excess heat can be dissipated by radiation, conduction, convection and evaporation. Radiation ($\sim$60 %) and convection ($\sim$15 %) make up the greatest part of heat loss at rest. The proportion of heat loss by evaporation rises during exercise and is the main source for heat dissipation in warm environmental conditions. The two main physiological mechanisms for heat loss are an increase in skin blood flow and sweating. Potential strategies to counter health risks and performance decrements when performing in extreme environments are heat acclimation, appropriate hydration, precooling and adequate clothing.

## 4.1 Introduction

Marathon running has a long tradition and gained increasing popularity during the last decades. Elite marathon athletes receive notable public and scientific attention. The "race" for the first sub two-hour marathon among the world's best runners as

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C. Zinner and B. Sperlich (eds.), *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*, DOI 10.1007/978-3-319-29728-6_4

well as scientists has been opened (Joyner et al. 2011; Hunter et al. 2015). Also a huge amount of recreational runners join marathon runs all around the world.

The marathon is a psycho-physiologically demanding endurance sport. Seventy-five to 80 % of the total energy produced during endurance work is converted to heat (Maughan et al. 2007). Dealing with heat production represents a meaningful challenge for the human organism, particularly for the thermoregulatory system.

This chapter aims at summarizing the physiological basis of marathon running with a particular emphasis on thermoregulatory processes. We discuss the influence of different environmental conditions on thermoregulation and marathon performance. Finally, we introduce various measures for adaptation to challenging environmental conditions in order to improve human thermoregulatory function during marathon running.

## 4.2 Physiological Basis of Marathon Running

The running velocity during a marathon is mainly determined by the oxygen uptake ($VO_2$) which can be maintained during the run and running economy, i.e. the $VO_2$ per unit distance or time (Jones 2006; Coyle 1995). A consistent race pace leading to a steady-state $VO_2$ which can be maintained for the complete distance is considered ideal for marathon performance (Abbiss and Laursen 2008; Ely et al. 2008).

Exercise intensities during marathon running typically range from 60 to 85 % of maximal oxygen uptake ($VO_2$max). Top athletes perform at relatively high intensities (>80 % $VO_2$max) and recreational runners at about 60 % $VO_2$max (Coyle 2007). However, in both groups of runners overall caloric expenditure is about the same, if running economy is comparable. Although elite runners utilize more fat compared to lower level runners, elite athletes burn more carbohydrates as they perform at relatively higher intensities and respiratory exchange ratio is higher. Muscle glycogen depletion and hypoglycemia are considered the main reasons for premature fatigue and termination, particularly in temperate environments. The rate of energy turnover, which can be up to 20 kcal per minute in elite runners (Gonzalez-Alonso 2007), may vary with environmental conditions (Coyle 2007).

It is important to choose an appropriate marathon pace which can be maintained without developing premature hyperthermia as this negatively affects the cardiovascular, central nervous and muscular systems. Changes in body temperature during long-distance endurance events are the result of heat production and heat dissipation. The vast amount of metabolic energy produced during endurance events is transferred to heat (Maughan et al. 2007). Heat production is proportional to running $VO_2$. In consequence, runners with a better running economy produce less heat compared to athletes with diminished running economy at the same absolute intensity.

Several physiological mechanisms contribute to heat provoked fatigue. Nybo (2008) postulated a combination of central and peripheral mechanisms which may play a part in heat-induced fatigue during endurance exercise. In the heat, the contribution of the central nervous system to fatigue might be larger than at moderate temperatures (Nielsen and Nybo 2003; Maughan and Shirreffs 2004). There is also evidence suggesting that volitional muscle contraction could only be sustained up to a certain core body temperature (Nielsen et al. 1993; Walters et al. 2000). Furthermore, heat causes hyperventilation and, thus, also hypocapnia; consequently, cerebral blood flow can be reduced. A lower oxygen partial pressure causes central fatigue before cerebral metabolism and muscular motor function are impaired. Temperature changes can also influence cardiovascular function. Due to the redistribution of blood from the core to the periphery (increased skin perfusion due to vasodilatation of the blood vessels of the skin to improve heat dissipation), an adequate cardiac output is maintained by an increased heart rate. Stroke volume is decreased with increasing core body temperature, because the reduced central blood volume leads to a lower filling pressure, and diastolic filling time is reduced due to a higher heart rate (Gonzalez-Alonso and Calbet 2003). In this context, the arteriovenous anastomoses of the skin play an important role, as they are opened with increasing body temperature and create a short cut between arteries and veins. Blood flow through these cross connections does not run through capillaries and can thus not be used for exchange of nutrients and oxygen.

## 4.3 Thermoregulation During Endurance Exercise

Body temperature is usually determined by exercise intensity (i.e. running velocity during the marathon) and kept within a narrow range of about 1 °C when ambient conditions are moderate (Maughan et al. 2007). Excess heat can be dissipated by several mechanisms.

### *4.3.1 Physiological Mechanisms of Heat Exchange*

The heat balance equation describes heat body storage as the sum of metabolic heat production as well as heat exchange by radiation, conduction, convection and heat loss by evaporation (Maughan 2010; Wendt et al. 2007; Kenefick et al. 2007). The human organism is able to loose heat mainly via the latter four mechanisms. Radiation, convection and conduction can also contribute to heat gain when ambient temperature is higher than skin temperature.

Radiant heat exchange is the loss or gain of heat in form of infrared heat rays. The human body dissipates and receives heat rays at the same time. When body temperature is higher than ambient temperature, more heat emits than is received (Wendt et al. 2007). Convection is heat transfer via a moving gas or fluid, for instance the heat transport from the body core to the periphery via blood. Conduction describes the heat transfer from the body to an object or vice versa.

Finally, evaporation is heat loss in form of insensible water loss or sweating. Insensible water loss means processes such as ventilation or diffusion and cannot be controlled or regulated, respectively. In contrast, sweating can be physiologically regulated and is the most important means of heat transfer from the body to the surroundings under unfavorably warm conditions. The heat loss per mL of evaporated water is about 2.4 kJ and high-level athletes are able to evaporate water up to 3.5 L per hour. At rest in a temperate room, radiation (~60 %) and convection (~15 %) make up the greatest part of heat loss. The contribution of conductive heat loss can be regarded negligible, particularly during exercise. Whereas the amount of heat loss by evaporation is about 25 % at rest, this proportion rises during exercise and is the main source for heat dissipation in warm environments.

The two main physiological mechanisms for heat dissipation are an increase in skin blood flow and sweating. The hypothalamus is the central unit responsible for thermoregulatory responses. There is a high density of heat-sensitive neurons together with (a lower amount of) cold-sensitive neurons in the preoptic, anterior part of the hypothalamus (Wendt et al. 2007). These neurons continuously monitor blood temperature in the brain. In addition, afferent feedback from thermoreceptors distributed throughout the whole organism is collected by the hypothalamus. This information from the periphery as well as from the brain is integrated and compared. When temperature increases the hypothalamus sends inhibitory signals to motor control centers (Nybo 2008).

The normal temperature of the human body is about 37 °C. There is slight variation around 1 °C above and below this temperature set-point (e.g. due to circadian rhythm and/or menstrual cycle) and the organism strives to maintain this temperature within a narrow range. If body temperature falls below or rises above this range, thermoregulatory responses are initiated. In case of a drop in body temperature, an increase in metabolic heat production, e.g. via shivering and cutaneous vasoconstriction is initiated. When body temperature rises, skin blood flow is mediated by cutaneous vasodilation in order to increase heat flux from body core to the skin. During exercise there are competing demands regarding cutaneous circulation. Vasomotor reflexes are initiated in order to redistribute blood from inactive tissue (including the skin). This mechanism guarantees appropriate transport of oxygen and energy-rich substrates to skeletal muscle and is also important to maintain blood pressure, particularly, in warm environments when sweating can lead to considerable fluid loss and, thus, a decrease in plasma volume.

Besides an increase in skin blood flow, the activation of eccrine sweat glands is a powerful mechanism for heat dissipation. This mechanism is becoming increasingly relevant for heat loss when ambient temperature exceeds skin temperature and no further heat loss via radiation and convection is possible. Sweat is a hypotonic solution as compared to plasma with sodium chloride being the primary electrolyte in sweat (besides small amounts of potassium, calcium, and magnesium). In warm environments, 1.0–2.5 L of sweat per hour is commonly observed, although amounts greater than 2.5 L per hour are not unusual in high-level athletes under extraordinary ambient conditions.

### *4.3.2 Determinants of Body Temperature During Endurance Running*

Models that intend to simulate the effects of environmental conditions on human endurance performance and thermoregulatory responses are based on the heat balance equation. Metabolic heat production, thermal environmental heat load and the capacity of heat loss are the key components of this equation. Theoretically, these equations should enable the estimation of endurance performance under various physiological and environmental assumptions. The accuracy of such estimations, however, has been questioned as the detrimental effect on marathon performance in the heat has been largely overestimated. Whether mere physical laws can be applied to estimate the impact of environmental conditions on performance has been doubted. Maughan et al. (2007) suggest that the factors influencing heat exchange and consequently performance in the heat are manifold. Pace during marathon running and, thus, energy expenditure is not constant, but varies (e.g. with velocity, wind, terrain, due to race tactics etc.). Environmental conditions are also not constant during the course of a marathon. For instance, temperatures in the morning at the start can considerably deviate from those during the final kilometers of the race. Sweat distribution and skin temperature are not constant on the whole body surface. Wind velocity is important for evaporation and can vary largely with wind and running velocity and, potentially much more with limb velocity. When sweat evaporates, the skin surface is covered by a concentrated salt solution. This may affect osmolality and skin temperature and, consequently vapor pressure and the ability to evaporate sweat (Wendt et al. 2007; Maughan 2010).

## 4.4 Factors Influencing Thermoregulation

### *4.4.1 Environment*

Marathons are performed under a broad range of different environmental conditions (e.g. with regard to temperature, humidity, sunshine, wind, rain) (Kenefick et al. 2007). Ambient temperature and relative humidity have a considerable influence on the ability of the organism to loose heat (Maughan and Shirreffs 2004). Performance may be compromised, but also well-being and health may be threatened under extreme environmental conditions. The effectiveness of the above mentioned mechanisms for heat exchange is to a large extent determined by environmental conditions.

In between extreme environmental conditions there is an optimal setting for performance. This optimal condition, however, may considerably vary between individual athletes. In addition, typical temperature differences in the range of moderate climatic environments (e.g. 11 and 21 °C) may relevantly affect endurance performance and, thus, thermoregulation can be affected even in temperate conditions (Galloway and Maughan 1997).

Cool temperatures alone are usually not a particular challenge for the human organism. Heat loss is to a large extent covered by radiation and convection (Wendt et al. 2007). If low temperatures meet wind and rain, however, there is considerable risk of hypothermia or superficial wind-chill injury (Maughan et al. 2007).

With increasing ambient temperature, heat loss is mainly covered by evaporation of sweat from the skin surface. If air temperature increases above ~36 °C, evaporation is the only effective way of cooling. The effectiveness of cooling by evaporation is determined by the water vapor pressure gradient between skin and environment and moving air. In relatively dry air there is large potential for evaporation, whereas in a humid environment sweat will accumulate and, thereby, impair heat loss by evaporation. In a hot and humid environment, athletes are exposed to a critical heat load and the risk for heat illness, particularly heat stroke is increased.

Sweat production is covered by body water from blood plasma. To maintain blood volume, intracellular fluid is mobilized. In extremely high temperatures, when large volumes of sweat are produced, a progressive reduction of blood and consequently stroke volume together with dehydration occur. This effect may lead to a reduced muscle blood flow. Further, an increased skin blood flow is needed to support heat loss. When relative humidity is high, the large sweat volumes cannot be effectively evaporated. In consequence, body temperature further rises resulting in increased cardiovascular and thermoregulatory stress and, finally, in an impaired performance capacity and potentially in health threats. Although there is a large amount of convincing evidence that heat and humidity impair endurance performance, the absolute performance decrement is surprisingly small in elite runners (Maughan et al. 2007). The differences between cold to temperate and hot conditions is a few minutes.

### *4.4.2 Dehydration*

Besides environmental conditions, dehydration is considered the most important factor that affects thermoregulation while exercising in the heat. Available evidence suggests that a sweat loss of at least 3 % of body mass can negatively affect endurance performance, particularly when exercising in the heat (Hew-Butler et al. 2015). A reduction in body water content as a result of dehydration has a detrimental effect on plasma volume. Thus, blood flow to the exercising muscles and, consequently, oxygen and substrate availability is directly diminished. Dehydration also adversely affects thermoregulation as skin blood flow as well as sweating response, i.e. the two most important mechanisms for heat loss during exercise in the heat can be deteriorated when dehydration is present. It is generally recommended that fluid intake should be appropriate to match sweat loss in order to avoid dehydration.

## 4.5 Strategies to Cope with Thermoregulatory Challenges

Various intervention strategies have been introduced and scientifically evaluated in order to cope with the thermoregulatory challenges during long distance endurance exercise. Reducing health risks and declines of performance in the heat were the main purpose. As hot and humid environmental conditions pose the largest demands on the human organism, most of these interventions focus on reducing thermal stress. Heat acclimation and rehydration are considered the most important options. In addition, further measures such as whole-body precooling, hyperhydration and clothing are widely applied and scientifically discussed. A summary of the main intervention strategies to reduce health risks and performance decrements while exercising in the heat is given in Table 4.1.

**Table 4.1** Intervention strategies to attenuate the health risks and performance decrements potentially associated with marathon running in extreme environmental conditions (based on Racinais et al. 2015; Wendt et al. 2007)

| | |
|---|---|
| Heat acclimation | • Repeated training in the heat to obtain biological adaptations<br>• At least 60 min exercise per day to increase core and skin temperatures and to stimulate sweating<br>• Preferably in the same environment as competition<br>• Preferably two weeks in order to maximize adaptations (although most adaptations are obtained after one week) |
| Hydration | • Start exercise euhydrated (drinking 6 mL fluid per kg body mass every 2–3 h prior to the start)<br>• Minimize water loss during exercise (without increasing body mass)<br>• Sodium requirements are increased when exercising in the heat<br>• Appropriate rehydration after exercise with appropriate amounts of fluid, carbohydrate, sodium and protein |
| Cooling | • Precooling may increase heat storage capacity and, thereby, endurance performance in the heat (>27 °C)<br>• Mixed-methods cooling (external, i.e. cooling vests, combined with internal, i.e. ice slurries) is most promising<br>• Individualized application and familiarization prior to main competition |
| Clothing | • In hot, humid environments minimal clothing pose the least amount of resistance to evaporation<br>• Bright clothing can protect from sun and reduce radiant heat gain<br>• In cold environments appropriate levels of insulation layers to maintain body temperature and block air movements |
| Event organizers | • Scheduling the event according to expected weather conditions and patterns<br>• Inform and appropriately advise participants on environmental conditions and potential risks<br>• If necessary, canceling the event |

### *4.5.1 Acclimation*

Heat acclimation (i.e. performing repeated training sessions in the heat) is potentially the most effective strategy to prepare for endurance competitions in hot environments. Several beneficial physiological adaptations have been reported in the literature (Wendt et al. 2007; Racinais et al. 2015). After a sufficient period of heat acclimation resting core body temperature is lower. This enables a greater increase in body temperature until a critical temperature is reached. A further important adaptation is an increase in plasma volume which, in turn, leads to a reduced exercise heart rate. Cutaneous vasodilatation is also increased after successful adaptation. Sweat rates in the heat are increased, but sodium and chloride losses are reduced.

Full adaptation takes at least 7 up to 14 days, but relevant effects can be observed after the first 3 days (Wendt et al. 2007). In order to maximize adaptive responses, acclimation time should be at least two full weeks (Racinais et al. 2015). Adaptive responses can be maintained for at least one week, but can last up to one month. It is recommended to induce heat acclimation by strenuous interval training or continuous exercise at ≥50 % of maximal oxygen uptake for at least one hour every 3 days. Exercise bouts of at least 90 min to two hours seem most appropriate. Preferably the environmental conditions during the acclimation period should be the same as the competition venue (Racinais et al. 2015).

### *4.5.2 Hydration*

Besides acclimation, rehydration during exercise in the heat represents the second important strategy to counter the harmful effects of exercising in hot environments. As mentioned above, heat acclimation increases sweating rates during exercise. Consequently, fluid requirements during exercise are also increased. For optimal fluid replacement, no general recommendations exist. The effectiveness of fluid intake is determined by (a) the rate of gastric emptying, (b) the intestinal absorption and (c) the ability to retain fluid in intra- and extracellular compartments. Larger drinking volumes may result in faster gastric emptying, but this depends on the energy content (amount of carbohydrates) and osmolality of the beverage. Repeated drinking of smaller single doses may support fluid replacement (Wendt et al. 2007). It has to be considered that the absorption of water is a mainly passive process depending on the osmotic gradient which is beneficially affected by the carbohydrate content. Sodium supports fluid retention and may improve palatability. Thus, the amount of fluid which is replaced may be increased when sodium is added to the beverage. Drinking large volumes of plain water during exercise can result in a rapid fall in plasma sodium concentration and osmolality. This can lead to severe adverse conditions (e.g., hyponatremia). Exercise-associated hyponatremia is defined as a drop of serum, plasma or blood sodium concentration below the normal range of the reference values of the test laboratory occurring during or up to 24 h after exercise (Hew-Butler et al. 2015). In most cases, hyponatremia develops as a result of a relative excess in total body water during long-lasting endurance events. One of the main risk factors is overdrinking plain water or hypotonic beverages, i.e. a fluid intake larger than fluid losses via sweating and urinary excretion.

The intake of fluids should closely match the rate of fluid loss during exercise. The ingested fluids are evenly distributed throughout the body after about 20–30 min. Sports beverages with about 7 % carbohydrates improve intestinal absorption. In order to achieve optimal water retention, the sodium concentration of the sports drink should be at least 50 mmol/L. In temperate environments drinking to thirst is considered an appropriate stimulus for adequate fluid replacement. Thirst is an evolutionarily fine-tuned regulatory mechanism to protect plasma volume and osmolality (Hew-Butler et al. 2015). During exercise in warm, humid conditions when fluid loss via sweating can exceed gastric emptying so that dehydration occurs rapidly, drinking before thirst should be considered. However, an increase in body weight as a result of excessive overdrinking should be avoided (Racinais et al. 2015). Beverages containing appropriate amounts of sodium should be used to reduce the risk of hyponatremia, although this approach is not sufficient in case of excessive overdrinking (Hew-Butler et al. 2015).

Another strategy to reduce dehydration during long-distance endurance exercise might be hyperhydration, particularly by consuming high amounts of glycerol solutions (not plain water). It has been speculated that such an approach may reduce thermal stress during exercise. To date, there is no valid evidence in this regard, particularly when compared to an euhydrated state before exercise (Wendt et al. 2007). In order to start exercise in an euhydrated state it is recommended to drink 6 mL of fluid per kg body mass every two to three hours prior to competition or training in the heat (Racinais et al. 2015). Appropriate rehydration after exercise with fluid volumes corresponding to 100–150 % of exercise-induced body mass loss together with appropriate amounts of carbohydrates, sodium and protein is recommended (Racinais et al. 2015).

### *4.5.3 Cooling Strategies and Clothing*

Further strategies to reduce health risks or performance decrements when exercising in thermally challenging environments refer to whole-body precooling and appropriate clothing.

The starting point for cooling strategies is the observation that voluntary exhaustion occurs at a similar core body temperature in different individuals during endurance exercise in the heat (Maughan 2010; Martin 2007). The potential mechanism of cooling procedures before the start of exercise is a reduction of core temperature and, thereby an increase in heat storage capacity (Wegmann et al. 2012). Body cooling can be performed by means of cold air exposure, cold water immersion, cooling packs or garments or drinking cold beverages. Our research group recently analysed the effects of various precooling techniques on endurance performance in a systematic review and meta-analysis (Wegmann et al. 2012). The main result was that there is a performance-enhancing effect of precooling under specific circumstances. High-level endurance athletes can increase their performance by up to 4 % during time trials, i.e. under realistic conditions. A beneficial effect was particularly present when environmental temperature was higher than 27 °C and cold drinks, cooling packs and vests were the most feasible methods. Mixed-methods cooling, i.e. combining external cooling (cooling vest) with internal cooling (cold beverages or ice slurries) seems most promising (Racinais et al. 2015).

The performance-enhancing effect was, however, limited to endurance events lasting up to one hour (Wegmann et al. 2012). Few studies evaluated endurance exercise lasting longer and the reported results were less clear. It might be speculated that the cooling effect is of limited duration and, thus, performance during longer events may be unaffected. This may have particular relevance for marathon running as even the fastest runners perform longer than two hours. Furthermore, the main increase in core temperature usually occurs during the last 10 km of a race. Therefore, a beneficial effect of precooling in marathon running is questionable and without convincing evidence to date. A possible solution might be the ingestion of cold drinks during exercise. The palatability might be limited as athletes usually are not used to consume cold drinks or even ice slurries. Familiarization to cooling procedures during training periods, preferably under environmental conditions typical for the main competition, and individualized application are therefore recommended (Wegmann et al. 2012; Racinais et al. 2015).

Besides cooling strategies, appropriate temperature- and climate-adapted clothing might support withstanding thermal challenges. The type and amount of clothing can have a considerable impact on heat loss. Clothing represents a layer of insulation and, thus, impairs heat transfer and sweat evaporation from the skin surface (Gavin 2003). In hot, humid environments clothing should impose the least amount of resistance to evaporation, i.e. minimal clothing, particularly bright garments are considered most appropriate (Wendt et al. 2007). Otherwise, appropriate clothing can also protect from sun and, thereby, reducing radiant heat gain and thermal stress in high ambient temperatures (Gavin 2003). Exercising in cold environments, particularly when temperature falls below 0 °C, requires appropriate levels of insulation layers to maintain body temperature (Gavin 2003). Clothing in winter ideally blocks air movements, but enables water vapor to escape when sweating occurs (Gavin 2003).

### *4.5.4 Recommendations for Organizers of Marathon Events*

In order to minimize the risk of adverse events as a result of extreme environmental conditions, the organizers of endurance events, particularly of marathons with mass participation have the particular responsibility to adopt preventive strategies

(Racinais et al. 2015). The specific climatic conditions and the typical weather patterns of the competition venue should always be taken into account and medical support and, potentially, cooling facilities may be arranged in anticipation. Additionally, scheduling the starting time according to the anticipated weather conditions, for instance, early in the morning or late afternoon according to the expected peak temperatures or temperature course for the duration of the event, is an appropriate approach. Particularly, in mass participation events there might be a higher risk of heat illness. Thus, appropriate information and advice is recommended and, under extreme conditions canceling an event might be the safest proceeding for participants.

## 4.6 Gender Differences

The number of women participating in marathon events has considerably increased during the last decades and scientific efforts are made to particularly understand and improve female marathon performance (Jones 2006; Hunter et al. 2015). There are anthropometric, physiological and hormonal differences between male and female athletes. Therefore, it has been speculated that thermoregulation may also differ between genders (Cheuvront and Haymes 2001).

Women have a smaller body mass and a larger surface area-to-mass ratio as well as a higher body fat content as compared to men. Body fat is an insulating layer and, thus, may reduce the ability to dissipate heat. However, differences in body fat do not seem to affect thermoregulation (Cheuvront and Haymes 2001). Heat production is proportional to body mass and heat loss a function of body surface area. Thus, it has been assumed that women may have an advantage from a thermoregulatory perspective (Dennis and Noakes 1999). Males produce more sweat than females in relative as well as in absolute terms and, thus, it has been suggested that dehydration and the need for fluid replacement is lower in women. It is well known that rectal temperature and skin blood flow are affected by menstrual cycle with a rectal temperature about 0.5 °C higher in the luteal as compared to the follicular phase. This difference also leads to a higher threshold for the initiation of sweating and cutaneous vasodilation.

Recent research suggests that women may adopt more appropriate pacing strategies during a marathon compared to men, i.e. women are more likely than men to maintain race pace through the run (March et al. 2011), particularly in temperate conditions. When race temperature increases, the velocity decline is augmented. Trubee et al. (2014) recently reported that non-elite women paced consistently better than non-elite men and that this difference increased from cold to warm race temperatures. Pacing of elite runners was similar for both genders. In a hotter environment, novice runners should start at a slower initial velocity to maintain or increase running velocity later in the race.

Research on thermoregulation in female marathon runners during realistic outdoor conditions is limited. Although there are plausible reasons which suggest differences in thermoregulatory responses between genders, it seems likely that women respond to thermal stress in a similar way than men. In extreme ambient conditions, however, gender differences in thermoregulation may become apparent (Cheuvront and Haymes 2001).

## 4.7 Summary and Practical Implications

Marathon running is physiologically and psychologically very demanding. The majority of the energy produced during a marathon is converted to heat. Hence, marathon running is particularly challenging for the thermoregulatory system, especially in extreme environmental conditions. The main factors affecting thermoregulation are environmental conditions and dehydration. Changes in body temperature during long-distance endurance events are the result of heat production and heat loss. Premature hyperthermia impairs cardiovascular, central nervous and muscular systems. Excess heat can be dissipated by radiation, conduction, convection and evaporation. At rest radiation and convection make up the greatest part of heat loss. The proportion of heat loss by evaporation rises during exercise and is the main source for heat dissipation in warm environmental conditions. The two main physiological mechanisms for heat loss are an increase in skin blood flow and sweating. Potential strategies to counter health risks and performance decrements when performing in extreme environments are heat acclimation, appropriate hydration, precooling and appropriate clothing. In addition, the organizers of endurance events, particularly of marathons with mass participation have the particular responsibility to adopt preventive strategies in order to minimize the risk of adverse events as a result of extreme environmental conditions.

## References

Abbiss CR, Laursen PB (2008) Describing and understanding pacing strategies during athletic competition. Sports Med 38(3):239–252

Cheuvront SN, Haymes EM (2001) Thermoregulation and marathon running: biological and environmental influences. Sports Med 31(10):743–762

Coyle EF (1995) Integration of the physiological factors determining endurance performance ability. Exerc Sport Sci Rev 23:25–63

Coyle EF (2007) Physiological regulation of marathon performance. Sports Med 37(4–5):306–311

Dennis SC, Noakes TD (1999) Advantages of a smaller bodymass in humans when distance-running in warm, humid conditions. Eur J Appl Physiol Occup Physiol 79(3): 280–284. doi:10.1007/s004210050507

Ely MR, Martin DE, Cheuvront SN, Montain SJ (2008) Effect of ambient temperature on marathon pacing is dependent on runner ability. Med Sci Sports Exerc 40(9):1675–1680. doi:10.1249/MSS.0b013e3181788da9

Galloway SD, Maughan RJ (1997) Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. Med Sci Sports Exerc 29(9):1240–1249

Gavin TP (2003) Clothing and thermoregulation during exercise. Sports Med 33(13):941–947
Gonzalez-Alonso J (2007) Hyperthermia impairs brain, heart and muscle function in exercising humans. Sports Med 37(4–5):371–373
Gonzalez-Alonso J, Calbet JA (2003) Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. Circulation 107(6):824–830
Hew-Butler T, Rosner MH, Fowkes-Godek S, Dugas JP, Hoffman MD, Lewis DP, Maughan RJ, Miller KC, Montain SJ, Rehrer NJ, Roberts WO, Rogers IR, Siegel AJ, Stuempfle KJ, Winger JM, Verbalis JG (2015) Statement of the 3rd international exercise-associated hyponatremia consensus development conference, Carlsbad, California. Br J Sports Med 49(22):1432–1446. doi:10.1136/bjsports-2015-095004
Hunter SK, Joyner MJ, Jones AM (2015) The two-hour marathon: What's the equivalent for women? J Appl Physiol (1985) 118 (10):1321–1323. doi:10.1152/japplphysiol.00852.2014
Jones AM (2006) The physiology of the world record holder in the women´s marathon. Int J Sports Sci Coaching 1(2):101–116
Joyner MJ, Ruiz JR, Lucia A (2011) The two-hour marathon: who and when? J Appl Physiol 1985 110 (1):275–277
Kenefick RW, Cheuvront SN, Sawka MN (2007) Thermoregulatory function during the marathon. Sports Med 37(4–5):312–315
March DS, Vanderburgh PM, Titlebaum PJ, Hoops ML (2011) Age, sex, and finish time as determinants of pacing in the marathon. J Strength Conditioning Res 25(2):386–391. doi:10.1519/JSC.0b013e3181bffd0f
Martin DE (2007) Strategies for optimising marathon performance in the heat. Sports Med 37(4–5):324–327
Maughan RJ (2010) Distance running in hot environments: a thermal challenge to the elite runner. Scand J Med Sci Spor 20:95–102. doi:10.1111/j.1600-0838.2010.01214.x
Maughan R, Shirreffs S (2004) Exercise in the heat: challenges and opportunities. J Sports Sci 22(10):917–927
Maughan RJ, Watson P, Shirreffs SM (2007) Heat and cold—what does the environment do to the marathon runner? Sports Med 37(4–5):396–399. doi:10.2165/00007256-200737040-00032
Nielsen B, Nybo L (2003) Cerebral changes during exercise in the heat. Sports Med 33(1):1–11
Nielsen B, Hales JR, Strange S, Christensen NJ, Warberg J, Saltin B (1993) Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. J Physiol 460:467–485
Nybo L (2008) Hyperthermia and fatigue. J Appl Physiol (1985) 104 (3):871–878. doi:10.1152/japplphysiol.00910.2007
Racinais S, Alonso JM, Coutts AJ, Flouris AD, Girard O, Gonzalez-Alonso J, Hausswirth C, Jay O, Lee JK, Mitchell N, Nassis GP, Nybo L, Pluim BM, Roelands B, Sawka MN, Wingo J, Periard JD (2015) consensus recommendations on training and competing in the heat. Sports Med 45(7):925–938. doi:10.1007/s40279-015-0343-6
Trubee NW, Vanderburgh PM, Diestelkamp WS, Jackson KJ (2014) Effects of heat stress and sex on pacing in marathon runners. J Strength Cond Res 28(6):1673–1678. doi:10.1519/JSC.0000000000000295
Walters TJ, Ryan KL, Tate LM, Mason PA (2000) Exercise in the heat is limited by a critical internal temperature. J Appl Physiol 89(2):799–806
Wegmann M, Faude O, Poppendieck W, Hecksteden A, Frohlich M, Meyer T (2012) Pre-cooling and sports performance: a meta-analytical review. Sports Med 42(7):545–564. doi:10.2165/11630550-000000000-00000
Wendt D, van Loon LJ, Lichtenbelt WD (2007) Thermoregulation during exercise in the heat: strategies for maintaining health and performance. Sports Med 37(8):669–682 3782 [pii]

# Chapter 5
# Coping with Stress During a Marathon

**Christian Zepp**

**Abstract** To successfully finish a marathon, athletes have to deal with a variety of stressful situations and demands during a race. These stressors can have different detrimental effects on athletes' pace, performance, or well-being. In order to support athletes to effectively cope with stressors during a marathon, the present chapter gives an overview of the development and effects of stress on endurance athletes, based on the transactional model of stress and coping (Lazarus and Folkman 1984) and the cognitive-motivational-relational theory (Lazarus 1991). Furthermore, several internal and external stressors that can occur during a marathon are presented, as well as their potential effects on the athlete. In addition, several coping strategies from sport psychology literature are introduced and discussed in terms of their effectiveness in specific subgroups. Finally, a stepwise approach is presented to allow athletes to prepare themselves for, and to actively deal with, the potentially stressful situations and demands during a marathon.

**Keywords** Stress · Coping · Strategies · Endurance

For both recreational and competitive athletes, participating in a marathon (26.2 miles/42.2 km) is a very demanding and, in many situations, a very stressful experience. The physical and mental requirements necessary to successfully finish a marathon are greater than those of other distances and sports (e.g., Kellmann 2002; Mann and Schaad 2001). Besides the physical preparation, mental preparation is crucial to equip oneself with the strategies to negate potentially stressful situations experienced during the race. Whilst this mental preparation for a long distance endurance competition can take months or years (O'Neil and Steyn 2007), its importance is clear as it has been demonstrated that perceived stress can lead to higher levels of competitive anxiety in marathon runners and, therefore, impaired performance (Hammermeister and Burton 2001).

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C. Zinner and B. Sperlich (eds.), *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*, DOI 10.1007/978-3-319-29728-6_5

The present chapter aims to further the understanding of stress development and to offer insights into the strategies used to improve coping with stressful situations and demands. To this end, the chapter comprises three aspects: firstly, the development of stress and emotions, including the types and effects of potential stressors that may occur during a marathon will be described; secondly, several coping strategies will be presented that have been discussed in sport psychology literature in previous years; and finally, suggestions for athletes about how to prepare themselves for potential stressors during a marathon conclude the chapter.

## 5.1 Development of Stress and Emotions During the Marathon

The contributions of Lazarus and Folkman (1984) and Lazarus (1991, 1999) to the theoretical approaches to stress, emotion, and coping have been significant. With their development of the *transactional model of stress and coping* (Lazarus and Folkman 1984) and the *cognitive-motivational-relational theory* (Lazarus 1991, 1999, 2000a), they have helped to identify the factors that influence the development of stress and to assist athletes in coping with perceived stress. Within their frameworks, they consider the stimulus input, the evaluation of this stimulus, and the individual response (Levine and Ursin 1991).

The transactional model of stress and coping states that stress develops through a process that involves a dynamic transactional relationship between the athlete and his environment (cf. Fig. 5.1; Lazarus and Folkman 1984): As soon as the athlete is confronted with a potentially stressful situation or demand, the athlete initiates an evaluation process which determines the emotional response and level of perceived stress. This evaluation process comprises a *primary appraisal*, a *secondary appraisal*, and the assessment of *perceived coping resources*, a process that is influenced by *individual* (e.g., self-esteem, previous experiences, personality, goals) and *situational factors* (e.g., weather conditions, distance to aid station, number of

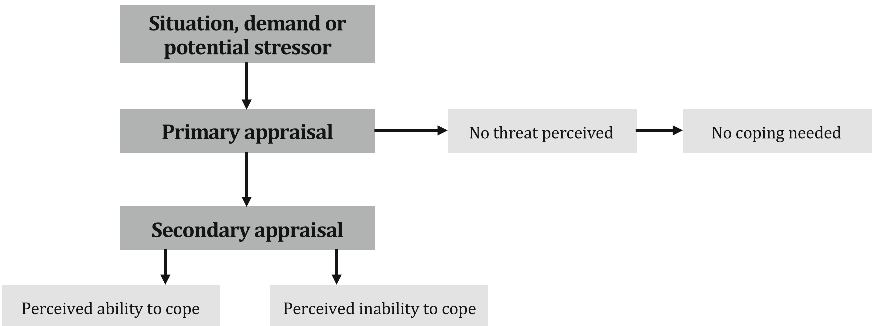


**Fig. 5.1** Transactional model of stress and coping based on Lazarus and Folkman (1984)

spectators). During the *primary appraisal* process, a marathon runner will evaluate the impact of a stressor (e.g., situation, demand) in regard to personal goals, commitments, and values. The result of this evaluation process might either be irrelevant (i.e., it has no influence on well-being or performance), beneficial (i.e., it maintains or increases well-being or performance), or stressful (i.e., it has a negative impact on well-being or performance). In the case of a stressful situation or demand, the athlete experiences this as either a challenge, a threat, as harmful, or as detrimental to well-being and/or performance (Lazarus and Folkman 1984). Simultaneously to the athlete's evaluation of the situation or demand as stressful, a cognitive evaluation is made of their ability to cope with the appraised challenge, threat, harm, or detriment during *secondary appraisal*. During this secondary appraisal, the athlete evaluates whether or not they possess sufficient coping resources to execute the necessary cognitive and behavioural coping strategies and successfully deal with the perceived challenge, threat, harm, or detriment identified during primary appraisal. Dealing with coping resources such as psychological, physiological, social and material aspects, and eventually perceiving control over the stressor is most important for athletes to successfully cope with the situation or demand (Lazarus 1991).

While the transactional model of stress and coping predominantly deals with psychological states that athletes experience during potentially stressful situations or demands, it does not include the influence of emotions. Thus, Lazarus (1991, 1999) extended the early transactional model of stress and coping by including emotions as an important factor for the development of stress in the cognitive-motivational-relational theory. Cognitive-motivational-relational theory considers the relationship between the athlete, i.e., the athlete's motives and beliefs that influence their emotions, and the athlete's environment, i.e., the primary and secondary appraisal of situations or demands (Lazarus 1991, 1999, 2000a). According to cognitive-motivational-relational theory there are up to six appraisal-related decisions to make for each emotion. Hence, experiencing potentially stressful situations or demands leads to a diverse cognitive patterns which can describe the relational meaning, distinguishing any emotion from each of the other emotions (cf. Lazarus 1991). For the primary appraisal, decisions relate to goal relevance, goal congruence/incongruence, and type of ego-involvement. Regarding the secondary appraisal, decisions relate to the evaluation of blame or credit, coping potential, and future expectations. Consequently, the elicited emotion, and the type and intensity of that emotion, is dependent upon the specific combination of primary and secondary appraisals (Lazarus 1991, 1999, 2000a).

The comprehensive framework of cognitive-motivational-relational theory is the most commonly applied theory for stress and emotions in sport contexts (e.g., Neil et al. 2013; Wolf et al. 2014) and has been adapted for endurance sport athletes (Hammermeister and Burton 2001, 2004). Research shows that the combined effect of primary appraisal, secondary appraisal, and perceived coping resources best predicts the development of cognitive and somatic state anxiety in endurance athletes.

## 5.2 Stressors During the Marathon

In addition to experiencing longitudinal stressors in preparation for the marathon (e.g., overload training, reduced time of recovery, infectious episodes; Niemann and Lee 1990; O'Connor 2007), athletes are likely to experience several different potentially stressful situations and demands during the race. It is crucial for athletes to identify stressors prior to the marathon, in order to be able to prepare themselves for the potentially stressful situation by developing appropriate coping strategies, or to look for assistance to do so (Devonport 2015). Stressful situations and demands can be categorised as *internal* and *external stressors*.

*Internal stressors* describe all demands that develop due to psychological or physiological experiences, including dealing with pain, fatigue, injury, personal goals, previous negative experiences or results, recovery deficits, perceived motivational climate, and anticipating "hitting the wall" (Buman et al. 2008b; Freund et al. 2013; Marcora et al. 2009; Pensgaard and Roberts 2000).

Experiencing pain during an endurance task such as a marathon is common among athletes (Buman et al. 2008b) and leads to feelings of stress and increased negative affect (Baden et al. 2005; Forys and Dahlquist 2007; St Gibson et al. 2006). Based on the model of pain in sport developed by Addison et al. (1998), fatigue/discomfort, as well as positive and negative pain can be identified as types of pain. It has been shown that personality factors influence the pain perceptions in long endurance athletes (Freund et al. 2013), for example, athletes with rather depressive traits show low pain tolerance (e.g., Willoughby et al. 2002), whilst athletes high in self-efficacy beliefs are more likely to tolerate pain (e.g., Dolce et al. 1986).

The potential occurrence of injuries during competition is a stressor that athletes think about during long endurance runs (Samson et al. 2015). Previous experience of stressful situations seem to make athletes particularly susceptible to injury (Andersen and Williams 1988, 1999; Williams and Andersen 1998). Whether athletes are more or less likely to experience an injury when they face a potentially stressful and injury-inducing situation depends on the personality characteristics of an athlete, their history of stressors, and their coping resources. The outcome of an athlete's appraisal of a stressful situation determines the psychological and psycho-physiological responses that are responsible for the development of an injury, particularly in the case of athletes who have experienced injuries before as they are more likely to experience further injury due to stress during competition than athletes who have not experienced injury (Kleinert 2002).

Another physical source of stress derives from the muscular and mental fatigue experienced during long endurance events (e.g., Marcora et al. 2009). Athletes who are mentally fatigued reach exhaustion significantly faster than athletes who do not report mental fatigue (Marcora et al. 2009).

Cognitive processes experienced during a long endurance run, such as thoughts about pace, distance, pain, discomfort and the environment, can be potential stressors for athletes (Samson et al. 2015). For example, thinking about personal goals can be a potential stressor, particularly when athletes are threatened by the possibility of not reaching their goals and feel helpless to improve the situation, which evokes an emotional response (Buman et al. 2008b). This phenomenon has been referred to as competitive suffering in the sport psychology literature and is associated with perceived pressure in athletes. Subsequently, pressure to perform well has been shown to elicit stress and anxiety (Laborde et al. 2014a, b) and, therefore, has the potential to negatively impact on cognitive processes such as decision-making (Laborde et al. 2013). To cope with such emotions during the marathon, athletes will react with an increased effort in order to regulate the stressful situation (Beedie et al. 2012), thus it is necessary for athletes to have effective stress and emotion regulating strategies available in order to immediately deal with the stressor at hand.

One potential stressor of particular concern is the anticipation of "hitting the wall", which normally occurs between miles 18 and 21 (29-34 km; Buman et al. 2008b; Masters and Lambert 1989; Stevinson and Biddle 1998). "Hitting the wall" is a multi-dimensional phenomenon that is beyond normal fatigue (Buman et al. 2008b), said to consist of affective (e.g., discouragement, frustration), behavioural (e.g., pace disruption, running difficulties), cognitive (e.g., anxiety, trouble focusing), motivational (e.g., desire to quit/walk, decreased motivation), and physiological (e.g., general/leg-related fatigue, cardio-respiratory) dimensions (Buman et al. 2008b), and is experienced by approximately half of all marathon runners (Buman et al. 2008a; Morgan and Pollock 1977; Stevinson and Biddle 1998; Summers et al. 1982). Although it is predominantly those runners who anticipate "hitting the wall" that suffer from the experience of really hitting the wall, it seems that male runners are more susceptible to this experience than female runners (Buman et al. 2008a; Stevinson and Biddle 1998). Interestingly, at least one-third of affected athletes report a lack of coping strategies in order to deal with the phenomenon (Buman et al. 2008b). Thus, anticipating and eventually "hitting the wall" are powerful stressors for marathon runners.

*External stressors* describe all situations and demands that are relate to environmental, organisational, and interpersonal factors. Whereas environmental stressors refer to heat, cold, rain, wind, altitude, terrain, or distance, organisational stressors can relate to poor hydration, poor nutrition, or sleep deprivation (based on O'Neil and Steyn 2007). In addition, interpersonal stressors can include social relationships, social evaluations, external pressure to perform, conflicts, or lack of social support (e.g., Hammermeister and Burton 2001; Hanton et al. 2005).

Studies in other sports describe various additional stressors. For example, in a study with elite athletes from different sports (Hanton et al. 2005), competitive and organizational stressors were identified that influenced athletes: Performance issues that directly relate to competition included preparation (e.g., inadequate mental/physical preparation), injury (e.g., risk of injury, competing despite of injury), pressure (e.g., performing under pressure, international competition), opponents (e.g., intimidation by opponents, competing against better athletes), self (e.g., body type, physical appearance), event (e.g., start of the event, nature of competition), and superstitions (e.g., particular venue). In addition, Scanlan (1991)

| Internal stressors | | External stressors | | |
|---|---|---|---|---|
| **Physiological stressors** | **Psychological stressors** | **Social stressors** | **Environmental stressors** | **Organisational stressors** |
| • Pain<br>• Muscular/mental fatigue<br>• Past/potential injury<br>• Recovery deficits<br>• etc. | • Anticipating to "hit the wall"<br>• Pressure to perform<br>• Personal goals<br>• Perceived lack of control<br>• etc. | • Relationships<br>• External pressure to perform<br>• Conflicts<br>• Lack of social support<br>• etc. | • Weather<br>• Altitude<br>• Terrain<br>• Distance<br>• etc. | • Lack of hydration<br>• Lack of nutrition<br>• Sleep deprivation<br>• Distance<br>• etc. |

**Fig. 5.2** Potential stressors during a marathon

was able to identify negative aspects of competition, negative significant-other relationships, demands or costs of the sport, and traumatic experiences as sources of stress in elite figure skaters. Some of these stressors are potentially present in marathon competitions as well, leading to several emotional responses, which impact differently on individual athletes (Fig. 5.2).

## 5.3 Effects of Stress and Emotions During the Marathon

Importantly, when dealing with stress and emotions in sport, one should be aware that classifying emotions as 'positive', 'negative', 'helpful', or 'unhelpful' is inappropriate (Hanin 2007; Nesse and Ellsworth 2009) because emotions are functional in nature, providing valuable information to the athlete (Friesen 2015). With this in mind, it is important to consider that the experience of a certain emotion by different runners can be appraised in different ways, such that one athlete may need to cope with the emotion while the other athlete has no need to cope with the emotion.

Stressful situations can have a range of psychological, cognitive and physical effects, such as anxiety, poor performance, lack of perceived control, decreased well-being, perceptual distortions, or even experiencing injuries (e.g., Hammermeister and Burton 2001; Hanin 2010; Raglin 2007).

Athletes are likely to experience anxiety as an emotional response to the stressful situations and demands experienced prior to or during a marathon race (Raglin 2007). Research has shown that the influence of anxiety on the performance of athletes varies considerably, with 30–45 % of athletes achieving their best performances under conditions of high anxiety (Raglin and Hanin 2000). It seems, therefore, that even emotions perceived as potentially negative can have positive influences on performance (Hanin 2007).

Previous studies have found that emotions described as predominantly positive are not necessarily associated with optimal performance, and that emotions described as mainly negative are not necessarily associated with poor performances (Beedie et al. 2000). Moreover, the emotion-performance relationship differs between individuals (Hanin 2010), emphasising the need for athletes to find out their personal optimal competitive emotional states in order to positively influence their athletic performance and psychological well being.

Jones et al. (2009) demonstrated that the perception of challenge and threat during competition is an important determinant of perceived control in athletes. For example, pacing, an endurance tactic that is usually externally controlled by a pacemaker for elite-athletes or even for non-elite athletes, may result in perceived stress and negative emotional states (cf. Brick et al. 2014). Experiencing stress leads to decreased efficacy beliefs in athletes, while positive emotional states increase athletes' efficacy beliefs during training periods (Samson 2014).

Of particular concern to those involved in competitive sports is the detrimental influence of stress and emotion on performance (e.g., Bueno et al. 2008; Lazarus 2000b). During competition, stress and emotion can draw attention away from the competitive task at hand and divert it towards different goals than those defined prior to the race (Bueno et al. 2008). Hence, stress and emotions can be misleading and destructive during a marathon. To compound the problem, endurance athletes who fall behind their goals during the race are likely to experience competitive suffering and, in turn, adapt their coping efforts to manage reactions to goal failure (Bueno et al. 2008).

In addition to impairing athletic performance, stressful situations and demands also affect the general psychological well-being and mental health of athletes (Golenia and Sulprizio 2007; Hammermeister and Burton 2001, 2004; Lazarus 2000a; Sulprizio and Kleinert 2011, 2014). Moreover, stress and the concomitant emotions also have an effect on the physiological level. Typical physiological responses to stressful situations and demands include increased heart rate, sweating, muscular tension during competition or adjusted heart rate variability (e.g., Crocker and Hadd n.d.; Laborde et al. 2015). Responses such as these raise the energy cost of the activity, potentially leading to a reduced ability to perform to one's physiological maximum.

As the transactional model (Lazarus and Folkman 1984) points out, different runners can appraise potentially stressful situations or demands, such as hot weather or pain, in different ways during the marathon. For example, a newcomer to marathon running may be unable to cope with extreme weather when confronted with it for the first time, whereas an experienced runner who has competed in all kinds of weather may well have developed effective coping strategies specific to the extreme conditions, such as focusing on the task at hand (e.g., running) and not on the weather, or motivating self-talk. Through the use of strategies such as these, the athlete will appraise the situation as irrelevant and will, eventually, ensure that it has no impact on personal well-being or performance. In contrast, the less experienced runner might appraise the situation as stressful and as threatening towards their goals. This example shows that a situation or demand can be appraised in different ways and can represent two different meanings to two different runners, thus evoking different emotions that each require their own coping strategies (Richards 2012).

For some people, engaging in challenging and stressful tasks is enjoyable and can lead to joy and even euphoria (Selye 1978), however, some struggle to effectively cope with stressors and emotions. With this in mind, it's recommended to consider an individual athlete's responses to stress and concomitant development of emotions with reference to their individual zone of optimal functioning (IZOF; Hanin 2000), in which an athlete is able to perform best. Within the IZOF model it is assumed that optimal stress intensities may vary from very low to extremely high between athletes. Indeed, the notion that it is not only low or moderate intensities of stress and emotions or anxiety that enable athletes to compete at their best is supported in the literature, with studies showing that almost a third of all athletes benefit from high levels of stress and anxiety prior to or during the competition (Raglin and Hanin 2000). Research based on the IZOF model indicates that coping with stressors and emotions during competition is highly individual (Friesen 2015). For example, learning and applying relaxation techniques prior to and during competition appears beneficial for some athletes (e.g., Patrick and Hrycaiko 1998), but counterproductive for others (Raglin 2007).

## 5.4 Assessment of Perceived Stress and Coping Strategies in Long Distance Runners

The assessment of coping with stress and emotions during a marathon is somewhat challenging. Athletes perceive potentially stressful situations and demands, along with the concomitant emotions, while they run. In marathon competitions, both the appraisal of stressors and the coping process occur over a long time of physical activity, limiting the proximity and therefore the accuracy of assessment to the running experience (Buman et al. 2008b). Hence, numerous retrospective instruments exist, like the Perceived Stress Questionnaire (PSQ; Cohen et al. 1983; Fliege et al. 2005), the COPE inventory (COPE; Carver et al. 1989), the Ways of Coping Questionnaire (WOCQ; Folkman and Lazarus 1985), the Coping Inventory for Stressful Situations (CISS; Endler and Parker 1994), and the Coping Inventory for Competitive Sport (CICS; Gaudreau and Blondin 2002; Gaudreau et al. 2005) to name but a few (for a detailed overview see Crocker et al. 2015), that require athletes to *remember* all stressors and emotions they experienced during the competition and how they coped with them. This approach has been described as hardly appropriate for the assessment of cognitions and coping processes because the instruments provide generalised responses that may be adversely affected by an inaccurate memory recall (cf. Eccles 2012). In order to be able to assess cognitions and coping processes as close to real time as possible, recently developed and applied assessment instruments, like ecological momentary assessment (Cerin and Barnett 2006), think-aloud (Nicholls et al. 2008), the delayed retrospective report method (Calmeiro et al. 2010), and the video-mediated recall method (Evans et al. 2014) have been applied. Both quantitative and qualitative methods possess several strengths and advantages. Whereas quantitative methods can help to evaluate coping in specific populations, qualitative methods help to compare coping across studies, as well as to model and evaluate hypotheses and research questions, to understand stressors and coping in sport and to identify antecedents and consequences of coping (cf. Crocker et al. 2015).

## 5.5 Coping with Stress and Emotions During a Marathon

Adequate coping strategies can facilitate the successful adaptation to highly demanding and stressful situations (Crocker et al. 2015) and influence personal and social outcomes like performance (Lazarus 2000a). Thus, the ability to cope with potentially stressful situations and demands is crucial in order to regulate the emotional response during a marathon race. Coping is a learning process (Pensgaard and Ursin 1998) that includes deliberate, conscious attempts to overcome a stressful situation (Richards 2012). Based on Lazarus and Folkman's (1984) model, coping can be further defined as the "…constantly changing cognitive and behavioural efforts to manage specific external and/or internal demands that are appraised as taxing or exceeding the resources of the person" (Lazarus and Folkman 1984, p. 141). Coping can be classified into *problem*-, *emotion*-, or *avoidance focused strategies* (Nicholls and Polman 2007), and involves volitional thoughts and actions to deal with physically and psychologically difficult situations (Lazarus 1999). These strategies are not distinct action types into specific directions, leading to the fact that a single coping effort of an athlete may serve one or more directions and functions (Lazarus 1999). In detail, *problem-focused coping* strategies are directed towards the stressor itself and are used to minimize distress by reducing or eliminating the stressor, and are applied in situations appraised as being controllable (Folkman and Lazarus 1980). Moreover, problem-focused coping aims to change the stressful situation or demand, and includes cognitive and/or behavioural cues, task-oriented coping, increased effort, planning, suppression of competing activities, a focus on goals and seeking instrumental and informational support (e.g., Kaiseler et al. 2012b; Nicholls and Polman 2007). In contrast, *emotion-focused coping* is used to regulate emotional arousal and distress in order to increase psychological well-being and to decrease emotional stress (e.g., Hammermeister and Burton 2001; Kaiseler et al. 2012b). Emotion-focused strategies include getting emotional social support, imaging/visualizing, positive reinforcement, acceptance, venting unpleasant emotions, humour, remaining confident, or turning to religion (e.g., Lazarus and Folkman 1984; Nicholls and Polman 2007; Stanley et al. 2012). *Avoidance-focused coping* refers to the athlete's effort to remove oneself mentally or even physically from the stressful situation (Johnson et al. 1998). Applying avoidance coping strategies involves behavioural and psychological efforts to deny or disengage from a stressful event (Krohne 1993; Nicholls and Polman 2007). Problem-, emotion-, and avoidance focused coping strategies can include adjusting behaviour (e.g., adjusting pace, relaxation, focus on venting of emotions, behavioural disengagement), and are regularly applied by long distance runners (e.g., Buman et al. 2008b).

Using coping strategies is associated with (a) the appraisal of harmful situations that lead to emotions and anxiety (Nicholls and Polman 2007; Ntoumanis and Biddle 1998), (b) positive appraisals of performance (Calmeiro et al. 2010), and (c) positive affective states following competition (Hadd and Crocker 2007). Importantly, these positive outcomes towards dealing effectively with stressful situations and demands during a marathon are derived from both problem-focused and emotion-focused strategies. However, problem-focused strategies are more effective when athletes have some degree of control over the situation, whereas emotion-focused strategies are more effective when athletes perceive little or no control over the situation (Nicholls and Polman 2007). Hence, the application of problem- or emotion-focused coping strategies depends on the situations and demands (Gaudreau et al. 2010) and the IZOF (Hanin 2000).

Evans et al. (2014) were able to show that runners reduce the application of avoidance coping strategies regarding a competitive situation over a single competitive race, trying instead to successfully cope with the emotions they experienced during this situation. In addition, problem-focused coping strategies (e.g., changing the situation for the better) also appear important during competitive suffering.

When using problem-, emotion- or avoidance coping strategies, athletes can shift their attention between internal and external dimensions (Gill and Strom 1985; Morgan and Pollock 1977). The internal dimension in this case focuses on an athletes' own bodily sensations, thoughts and emotions, as well as physical sensations that relate to the task at hand, whereas the external dimension focuses on stimuli from the environment outside one's own body (cf. Pen and Fisher 1994). These dimensions are often used in conjunction with the terms association or dissociation (Masters and Ogles 1998), classifying four distinct and effective ways to enhance endurance performance (Weinberg et al. 1984). Association refers to perceiving and dealing with factors that are relevant to the performance and goal achievement. In contrast, dissociation refers towards the distraction of the athlete from the experience of any potentially stressful situation or demand during the race. To expand the unidimensional conceptualization of attention focussing in sports, Stevinson and Biddle (1999) developed a two-dimensional model of attention, integrating both the process (e.g., associative vs. dissociative) and the direction of the attention focus (e.g., internal vs. external). The proposed model distinguishes between four directions of an athlete's focus during competition: (1) external association (e.g., keeping the pace, setting detailed goals on the track), (2) external dissociation (e.g., focussing on spectators/environment, watching the landscape), (3) internal association (e.g., physical sensations like feeling one's heart beat, focusing on one's respiration), and (4) internal dissociation (e.g., solving arithmetic problems, thinking about work/friends). More recently, Brick et al. (2014) proposed to expand the associative dimension of Stevinson and Biddle (1999) by further distinguishing between internal sensory monitoring and active self-regulation, whereby internal sensory monitoring deals with directing attention towards one's breath, muscle soreness, fatigue, thirst, etc., active self-regulation refers to one's cadence, pacing, running technique or race strategies (Brick et al. 2014). In addition, on the dissociative level, Brick et al. (2014) refer to active distraction instead of internal dissociation and involuntary distraction instead of external dissociation, whereby active distraction describes solving mathematic problems, intentional distraction, or conversing and involuntary distraction relates to directing attention to unimportant scenery, spectators, turning to religion or imagining music.

## 5.6 Differences in the Application of Coping Strategies

Marathon runners respond and cope differently to stressors during competition, with some even benefitting from emotions generally considered to be negative that derive from stressful situations and demands (e.g., Hanin 2000; Raglin 2007). Research shows that endurance performance can successfully be enhanced through the use of both associative and dissociative coping strategies (Weinberg et al. 1984). However, it appears that associative strategies may be more effective compared to dissociative/distractive strategies, provided that the runner in question is able to keep an objective and non-emotional perspective on pain perception. In contrast, if the runner is emotionally influenced by the bodily sensations and their attention is directed towards the pain, applying dissociative/distractive strategies to distract from the negative sensation would be more beneficial (cf. Brewer and Buman 2006). Moreover, differences exist between elite/experienced athletes and non-elite/inexperienced athletes with regard to the application of association and dissociation for coping with stress and emotion. Elite long distance athletes perform better when applying associations, whereas non-elite athletes prefer dissociations and tend to perform better when applying such strategies (Brewer and Buman 2006). For example, newcomers and non-elite athletes may try a general relaxation strategy when experiencing stress and emotions during the race, but experienced and elite athletes focus on relaxing specific muscle groups, such as the shoulder girdle or their thighs (Schomer 1986; Tammen 1996). It is important to note that although elite and experienced runners predominantly utilize associative coping strategies during long distance endurance competitions, they also use dissociative coping strategies, depending on the demands of the situation (cf. Brick et al. 2014). In their classic publication on the psychological characteristics of elite distance runners, Morgan and Pollock (Morgan and Pollock 1977) found that non-elite runners use dissociative strategies to deal with stress, pain and fatigue, while elite-runners apply associative strategies. Specifically, elite runners intensively focussed on bodily feelings in their feet and legs and their respiration, to the extent that they were able to maintain pace by listening to these sensations. Moreover, elite marathon runners identified specific other competitors that they would like to keep up with or stay with during the race, but this decision was considered optional rather than mandatory. In addition, elite-runners applied self-talk strategies during the race, telling themselves to keep calm or to relax. Lastly, elite runners did not identify any pain zones during the race. Importantly, they did not believe in the phenomenon, or rather the myth, of “hitting the wall” and, as such, they did not report “hitting the wall” during the race (Brewer and Buman 2006; Buman et al. 2008b; Morgan and Pollock 1977). In contrast, non-elite runners employ dissociative cognitive strategies, like rehearsing or reconstructing previous experiences and images (e.g., think about the entire educational experiences; building and constructing a house in the mind; mentally listening to specific music; doing simple to complex mathematical calculations). Applying such dissociative strategies appears to be directed towards distracting the runner from stressful situations and demands, as well as painful sensations. As has been proved in several studies, dissociative and distractive thoughts lead to decreased pain perception (Baden et al. 2004) or decreased perceived exertion (Stanley et al. 2007) by focussing attention on other demands, sensations or perceptions unrelated to the pain (Brewer and Buman 2006) or exertion. Overall, it can be said that applying dissociative strategies appears to be more effective in non-elite athletes, perhaps because non-elite marathon runners have insufficient experience to have developed effective strategies to cope with the task at hand, when compared to elite athletes (Brewer and Buman 2006; Buman et al. 2008b).

Interestingly, runners that use association during a marathon complete the distance faster compared to those athletes who use dissociative coping strategies during the competition (Brewer and Buman 2006; Masters and Lambert 1989; Morgan and Pollock 1977; Tammen 1996). In addition, the pace of the run is related to the use of associative and dissociative coping strategies. Elite athletes change from dissociation during low running intensity to association as the pace increases (Tammen 1996).

Regarding gender differences in the application of coping strategies, the existing literature points out that there are more similarities than differences between genders (see Crocker et al. 2015). Nevertheless, if differences between male and female athletes are present, these may be due to different stressors and appraisal rather than differences between genders per se (Kaiseler et al. 2012a). For example, female athletes appraise potentially stressful situations and demands with higher levels of stress intensity (Kaiseler et al. 2012b; Tamres et al. 2002) and lower levels of perceived control over stressful situations during competitions (Hammermeister and Burton 2004) in comparison to male athletes. High perceptions of control have been associated with the application of problem-focused and less emotion-focused coping strategies (Zakowski et al. 2001).

Moreover, while some studies do not find any differences between male and female athletes regarding the use of different coping strategies (e.g., Crocker and Graham 1995; Kowalski et al. 2005), some others do (for a review see Nicholls and Polman 2007). It has been found that male endurance runners suppress competing activities and use association as emotion-focused strategies (Hammermeister and Burton 2004), whilst female athletes predominantly use emotion-focused coping strategies like venting emotions, emotional support, positive reinterpretation, and dissociation (Hammermeister and Burton 2004) along with coping strategies that involve verbal expressions (e.g., self talk, talking to others) (Tamres et al. 2002).

## 5.7 Specific Sport Psychology Techniques to Improve Coping

To date, the most common coping strategies in sport include increasing effort, seeking social support, avoidance, wishful thinking, changing tactics, problem-solving, confrontation, relaxation, arousal control, and planning (Crocker et al. 2015). In order to improve effective coping with stressors, athletes should learn, practice and apply different self-regulation skills that have been clearly proved to better coping during competition situations. Based on findings from research and experiences in working with athletes, some specific sport psychological techniques can be used to improve coping with stressors during a marathon. Such sport psychology techniques include self-talk, self-efficacy training, goal-setting, imagery and visualisation, and relaxation.

Using self-talk can be one major source of coping with potentially stressful situations and demands during the marathon (e.g., Hamilton et al. 2007; Morgan and Pollock 1977). Self-talk has been defined as a "dialogue [in which] the individual interprets feelings and perceptions, regulates and changes evaluations and convictions, and gives him/herself instructions and reinforcement" (Hackfort and Schwenkmezger 1993, p. 355). A recent study by van Raalte et al. (2015) found that runners utilize a variety of self-talk during a race. Specifically, this self-talk can be distinguished between associative self-talk, focussing on the athletes' bodies, dissociative self-talk, positive motivational self-talk, negative-motivational self-talks, short term goal-setting self-talk, incentive self-talk, mantras, spiritual self-talk or praying, and miscellaneous thoughts. In their paper the authors state that spiritual self-talk especially can be applied to reduce perceived stress during the race (van Raalte et al. 2015). Interestingly, it is not only those athletes that use positive and assisted positive self-talk (e.g., athletes are given external positive comments during the endurance task) that improve their performance, but also some athletes that use assisted negative self-talk (e.g., athletes are given external negative comments during the endurance task; Hamilton et al. 2007). Whereas positive self-talk might serve as motivational support, negative assisted self-talk can present an external challenge that the athlete faces and wants to master. Again, this finding supports the notion that the beneficial or detrimental effect of the type of self-regulation technique or coping strategy is highly dependent on the individual.

Regarding the ability to overcome stressors during a marathon (and, therefore, to remain resolute in the pursuit of one's goals), evidence exists possessing high levels of self-efficacy is beneficial to athletes (Feltz et al. 2008). Perceived self-efficacy is defined as an individuals' judgement of his capabilities to achieve desired outcomes in a variety of circumstances (Bandura 1997). Sources for self-efficacy are past performance accomplishments, vicarious experience, verbal persuasion, and interpretation of physiological/emotional states (Bandura 1997). While past performance accomplishments refers to previous successful performances in training or especially competition, vicarious experience refers to an individual learning from observing other athletes successfully completing the desired task. Verbal persuasion comprises feedback and verbal support from others (e.g., coach, spectators) or the athlete himself (e.g., self-talk). Interpretation of physiological and emotional states relates to the perception and interpretation of bodily information such as pain, strength, fitness, etc., as well as emotions and feelings that the athlete has about the task or in anticipation of crossing the finish line (Bandura 1997). Recently, Samson (2014) provided information that long distance runners use physiological states, verbal persuasion, and past performances most. Interestingly, novice runners rely more on verbal persuasion compared to experienced runners, which could be explained by the lack of past performances in this group of athletes. As a result, it appears to be important to create opportunities for novice runners to gain positive experience during their competition training, for example by using a competitive mimicry (e.g., creating competition-like circumstances during training) or by competing in shorter races (Samson 2014). These positive experiences can be beneficial as they are likely to familiarize the athlete with similar stressors as would be experienced during a marathon and, therefore, prompt the athlete to develop effective strategies to overcome them.

Using effective goal-setting prior to a competition has been linked with the ability to better cope with stressors that relate to goal failure, such as having slower transit times than planned (Bueno et al. 2008). In order to set effective goals, athletes should focus on goal specifity, goal difficulty, and goal proximity (Locke and Latham 1990). Athletes should set realistic goals that are not too demanding and difficult for themselves in order to prevent counterproductive effects on their affective arousal, because very demanding goals can be perceived as a potential stressor (Bueno et al. 2008). Nevertheless, goals should be difficult enough in order to trigger better performances than easy to reach goals (McCarthy 2012).

Applying imagery and visualisation is another method that has been shown to be related to effective goal-setting (Munroe et al. 2000), reduced anxiety (Vadocz et al. 1997), and to increased self-confidence (Callow et al. 2001) in athletes. Imagery has been defined as "those quasi-sensory and quasi-perceptual experiences of which we are self-consciously aware and which exist for us in the absence of those stimulus conditions that are known to produce their genuine sensory or perceptual counterparts" (Richardson 1969, pp. 2–3). Athletes using imagery in training and competition can perceive potential stressors and demands as facilitative and under control (Cumming et al. 2007; Jones et al. 2002). Athletes that are better able to use imagery during potentially stressful situations have been shown to be higher in sport confidence (Williams and Cumming 2012). Consequently, it seems appropriate for athletes to practice and apply imagery during training sessions in order to effectively apply this technique during a marathon.

Although it is detrimental for some athletes to practice relaxation during the competition (Raglin 2007), it can clearly benefit other athletes (Schomer 1986; Tammen 1996). Relaxation techniques known to impact upon physiological reactions, behaviours, emotions and cognitions, and include methods like hypnosis, autogenous training, meditation, progressive muscle relaxation and biofeedback (Vaitl 2000). Athletes report that relaxation techniques help them to focus on their inspiration of breath and also to vent problems, stressors and emotions during the expiration of breath (Buman et al. 2008b; Hammermeister and Burton 2004). However, it is not the type of relaxation technique that is important, but rather the athletes' ability to control stressors and cope with them. Athletes who can apply self-control techniques usually do not experience permanently increased stress levels (Neumann 2003). Williams and Harris (1998) suggest offering athletes a wide variety of relaxation techniques to help the athlete identify the most effective technique, so as to optimally impact the athletes' performance (e.g., Patrick and Hrycaiko 1998).

## 5.8 From Theory to Practice

To successfully cope with different stressful events during a marathon, an athlete needs to have excellent coping skills, use problem- and emotion-focused strategies separately or simultaneously, and, most importantly, be able to apply them when needed (Hammermeister and Burton 2001; Lazarus 1991). Because some studies find that athletes use different coping strategies to deal with the same problem (cf. Pensgaard and Ursin 1998), and the development of coping strategies is highly individual and depends on the context, situation and athlete, a recommendation regarding specific coping strategies for long distance athletes is difficult. Nonetheless, using evidence from literature and existing coping guidelines (e.g., Kaluza 1997), four steps on how marathon runners can learn to deal with potential stressors and the concomitant emotions either individually or in conjunction with a sport psychology consultant will be presented.

Firstly, because *preventing* the occurrence of stress is more desirable than *curing* stress during the marathon competition (cf. Lane et al. 2012), it is crucial for athletes to identify potential stressors that might arise in a marathon race during the preparation period. Subsequently, they can develop individual coping strategies in order to successfully cope with the various stressors. Athletes should prepare themselves for stressful situations, demands or phenomena that they are likely to experience during competition and group these factors into internal (e.g., pain, fatigue, chance of missing personal goals, lack of motivation) or external stressors (e.g., weather conditions, poor hydration, other competitors, pressure from spectators). With this preparation, marathon runners can become highly familiar with the stressful situations and demands that affect them and efficient in utilizing their individual strategies to cope with each specific stressor should they really occur.

Secondly, because the level of optimal functioning and the performance-related biopsychosocial states are highly individual, marathon runners should identify their IZOF (Hanin 2000). In doing so, athletes should assess the perceived intensity of functional and dysfunctional emotional states in relation to the quality of their performance. To improve this identification process, it is beneficial to refer to the personal performance history and to evaluate the degree of similarity or dissimilarity between the optimal emotional state and actually experienced states. In this way, it is likely that athletes will be able to identify specific levels of emotional states (e.g., anxiety) that lead to optimal or very poor performances. The optimal emotional states necessary for an athlete to achieve their best performance are those which are most appropriate and relevant to the individual under specific conditions (Hanin 2000). The optimal performance level includes both the positive and negative emotions that a runner might experience in order to perform to their maximum. When assessing the benefit of positive and negative emotions, an athlete should factor in the anticipated intensity level, as the effectiveness of coping strategies appears to be dependent on the task intensity (e.g., Stanley et al. 2007). Hence, an athlete who strives for optimal functioning during a marathon should not only deal with potential stressors that might occur during competition, but also with the intensity of the associated emotions.

Thirdly, when developing individual coping strategies for all stressors that do not fit into the IZOF, the application of a two-dimensional model of coping is recommended, based on previously developed attention models (Brick et al. 2014; Stevinson and Biddle 1999). In order to cope with identified internal and external stressors, athletes can develop coping strategies that direct their attention to (1) internal sensory monitoring (e.g., focusing on breath, heart beat, bodily sensations), (2) internal active self-regulation (e.g., cadence, pacing, running technique, race strategies), (3) internal active distraction (e.g., solving mathematic problems, intentional distraction, conversing), (4) external involuntary distraction (e.g., focussing on spectators/scenery, imagining music, turning to religion), and (5) external association (e.g., keeping the pace, reaching mile marker). Within these dimensions, athletes can apply problem-focused coping and emotion-focused coping (Nicholls and Polman 2007) that can serve one or more directions and functions (Lazarus 1999) of the two-dimensional model. However, it is not recommended to apply avoidance coping strategies as it has been shown that trying to mentally or even physically deny or disengage from a potentially stressful event can lead to impaired performances or even dropping out of the competition (e.g., Crocker et al. 2015; Evans et al. 2014).

When developing, practicing, and applying problem-focused strategies, athletes should be task oriented, focused on goals and suppressing competing activities. Emotion-focused strategies, which can be used concurrently with problem-focused strategies, involve regulating emotional arousal through imagery and visualisation, relaxation or getting emotional support. For example, when a marathon runner experiences faster heart rate (internal sensory monitoring), problem-focused coping could involve focusing on the task of maintaining heart rate within a predefined area and to stay calm, whilst emotion-focused coping could involve self-talk to affirm that a slight increase in heart rate is not a threat. Equally, an athlete that is impacted by negative comments from spectators could direct attention to running technique in order to become task oriented again (problem-focused coping), or to visualise the spectators offering emotional support through their comments (emotion-focused coping).

Although some studies show that association strategies seems to have a stronger relation with faster marathon performances, and that marathon runners with sufficient experience in running this distance might learn, practice and apply such strategies, other studies show that athletes can benefit from dissociative strategies, provided that they keep an objective and non-emotional perspective towards stressors. Thus, the effectiveness of applying either association or dissociation is highly individual. As a result, it is suggested that athletes should choose coping strategies that fit their level of experience, their objectivity, and their demands, rather than applying a general coping strategy. Likewise, the same is true for the application of various sport psychology techniques that athletes can use during a marathon. Techniques such as self-talk, self-efficacy training, goal-setting, imagery and visualisation, directing attention, and relaxation have proved to be effective to decrease stress and emotional arousal during competition. Athletes can either teach themselves to use these methods or consult a sport psychological consultant who will help them to successfully learn, adapt and apply the techniques.

Fourthly, it is suggested to evaluate the effectiveness of coping strategies the athlete uses during a marathon. In doing so he will look for reasons why some strategies and techniques might have helped to better cope with stressful situations or demands, whereas others might have failed to do so. Thus, the athlete will need to look at how he appraised different situations, evaluate whether or not this lead to emotions or anxiety, positive appraisals of performance or positive affective states during or after the marathon. Following this evaluation the athlete should start again with step 1, identifying potential stressors during a marathon and elaborate individual coping strategies that fit him and his individual zone of optimal functioning.

Finally, it is very important to address the phenomenon of "hitting the wall". It seems that athletes should adjust their mindset regarding this issue, as the literature indicates that it is almost exclusively those athletes who believe in the existence of "the wall", and therefore anticipate hitting it, that are susceptible to its effects (Morgan and Pollock 1977). Conversely, athletes that do not believe in the wall and, therefore, do not anticipate its occurrence during a marathon, are less likely to experience it. Consequently, athletes would do well to develop positive alternatives to "the wall" they expect in competition, such as anticipating flow or a runners high (e.g., Boecker et al. 2008) at certain mile markers, to help them reach the finish line. Alongside such mental preparations, athletes can organize their physical training in order to be prepared on the long distance they have to cover during the marathon. Current literature indicates that athletes who complete longer distances for their longest training run are less likely to experience hitting the wall than those athletes who complete shorter distances for their longest training run (Buman et al. 2008a). Hence, in order to prevent stress and negative impacts on cognitive, affective, behavioural, motivational, and physiological dimensions resulting from hitting the wall, athletes should complete longer distances during long training runs. Completing running distances in training conditions that are close to competition distance is likely to help elicit similar stressors as are found in competition. Indeed, this is also true for other factors, such as pace, track, environmental circumstances, etc. Competitive mimicry such as this will prepare an athlete's body and mind for the psychological and physiological demands of a marathon and reduce the possibility of "hitting the wall" during competition.

Overall, it is beneficial to perceive stressful situations and demands in a positive manner. Studies show that many athletes who appraise problems and difficulties as challenges that can be overcome, as learning opportunities, or as opportunities for personal growth are more successful than those who do not (Bandura and Locke 2003; O'Neil and Steyn 2007; Sheldon 2005).

## 5.9 Summary

This chapter summarized the development of stress and emotions during a marathon and presented practical methods to cope with them. By preparing for potentially stressful situations and demands that may occur during a marathon, athletes improve their ability to cope with stress and emotions. For high-performance and elite athletes the use of predominantly associative coping strategies is recommended due to their considerable running experience. Indeed, this group of runners may even improve their running performance by utilizing association. In contrast, less experienced runners should engage in dissociative coping strategies in order to better deal with the stressors of competition. Future research should aim to evaluate coping interventions in both experienced and non-experienced marathon runners with a view to identifying effective methods for individual athletes to improve their coping strategies and, ultimately, their performance.

## References

Addison T, Kremer J, Bell R (1998) Understanding the psychology of pain in sport. Irish J Psychol 19(4):486–503. doi:10.1080/03033910.1998.10558209

Andersen MB, Williams JM (1988) A model of stress and athletic injury: prediction and prevention. J Sport Exerc Psychol 3:294–306

Andersen MB, Williams JM (1999) Athletic injury, psychosocial factors and perceptual changes during stress. J Sports Sci 17(9):735–741. doi:10.1080/026404199365597

Baden DA, Warwick-Evans L, Lakomy J (2004) Am I nearly there? The effect of anticipated running distance on perceived exertion and attentional focus. J Sport Exerc Psychol 26:215–231

Baden DA, McLean TL, Tucker R, Noakes TD, St Clair Gibson A (2005) Effect of anticipation during unknown or unexpected exercise duration on rating of perceived exertion, affect, and physiological function. Br J Sports Med 39(10):742–746. doi:10.1136/bjsm.2004.016980

Bandura A (1997) Self-efficacy: the exercise of control. Freeman, New York

Bandura A, Locke EA (2003) Negative self-efficacy and goal effects revisited. J Appl Psychol 88 (1):87–99

Beedie CJ, Terry PC, Lane AM (2000) The profile of Mood States and athletic performance: two meta-analyses. J Appl Sport Psychol 12:49–68

Beedie CJ, Lane AM, Wilson MG (2012) A possible role for emotion and emotion regulation in physiological responses to false performance feedback in 10 mile laboratory cycling. Appl Psychophysiol Biofeedback 37(4):269–277. doi:10.1007/s10484-012-9200-7

Boecker H, Sprenger T, Spilker ME, Henriksen G, Koppenhoefer M, Wagner KJ, Tolle TR (2008) The Runner's high: opioidergic mechanisms in the human brain. Cereb Cortex 18(11):2523–2531. doi:10.1093/cercor/bhn013

Brewer BW, Buman MP (2006) Attentional focus and endurance performance: review and theoretical integration. Kinesiologia Slov 12(2):82–97

Brick N, MacIntyre T, Campbell M (2014) Attentional focus in endurance activity: new paradigms and future directions. Int Rev Sport Exerc Psychol 7(1):106–134. doi:10.1080/1750984X.2014.885554

Bueno J, Weinberg RS, Fernández-Castro J, Capdevila L (2008) Emotional and motivational mechanisms mediating the influence of goal setting on endurance athletes' performance. Psychol Sport Exerc 9:786–799

Buman MP, Brewer BW, Cornelius AE, van Raalte JL, Petitpas AJ (2008a) Hitting the wall in the marathon: Phenomenological characteristics and associations with expectancy, gender, and running history. Psychol Sport Exerc 9(2):177–190. doi:10.1016/j.psychsport.2007.03.003

Buman MP, Omli JW, Giacobbi PR, Brewer BW (2008b) Experiences and coping responses of "Hitting the Wall" for recreational marathon runners. J Appl Sport Psychol 20(3):282–300. doi:10.1080/10413200802078267

Callow N, Hardy L, Hall C (2001) The effect of a motivational general-mastery imagery intervention on the sport confidence of high-level badminton players. Res Q Exerc Sport 72:389–400

Calmeiro L, Tenenbaum G, Eccles D (2010) Event-sequence analysis of appraisals and coping during trapshooting performance. J Appl Sport Psychol 22(4):392–407. doi:10.1080/10413200.2010.495325

Carver CS, Scheier MF, Weintraub JK (1989) Assessing coping strategies: a theoretically based approach. J Pers Soc Psychol 56(2):267–283

Cerin E, Barnett A (2006) A processual analysis of basic emotions and sources of concerns as they are lived before and after a competition. Psychol Sport Exerc 7(3):287–307. doi:10.1016/j.psychsport.2005.07.002

Cohen S, Kamarck T, Mermelstein R (1983) A global measure of perceived stress. J Health Soc Behav 24(4):385–396

Crocker PRE, Hadd V (n.d.) Stress in sport. Retrieved from http://old.hkin.educ.ubc.ca/behavioural/Articles/4.pdf

Crocker PRE, Graham TR (1995) Coping by competitive athletes with performance stress: gender differences and relationships with affect. Sport Psychol 9:325–338

Crocker PRE, Tamminen KA, Gaudreau P (2015) Coping in sport. In: Mellalieu SD, Hanton S (eds) Contemporary advances in sport psychology. Routledge, Oxon, pp 28–67

Cumming J, Olphin T, Law M (2007) Self-reported psychological states and physiological responses to different types of motivational general imagery. J Sport Exerc Psychol 29:629–644

Devonport TJ (2015) Understanding stress and coping among competitive athletes in sport: applying psychological theory and research. In: Lane AM (ed) Sport and exercise psychology, 2nd edn. Routledge, New York, NY, pp 127–153

Dolce JJ, Doleys DM, Raczynski JM, Lossie J, Poole L, Smith M (1986) The role of self-efficacy expectancies in the prediction of pain tolerance. Pain 27:261–272

Eccles DW (2012) Verbal reports of cognitive processes. In: Tenenbaum G, Eklund RC, Kamata A (eds) Measurement in sport and exercise psychology. Human Kinetics, Champaign, pp 103–117

Endler NS, Parker JD (1994) Assessment of multidimensional coping: Task, emotion, and avoidance strategies. Psychol Assess 6:50–60

Evans MB, Hoar SD, Gebotys RJ, Marchesin CA (2014) Endurance athletes' coping function use during competitive suffering episodes. Eur J Sport Sci 14(4):368–375. doi:10.1080/17461391.2013.832803

Feltz DL, Short SE, Sullivan PJ (2008) Self-efficacy in sport: Research and strategies for working with athletes, teams, and coaches. Int J Sports Sci Coaching 3(2):293–295

Fliege H, Rose M, Arck P, Walter O, Kocalevent R-D, Weber C, Klapp B (2005) The perceived stress questionnaire (PSQ) reconsidered: validation and reference values from different clinical and healthy adult samples. Psychosom Med 67:78–88

Folkman S, Lazarus RS (1980) An analysis of coping in a middle-aged community sample. J Health Soc Behav 21:219–239

Folkman S, Lazarus RS (1985) If it changes it must be a process: study of emotion and coping during three stages of a college examination. J Pers Soc Psychol 48:150–170

Forys KL, Dahlquist LM (2007) The influence of preferred coping style and cognitive strategy on laboratory-induced pain. Health Psychol 26(1):22–29. doi:10.1037/0278-6133.26.1.22

Freund W, Weber F, Billich C, Birklein F, Breimhorst M, Schuetz UH (2013) Ultra-marathon runners are different: investigations into pain tolerance and personality traits of participants of the TransEurope FootRace 2009. Pain practice 13(7):524–532. doi:10.1111/papr.12039

Friesen AP (2015) Managing own and others' emotions in sport. In: Lane AM (ed) Sport and exercise psychology, 2nd edn. Routledge, New York, pp 154–177

Gaudreau P, Blondin J-P (2002) Development of a questionnaire for the assessment of coping strategies employed by athletes in competitive sport settings. Psychol Sport Exerc 3(1):1–34. doi:10.1016/S1469-0292(01)00017-6

Gaudreau P, El Ali M, Thierry Marivain (2005) Factor structure of the coping inventory for competitive sport with a sample of participants at the 2001 New York marathon. Psychol Sport Exerc 6:271–288

Gaudreau P, Nicholls AR, Levy AR (2010) The ups and downs of coping and sport achievement: an episodic process analysis of within-person associations. J Sport Exerc Psychol 32:298–311

Gill DL, Strom EH (1985) The effect of attentional focus on performance of an endurance task. Int J Sport Psychol 16:217–223

Golenia M, Sulprizio M (2007) Burnout im Leistungssport. MedicalSportsNetwork 2(1):60–62

Hackfort D, Schwenkmezger P (1993) Anxiety. In: Singer RN, Murphey M, Tennant LK (eds) Handbook of research on sport psychology. Macmillan, New York, pp 328–364

Hadd VN, Crocker PR (2007) The effect of stress-related factors on post-performance affects in competitive adolescent swimmers. Int J Sport Exerc Psychol 5(2):142–157. doi:10.1080/1612197X.2007.9671816

Hamilton RA, Scott D, MacDougall MP (2007) Assessing the effectiveness of self-talk interventions on endurance performance. J Appl Sport Psychol 19(2):226–239. doi:10.1080/10413200701230613

Hammermeister J, Burton D (2001) Stress, appraisal, and coping revisited: examining the antecedents of competitive state anxiety with endurance athletes. Sport Psychol 15:66–90

Hammermeister J, Burton D (2004) Gender differences in coping with endurance sports: are men from Mars and women from Venus? J Sport Behav 27:148–164

Hanin YL (2000) Individual zones of optimal functioning (IZOF) model. In: Hanin YL (ed) Emotions in sport. Human Kinetics, Champaign, pp 65–89

Hanin YL (2007) Emotions in sport: current issues and perspectives. In: Tenenbaum G, Eklund RC (eds) Handbook of sport psychology, 3rd edn. Wiley, Hoboken, pp 31–58

Hanin YL (2010) Coping with anxiety in sport. In: Nicholls AR, Hauppauge NY (eds) Coping in sport. Theory, methods, and related constructs. Nova Science, New York, 159–175

Hanton S, Fletcher D, Coughlan G (2005) Stress in elite sport performers: a comparative study of competitive and organizational stressors. J Sports Sci 23(10):1129–1141

Johnson JE, Weinert C, Richardson JK (1998) Rural residents' use of cardiac rehabilitation programs. Public Health Nurs 15(4)

Jones MV, Mace RD, Bray SR, MacRae AW, Stockbridge C (2002) The impact of motivational imagery on the emotional state and self-efficacy levels of novice climbers. J Sport Behav 25:57–73

Jones MV, Meijen C, McCarthy PJ, Sheffield D (2009) A theory of challenge and threat states in athletes. Int Rev Sport Exerc Psychol 2(2):161–180

Kaiseler M, Polman RCJ, Nicholls AR (2012a) Effects of the big five personality dimensions on appraisal coping, and coping effectiveness in sport. Eur J Sport Sci 12(1):62–72. doi:10.1080/17461391.2010.551410

Kaiseler M, Polman RCJ, Nicholls AR (2012b) Gender differences in appraisal and coping: an examination of the situational and dispositional hypothesis. Int J Sport Psychol 43:1–14

Kaluza G (1997) Stressbewältigungstraining. In: Hautzinger M, Linden M (eds) Verhaltenstherapiemanual. Techniken, Einzelverfahren und Behandlungsanleitungen. Springer, Berlin, pp 383–390

Kellmann M (ed) (2002) Enhancing recovery: preventing underperformance in athletes. Human Kinetics, Leeds

Kleinert J (2002) Das Stress-Wiederverletzungs-Modell: Psychologische Ansätze zur Erklärung und Vermeidung von Wiederverletzungen Sport. Schweiz Z für Sportmed 50(2):49–57

Kowalski KC, Crocker PRE, Hoar SD, Niefer CB (2005) Adolescents' control beliefs and coping with stress in sport. Int J Sport Psychol 36:257–272

Krohne HW (1993) Vigilance and cognitive avoidance as concepts in coping research. In: Krohne HW (ed) Attention and avoidance: strategies in coping with aversiveness. Seattle, Hogrefe & Huber, pp 19–50

Laborde S, Dosseville F, Raab M (2013) Introduction, comprehensive approach, and vision for the future. Int J Sport Exerc Psychol 11(2):143–150. doi:10.1080/1612197X.2013.773686

Laborde S, Lautenbach F, Allen MS, Herbert C, Achtzehn S (2014a) The role of trait emotional intelligence in emotion regulation and performance under pressure. Pers Individ Differ 57(43–47):2013. doi:10.1016/J.Paid.09.013

Laborde S, Raab M, Kinrade NP (2014b) Is the ability to keep your mind sharp under pressure reflected in your heart? Evidence for the neurophysiological bases of decision reinvestment. Biol Psychol 100:34–42. doi:10.1016/j.biopsycho.2014.05.003

Laborde S, Lautenbach F, Allen MS (2015) The contribution of coping-related variables and heart rate variability to visual search performance under pressure. Physiol Behav 139:532–540

Lane AM, Beedie CJ, Jones MV, Uphill M, Devonport TJ (2012) The BASES expert statement on emotion regulation in sport. J Sports Sci 30(11):1189–1195. doi:10.1080/02640414.2012.693621

Lazarus RS (1991) Progress on a cognitive-motivational-relational theory of emotion. Am Psychol 46(8):819–834

Lazarus RS (1999) Stress and emotion: a new synthesis. Springer, New York

Lazarus RS (2000a) Cognitive-motivational-relational theory of emotion. In: Hanin YL (ed) Emotions in sport. Human Kinetics, Champaign, pp 39–62

Lazarus RS (2000b) How emotions influence performance in competitive sports. Sport Psychol 14:229–252

Lazarus RS, Folkman S (1984) Stress, appraisal, and coping. Springer, New York

Levine S, Ursin H (1991) What is stress? In: Rivier MB, Koob G (eds) Stress. Neurobiology and neuroendocrinology. Marcel Decker, New York, pp 3–21

Locke EA, Latham GP (1990) A theory of goal setting and task performance. Prentice Hall, Englewood Cliffs

Mann D, Schaad K (2001) The complete guide to adventure racing. The insider's guide to the greatest sport on earth. Hatherleigh Press, New York

Marcora SM, Staiano W, Manning V (2009) Mental fatigue impairs physical performance in humans. J Appl Physiol 106(3):857–864. doi:10.1152/japplphysiol.91324.2008

Masters KS, Lambert MJ (1989) The relations between cognitive coping strategies, reasons for running, injury, and performance of marathon runners. J Sport Exerc Psychol 11:161–170

Masters KS, Ogles BM (1998) The relations of cognitive strategies with injury, motivation, and performance among marathon runners: results from two studies. J Appl Sport Psychol: 281–296

McCarthy P (2012) Enhancing positive emotion in sport. In: Thatcher J, Jones M, Lavallee D (eds) Coping and emotion in sport, 2nd edn. Routledge, Oxon, pp 167–193

Morgan WP, Pollock ML (1977) Psychologic characterization of the elite distance runner. Ann NY Acad Sci 301(1):382–403. doi:10.1111/j.1749-6632.1977.tb38215.x

Munroe KJ, Giacobbi PR Jr, Hall C, Weinberg RS (2000) The four Ws of imagery use—where, when, why, and what. Sport Psychol 14:119–137

Neil R, Hanton S, Mellalieu SD (2013) Seeing things in a different light: assessing the effects of a cognitive-behavioral intervention upon the further appraisals and performance of golfers. J Appl Sport Psychol 25:106130. doi:10.1080/10413200.2012.658901

Nesse RM, Ellsworth PC (2009) Evolution, emotions, and emotional disorders. Am Psychol 64 (2):129–139. doi:10.1037/a0013503

Neumann G (2003) Formtief: Wenn Leistungseinbrüche unerklärbar scheinen. In: Kleinert J (ed.) BLV Sportwissen. Erfolgreich aus der sportlichen Krise. Mentales Bewältigen von Formtiefs, Erfolgsdruck, Teamkonflikten und Verletzungen. BLV, München, pp 33–54

Nicholls AR, Polman RCJ (2007) Coping in sport: a systematic review. J Sports Sci 25(1):11–31. doi:10.1080/02640410600630654
Nicholls AR, Polman RC, Levy AR, Backhouse SH (2008) Mental toughness, optimism, pessimism, and coping among athletes. Pers Individ Differ 44(5):1182–1192. doi:10.1016/j.paid.2007.11.011
Niemann DC, Lee JW (1990) Infectious episodes in runners before and after the LA Marathon. J Sports Med Phys Fitness 30(3):316–328
Ntoumanis N, Biddle SJ (1998) The relationship of coping and its perceived effectiveness to positive and negative affect in sport. Pers Individ Differ 24(6):773–788. doi:10.1016/S0191-8869(97)00240-7
O'Connor PJ (2007) Monitoring and titrating symptoms a science-based approach to using your brain to optimise marathon running performance. Sports Med 37:408–411
O'Neil JW, Steyn BJ (2007) Strategies used by south african non-elite athletes to cope with the environmental stressors associated with endurance events. South Afr J Res Sport Phys Educ Recreation 29:99–107
Patrick TD, Hrycaiko DW (1998) Effects of a mental training package on an endurance performance. Sport Psychol 12:283–299
Pen LJ, Fisher CA (1994) Athletes and pain tolerance. Sports Med 5:319–329
Pensgaard AM, Roberts GC (2000) The relationship between motivational climate, perceived ability and sources of distress among elite athletes. J Sports Sci 18:191–200
Pensgaard AM, Ursin H (1998) Stress, control, and coping in elite athletes. Scand J Med Sci Sports 8(3):183–189. doi:10.1111/j.1600-0838.1998.tb00190.x
Raglin JS (2007) The psychology of the marathoner: of one mind and many. Sports Med 37 (4–5):404–407
Raglin JS, Hanin YL (2000) Competive anxiety. In: Hanin YL (ed) Emotions in sport. Human Kinetics, Champaign, pp 93–111
Richards H (2012) Coping processes in sport. In: Thatcher J, Jones M, Lavallee D (eds) Coping and emotion in sport, 2nd edn. Routledge, Oxon, pp 1–32
Richardson A (1969) Mental imagery. Springer, New York
Samson A (2014) Sources of self-efficacy during Marathon training: a qualitative, Longitudinal investigation. Sport Psychol 28(2):164–175. doi:10.1123/tsp.2013-0027
Samson A, Simpson D, Kamphoff C, Langlier A (2015) Think aloud: an examination of distance runners' thought processes. Int J Sport Exerc Psychol. doi:10.1080/1612197X.2015.1069877
Scanlan TK, Stein GL, Ravizza K (1991) An in-depth study of former elite figure skaters: III. Sources of stress. J Sport Exerc Psychol 13:103–120
Schomer H (1986) Mental strategies and the perception of effort of marathon runners. Int J Sport Psychol: 41–59
Selye H (1978) The stress of life. McGraw Hill, Oxford
Sheldon JP (2005) Physical and psychological predictors of perceived ability in adult male and female tennis players. J Appl Sport Psychol 17:48–63
St Gibson AC, Lambert EV, Rauch LHG, Tucker R, Baden DA, Foster C, Noakes TD (2006) The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. Sports Med 36(8):705–722. doi:10.2165/00007256-200636080-00006
Stanley CT, Pargman D, Tenenbaum G (2007) The effect of attentional coping strategies on perceived exertion in a cycling task. J Appl Sport Psychol 19(3):352–363. doi:10.1080/10413200701345403
Stanley DM, Lane AM, Beedie CJ, Friesen AP, Devonport TJ (2012) Emotion regulation strategies used in the hour before running. Int J Sport Exerc Psychol 10(3):159–171. doi:10.1080/1612197X.2012.671910
Stevinson C, Biddle SJ (1998) Cognitive orientations in marathon running and "hitting the wall". Br J Sports Med 32:229–235
Stevinson C, Biddle SJ (1999) Cognitive strategies in running: a response to Masters and Ogles (1998). Sport Psychol 13(2):235–236

Sulprizio M, Kleinert J (2011) "Mental Gestärkt"—eine Netzwerkinitiative zur psychischen Gesundheit im Leistungssport. In: Ohlert J, Kleinert J (eds) Sport vereinT. Psychologie und Bewegung in Gesellschaft. 43. Jahrestagung der Arbeitsgemeinschaft für Sportpsychologie (asp) vom 2. - 4. Juni 2011 in Köln. Feldhaus, Hamburg, p 166

Sulprizio M, Kleinert J (2014) Kein Stress mit dem Stress: Tipps und Lösungen für mentale Stärke und psychische Gesundheit im wettkampforientierten Leistungssport. Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, Dortmund

Summers JJ, Sargent GI, Levey AJ, Murray KD (1982) Middle-aged, non-elite marathon runners: a profile. Percept Mot Skills 54:963–969

Tammen VV (1996) Elite middle and long distance runners associative/dissociative coping. J Appl Sport Psychol 8(1):1–8. doi:10.1080/10413209608406304

Tamres LK, Janicki D, Helgeson VS (2002) Sex differences in coping behavior: a meta-analytic review and an examination of relative coping. Person Soc Psychol Rev 6(1):2–30. doi:10.1207/S15327957PSPR0601_1

Vadocz EA, Hall CR, Moritz SE (1997) The relationship between competitive anxiety and imagery use. J Appl Sport Psychol 9:241–253

Vaitl D (2000) Psychophysiologie der Entspannung. In: Vaitl D, Petermann F (eds) Handbuch der Entspannungsverfahren. Band 1: Grundlagen und Methoden 2nd ed, vol 1. Beltz Psychologie Verlags Union, Weinheim, pp 29–76

van Raalte J, Morrey RB, Cornelius A, Brewer BW (2015) Self-talk of marathon runners. Sport Psychol: 1–10. doi:10.1123/tsp.2014-0159

Weinberg RS, Smith J, Jackson A, Gould D (1984) Effect of association, dissociation, and positive self-talk strategies on endurance performance. Can J Appl Sport Sci 9:25–32

Williams J, Andersen MB (1998) Psychosocial antecedents of sport injury Review and critique of the stress and injury model. J Appl Sport Psychol 10(1):5–25. doi:10.1080/10413209808406375

Williams SE, Cumming J (2012) Sport imagery ability predicts trait confidence, and challenge and threat appraisal tendencies. Eur J Sport Sci: 1–10

Williams JM, Harris DV (1998) Relaxation and energizing techniques for reulation and arousal. In: Williams JM (ed) Applied sport psychology: personal growth to peak performance, 3rd edn. Mayfield Publications, Mountain View, pp 219–236

Willoughby SG, Hailey BJ, Mulkana S, Rowe J (2002) The effect of laboratory-induced depressed mood state on responses to pain. Behav Med 28:23–31

Wolf SA, Eys MA, Kleinert J (2014) Predictors of precompetitive anxiety response: relative impact and prospects for anxiety regulation. Int J Sport Exerc Psychol. doi:10.1080/1612197X.2014.982676

Zakowski SG, Hall MH, Klein LC, Baum A (2001) Appraised control, coping, and stress in a community sample: A test of the goodness-of-fit hypothesis. Ann Behav Med 23(3):158–165. doi:10.1207/S15324796ABM2303_3

# Chapter 6
# Motivation and Marathon Running

**Chris Hammer and Leslie Podlog**

> *If you want to run, run a mile. If you want to experience a different life, run a marathon.*
> –Emil Zatopek, the only person to ever win the 5000, 10,000 m, and marathon at the same Olympics.

**Abstract** In recent years, marathon running has become a sport for the masses. Over the past 35 years, the median finishing time for a U.S. marathon slowed by 47 min (for males), the median age for male marathoners increased from 34 (1980) to 40 years (2014), and the number of marathon finishers grew from an estimated 143,000 (1980) to over 550,000 (2014) (Running USA in 2014 Running USA annual marathon report, 2015). With slower finishing times, older participants, and dramatic increases in marathon participation rates, it is evident that marathon running has become a popular endeavor for individuals of all ages and athletic abilities. Given the appeal of marathon running, it seems worth asking the question: "why are so many individuals motivated to undertake such a grueling activity?" The issue of motivation among marathoners provides the focus of this chapter. In particular, the chapter is divided into four sections. First, as the term 'motivation' has been used to refer to an array of conceptually distinct constructs, we provide a scientifically sound definition of the construct. Second, the chapter focuses on empirical research examining the issue of why individuals choose to participate in marathon training and running. Here the discussion centers on three main issues including: the measurement of motivation in marathon runners; participation motives for engaging in marathon training and racing; and the relationship between motives for marathon running and marathon performance. Third, we examine detrimental outcomes associated with excessive motivation for marathon training. Finally, we highlight a number of directions for future research and provide a chapter summary.

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C. Zinner and B. Sperlich (eds.), *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*, DOI 10.1007/978-3-319-29728-6_6

**Keywords** Motivation · Training · Age · Gender · Family status · Marathon performance · Excessive motivation · Passion

Perhaps no other athletic event has a greater tradition than the marathon. The modern marathon was first run in 1896, commemorating the legend of Pheidippides, who in 490 B.C. ran from the Battle of Marathon to Athens, Greece to deliver a message of victory. In addition to being an incredible feat of stamina and determination, many people view completing a marathon as a testament to the human spirit, making the marathon a popular event for those wishing to experience the personal challenges and triumphs the marathon has to offer.

The popularity of marathon running has dramatically increased in recent decades. In the United States alone, there were over 1200 marathon events and 550,000 marathon finishers in 2014 (Running USA 2015). These numbers represent a substantial increase compared to the year 2000, when there were approximately 300 marathon events and 353,000 finishers in the United States (Running USA 2015). These record figures suggest that, in addition to the burgeoning popularity of the marathon, a substantial number of individuals are able to adhere to the demands of marathon training. Preparing for a marathon often involves time intensive, challenging training regimens, physical discomfort and pain, the need to carefully monitor one's diet, and scheduling social events around one's training regimen. It is therefore apparent that marathon runners take their training to levels far beyond that required for overall health and fitness (Ogles and Masters 2000). Such dedication and training commitment is in sharp contrast to the general population, of which a large portion struggles to adhere to minimal exercise guidelines. According to the Center for Disease Control (CDC), only 1 in 5 U.S. adults meet physical activity guidelines. Similarly low figures have been found in a number of Western European nations, with Portugal among the lowest prevalence rates (Martinez-Gonzalez et al. 2001).

Research on motivation and exercise adherence amongst the general populace may be helpful in understanding the motivational aspects of training for a marathon. Given however, the substantial level of motivation and adherence necessary to train for and complete a marathon, the motivational aspects of marathon running may be unique (Masters and Ogles 1995). As such, this chapter focuses exclusively on research concerning the motivation of marathon runners, and other long distance running populations. Researchers in this area have largely focused on sub-elite marathoners, a cohort often characterized as "recreational runners." The abilities of this population can vary immensely, from runners who complete the marathon in well under three hours to those exceeding five or six hours. To be consistent with the literature, we will define a "marathoner" as any individual completing the marathon distance, regardless of time or ability.

In this chapter, we examine four areas in relation to the motivational aspects of training and competing in a marathon. First, as the term 'motivation' has been used to refer to an array of conceptually distinct constructs, it is instructive to first specify the nature of motivation. Second, we describe research focused on motivation and marathon/long distance runners. In the penultimate section, "Can motivation to train be maladaptive?" we examine potential deleterious outcomes associated with excessive motivation for marathon training. The fourth and final section highlights a number of directions for further inquiry and includes a chapter summary.

## 6.1 What Is Motivation?

Roberts (2012), a noted sport psychologist has argued that *motivation* is an overused and vague term. Be it coaches, athletes, politicians, teachers, business people, or even motivational researchers, the definitions of motivation often vary substantially. For instance, motivation has been characterized as a matter of positive thinking, a high level of arousal, or a sense of confidence in one's ability to achieve a goal (Roberts 2012). Despite these differences, most contemporary motivation researchers view motivation as process—not an entity—that characterizes one's effort in terms of direction, intensity, and persistence towards achieving (or avoiding) an outcome (Roberts 2012). The direction component refers to "what" one is motivated to achieve, while the intensity dimension refers to how much effort or tenacity one puts forward in pursuit of a goal. The persistence dimension refers to how long an individual continues to strive towards their goal in the face of challenge, difficulty or setbacks. The term motivation or 'motives' also denotes the reasons why an individual undertakes a particular pursuit or endeavor (Ryan and Deci 2000). Such motives may for example be intrinsic in nature, as when an individual trains for a marathon because of the inherent enjoyment they derive from the act of running, or extrinsic motives such as achieving a certain time, receiving tangible rewards (contracts, endorsements, etc.), or trying to avoid a punishment (e.g., non-selection for a race or team).

Certainly, multiple motives or reasons may underlie the performance of any action or behavior. For the purposes of our discussion here, it is sufficient to note that different motives for undertaking an activity have been shown to influence a wide array of health, well-being, and performance outcomes across various life domains (see Ryan and Deci 2000 for a review). For example, intrinsic motives to compete in sport have been associated with more positive emotions and enhanced sport performance (e.g., Gillet et al. 2010; Podlog and Eklund 2005; Shin et al. 2014). Conversely, extrinsic motives have consistently predicted more deleterious health and well-being outcomes, such as greater athlete burnout (Londsdale et al. 2009), increased worry and concern following athletes' return to sport following injury (Podlog and Eklund 2005), and diminished persistence in sport tasks (Pelletier et al. 2001). Thus, understanding why individuals undertake an activity is essential for predicting the quality of their experiences as well as their well-being and performance outcomes.

## 6.2 Research on Motivation in Marathon Runners

The research on motivation among marathon runners has focused on three main topics, specifically: the measurement of motivation to train for a marathon; participation motives for engaging in marathon training and racing; and the relationship between motives for marathon running and marathon performance.

### *6.2.1 Measurement of Motivation in Marathoners*

In order to understand the nature of athletes' motives for marathon running, as well as potential predictors and outcomes of motivation, it essential to be able to measure the construct of interest in the specific setting of interest. As Masters et al. (1993) suggest "…empirical methods of developing sports motivational theories using select samples of athletes can lead to sport-specific findings" (p. 135). Towards this end, Masters et al. (1993) created the *Motivations of Marathoners Scale* (MOMS), an instrument designed to assess individuals' motives for undertaking marathon training. In devising the instrument, Masters et al. (1993) first reviewed relevant research concerning the motives of marathon and long distance runners (Carmack and Martens 1979; Clough et al. 1989; Curtis and McTeer 1981; Johnsgard 1985a, b, 1989; Masters and Lambert 1989; Summers et al. 1982, 1983). Based on the literature, four broad categories or reasons for running were identified including: psychological, achievement, social, and physical motives. Furthermore, nine specific themes emerged within these four broad categories. Within the psychological motives category, providing a sense of life meaning, enhancing self-esteem, and psychological coping were all specific motives for running. Achieving personal goals and competing with other runners comprised the achievement motives category. The social motives category contained themes revolving around the desire to receive recognition and approval from others and the desire to affiliate with other runners. Within the physical motives category, a general health orientation and a concern about weight emerged as themes.

Encompassing these nine specific themes, Masters et al. (1993) created the 56-item MOMS. Psychometric testing revealed that the MOMS possessed good internal consistency, retest reliability, factor validity, and construct validity (Masters and Ogles 1995, 1998; Masters et al. 1993; Ogles et al. 1995). With the creation of the MOMS, Masters et al. (1993) equipped researchers with a means to assess the motivations of marathon runners, potential demographic variables influencing individuals' motivation for marathon running, as well as motivational antecedents and outcomes. The next section describes empirical investigations, many of which utilized the MOMS, to examine the influence of demographic variables on marathoners' participation motives.

### *6.2.2 Participation Motives for Marathon Training and Racing*

The following section highlights research examining the motivation to train and compete in a marathon as a function of one's experience level, age, gender, and family status. Furthermore, research on a contemporary phenomenon—cause-based marathon running—is highlighted, given the increasing number of individuals who report running based on the desire to tackle a social issue. Finally, we highlight research indicating that different motivational profiles may characterize runners.

### *6.2.3 Motivation and Previous Marathon Experience*

Different theoretical perspectives recognize that the factors which motivate someone to initiate an activity may be different than those motivating the individual to maintain or persist in the behavior (Masters and Ogles 1995). Given this reasoning, Masters and Ogles (1995) utilized the MOMS to compare the motivation of 472 marathon runners based on their previous marathon experience. Results revealed that veteran marathoners, defined as individuals who ran more than three marathons, were largely motivated by social reasons, in particular, identity, recognition, and affiliation. Competitive reasons and health concerns were also salient motives reported among veteran marathoners. Masters and Ogles (1995) termed this cluster of motives the "marathon identity". Interestingly, the motives for this group were largely external in nature. Masters and Ogles (1995) posited that when taking into account the time and effort necessary to train for a marathon, social reinforcement might be necessary to facilitate one's perseverance to stick with the marathon. Mid-level marathon runners, that is, those who ran two or three marathons, appeared primarily motivated by the desire to improve their personal marathon performance and by the psychological benefits of running a marathon. The first time marathoners did not fit the profiles of either the veteran or mid-level marathon runners. Instead, they were primarily motivated by goal achievement, self-esteem, as well as health and weight concerns. Additional research supports the finding that people initiate their marathon involvement to accomplish a personal goal and to address health concerns (Johnsgard 1985a, b; Summers et al. 1982). For example, in a study collecting data both before and after participants' first ever marathon, Summers et al. (1982) found that pre-race reasons for marathon running centered on health and personal challenge, while after the race, the most frequent reason for wanting to run a subsequent marathon was a desire to run a faster time.

Johnsgard (1985b) also demonstrated changes in motives for marathon running as a function of experience levels in his study of 180 experienced American runners over the age of 50. Interestingly, reasons for initiating marathon running were positively related to those which motivated current running and focused on running for physical fitness and weight control, tension reduction and mood elevation, and personal identity. However, significant shifts in the emphasis on particular motives were evident with increased running experience. The strong initial motives regarding physical fitness and weight control both diminished slightly in value, while initially salient motives dealing with tension reduction, mood elevation, and identity became even stronger with experience. Results from Johnsgard (1985b), Summer et al. (1982) and Masters and Ogles (1995) suggest that motives for running a marathon may be influenced by one's experience level and that motives may shift from a focus on weight or health concerns to running as a source of identity, psychological benefits, and performance goals. As these studies were cross-sectional in nature, longitudinal studies would provide a more comprehensive understanding of how one's marathon motivation evolves as a consequence of experience levels.

### *6.2.4 Motivation and Age*

A similar, yet distinct, concept related to experience is age. As motivation to undertake exercise has been shown to vary across the lifespan (Biddle 1995), Ogles and Masters sought to examine potential differences in motivation among marathoners of different ages. In a study investigating the difference in participative motives of older and younger male marathon runners, Ogles and Masters (2000) had 104 older runners (ages 50 and up) and 110 younger runners (ages 20–28) complete the MOMS. They found that older runners were more motivated by a desire to develop and maintain a general health orientation, including a concern for weight, a desire to seek a sense of life meaning or purpose, and affiliation with other runners. On the other hand, younger runners were more motivated by personal goal achievement, such as running to beat personal best times. The populations did not differ significantly with respect to the participative motive of competitiveness. The authors suggested that differences between the two groups may reflect the evolution of running motives over the lifespan. In particular, the researchers argued that younger runners may initially pursue marathons in an effort to achieve personal goals, however, during the time spent training and meeting other runners, marathoners may begin to appreciate the other benefits of running. Moreover, as runners age, they inevitably lose some of their physical prowess making it increasingly difficult to set personal bests. Such physical decrements may in turn result in a diminished emphasis on achievement motives and a greater focus on life meaning motives. Once again, the cross-sectional nature of this investigation mitigates any time-order conclusions and suggests the need for prospective research on the topic.

### *6.2.5 Motivation and Gender*

In addition to differences in marathon participation motives as a function of experience level and age, research also reveals gender differences. Ogles et al. (1995)

administered the MOMS to a sample of 610 runners registering for races ranging from 5k to the marathon, with the majority signed up for the marathon. Results indicated that women were more likely to be motivated by weight concern (i.e., to maintain/lose weight, to stay physically attractive), affiliation (i.e., to meet people, socialize, and share group identity), self-esteem (i.e., to improve confidence, to feel sense of achievement), life meaning (i.e., to make life more purposeful, to feel at peace with the world), and psychological coping (i.e., to improve mood and feel less anxious). Women in this study also endorsed a wider range of motives than men, as they reported using running as a means to socialize, manage weight and health, and to psychologically take care of themselves. Finally, Ogles et al. (1995) found that men were disproportionately higher in their compulsion to run as defined by their history of race participation, miles trained per week, and anticipated miles training per week. Based on these findings the researchers argued that women may experience more psychological benefits from running than men. This conclusion was supported in subsequent research by Ogles and Masters (2003) in which they examined the existence of potential motivational subgroups of marathon runners. The group that endorsed all nine motives to run on the MOMS, termed the "running enthusiasts", was disproportionately female. On the other hand, the two clusters that were defined by motives to improve speed, reach potential (i.e., "personal goal achievers"), and compete with others (i.e., "competitive achievers") tended to be males.

A number of gender differences found in Ogles et al. (1995) study have been corroborated in other investigations. For example, Masters et al. (1993) found that weight concern was significantly more important to women as a reason to get involved with marathons than it was for men. Summers et al. (1983) revealed that, compared to males, women reported greater benefits of meeting people as well as relief from depression, a finding echoed in the work of Leedy (2009). In her case profile of five female marathon runners, Leedy (2009) found that women used marathon running as a coping mechanism during times of emotional stress. Based on the above work, it appears that marathon running may serve different functions for males and females.

### 6.2.6 Motivation and Family Status

Another factor that has been examined in relation to motives for marathon running is one's family status. Goodsell et al. (2013) investigated how motives to run a marathon were related to different family structures, as defined by marital and parental status. To that end, they purposefully selected thirty-three participants with varying marathon experience levels and different family life structures to participate in semi-structured interviews. They found that the motivation to start running or to begin running marathons were relatively similar across participants, regardless of family structure. A combination of three factors including: prior experience with running; an invitation from a family member or friend; or a desire to improve health through participation in a convenient, flexible form of exercise, often provided the impetus to begin running or to run a marathon.

Differences emerged with regard to the motivations to continue running marathons depending upon one's family structure. Specifically, marital status, birth of children, and the ages of those children all impacted one's motivation to run. Those who were not married and had no children were motivated by a sense of accomplishment, the health benefits of running, and the social aspect of running. Similarly, the married without children group were also motivated by health benefits and by accomplishments, particularly, the desire to improve on their previous race performances. This group also used running as a means to manage emotional issues or marital stress. However, the social aspect of running (e.g., meeting new people) did not particularly appeal to the married without children group, as they seemed more motivated by the intrinsic benefits to themselves or to their relationships with their spouses. Conversely, married runners with young children reported enjoying the social aspects of running, perhaps to create an identity separate from their family roles. This was especially true for women, who expressed the need to meet people and develop friendships, perhaps due to the relative isolation characteristic of those raising young children. Like the other two groups however, the most prominent reason to run among married individuals with young kids, was for health and well-being. Married runners with older children often described how running had become routine for them, and that external forces such as a need to comply with unyielding training routines did not play as significant a role in their motivation to run. Rather, for this group, running was a lifestyle. Although a sense of accomplishment remained important, notions of what constituted a sense of accomplishment differed from other groups. Concerns about race time, reaching goals, or winning the race, were of less importance than being in control of their health, demonstrating that they had "not become old just yet" (p. 346), and being able to complete marathons without being excessively fatigued. For married athletes whose children had moved out, also termed "empty nesters", the social aspects of running were reported to be most salient. Empty nesters indicated that the benefits of running with others encompassed both therapeutic (e.g., talk about problems) and stimulating (e.g., talk community events, politics, etc.) benefits.

Summarizing their findings, Goodsell et al. (2013) suggested that important differences by family structure in the motivations for continuing to run were evident. Marriage, the birth of children, and the ages of children living at home all influenced how runners viewed their physical activity. Although this investigation shed important qualitative insights regarding the role of social factors impacting motivation, this study failed to take into account the entire spectrum of family structure. For instance, further research would benefit from examining categories such as single parents.

### 6.2.7 Motivation and Caused-Based Marathon Training

Running a marathon to help fundraise for charity has grown in popularity. Oftentimes, participants are provided coaching and training opportunities in exchange for participant's commitment to fundraise. Jeffery and Butryn (2012) sought to understand the motivations of those participating in a caused-based marathon training program aimed at raising money for cancer research. They interviewed thirteen participants and found three motivational themes, including: a growing connection with the cause, improved fitness and athleticism, and mutual training support with the team. Twelve of the thirteen participants indicated that their time in the program had caused them to develop a deeper connection to the cause. While none of the participants cited the cause itself as the primary reason for joining the program, a growing connection to the cause was suggested to be a powerful motivator to train and complete the marathon. For many participants, training alongside other group members who embodied the cause of curing cancer fostered a deeper sense of commitment to the issue. Furthermore, several participants reported that despite extreme fatigue during the actual marathon, they were motivated to run faster when spectators cheered for the charity, while others indicated that their connection to the cause enabled them to overcome extreme discomfort and pain and complete the marathon.

The second main theme to emerge was improved fitness and athleticism. Specifically, as participants' fitness and running proficiency increased, so too did their motivation to train. Several participants reported feeling more motivated after discovering that they were fast runners. Moreover, several participants mentioned that they were motivated by the program's proven, effective, and reliable training schedule. The final main theme was mutual training support with the team. Almost all of the participants became increasingly connected with other members of the training group as the program progressed, which in turn resulted in a support network that facilitated the motivation to attend workouts. Unique to caused-based marathon training programs is the chance to develop a connection to the cause, which Jeffery and Butryn (2012) found to be a potentially compelling motivating factor. These findings suggest that tying individuals' participation in marathon running to a larger social issue or to group affiliation may have positive motivational implications. These suggestions require further empirical testing.

### 6.2.8 Motivational Subgroups of Marathon Runners

The aforementioned research suggests that motivation for marathon training and racing may be influenced by a variety of factors including, previous experience, age, gender, and family status. Furthermore, running for a cause may over time, provide a strong source of motivation as runners internalize the importance of the cause and begin to affiliate with other cause-based runners. Such studies however, did not address whether marathoners could be distinguished based on unique motivational profiles or clusters. To address this issue, Ogles and Masters (2003) conducted a multivariate cluster analysis based on a sample of 1519 participants competing in one of six different marathons. Responses to the MOMS revealed five distinct profiles: “running enthusiasts”, “lifestyle managers”, “personal goal achievers”, “personal accomplishers”, and “competitive achievers”. The “running enthusiast” motivational profile endorsed all of the nine motives measured by the MOMS. This group was disproportionately female, and tended to be older, to have run more marathons, and to run with other runners. This profile suggests that having multiple motives for marathon running and appreciating various facets of the marathon experience may be beneficial for extending one’s marathon running longevity.

The “lifestyle managers” motivational profile was characterized by an emphasis on personal goal achievement, self-esteem, health orientation, psychological coping, weight concern, and life meaning. Ogles and Masters (2003) concluded that runners in this group were primarily motivated by a desire to improve their physical and psychological well-being, and that running might serve as a means to handle negative emotions. Such results are consistent with Ogles and Masters (2000) who found that marathoners endorsing general fitness as a motive for running tended to run fewer miles per week, placed less emphasis on social and competitive motives, and were more likely to train alone. This group was also disproportionately female.

The “personal goal achievers” group did not appear to be strongly motivated by competition with other runners. Rather, as the name of this motivational cluster would suggest, an interest in improving for personal reasons seemed to predominate. This group was also disproportionately male, tended to be younger and faster, and ran more weekly miles than other groups. The “personal accomplishers” group was characterized by personal goal achievement, self-esteem, and a health orientation. They appeared similar to the “lifestyle managers” group but placed less emphasis on managing negative emotions. “Personal accomplishers” were also fairly average on training variables and miles run per week.

The fifth and final group, the “competitive achievers”, most strongly endorsed motives of personal goal achievement, self-esteem, health orientation, competition, and life meaning. This group tended to be younger males who trained more days a week than any other group and were more likely to train twice in one day. Besides the “running enthusiasts,” the “competitive achievers” were the only group motivated by competition with others. Interestingly, across all groups, competitive motives as well as social motives such as recognition and affiliation were of lesser importance than a health orientation, personal achievement, and self-esteem motives, all three of which were consistently valued the most (Ogles and Masters 2003). Additionally, psychological motives such as using running to become less anxious, to cope with worries, to solve problems, and to improve mood were endorsed to a greater extent than competitive or social motives. These results suggest that despite several divergences between motivational clusters, the majority of marathoners are motivated by personal life-enhancing reasons (Ogles and Masters 2003).

### *6.2.9 Motivation and Marathon Performance*

As indicated previously, different motivations, be it intrinsic versus extrinsic, have been shown to have differential consequences for athletes' emotions, health and well-being, and performance (Gillet et al. 2010; Podlog and Eklund 2005; Shin et al. 2014). Surprisingly, few studies have examined whether different motivations for competing in a marathon predicted the likelihood of marathon completion versus non-completion or different performance outcomes with respect to finishing times (Havenar and Lochbaum 2007; Ogles and Masters 2000, 2003; Lange and Crusius 2015). Havenar and Lochbaum (2007) prospectively compared the motivations of individuals completing the training and finishing the marathon versus those who dropped out prior to the race. Utilizing the MOMS, all data were collected prior to the beginning of the training protocol, with the marathon following approximately 6 months later. Of the 106 participants, 31 would go on to complete the training protocol as well as the marathon, while 75 were pre-race dropouts, a 71 % attrition rate. Furthermore, findings revealed significant differences between marathon finishers and pre-race dropouts on three of the MOMS scales—weight concern, social recognition, and affiliation—with pre-race dropouts endorsing these motives more than marathon finishers. Consistent with these findings, Masters et al. (1993) found that a low percentage of marathoners endorsed motives of weight concern and a desire for recognition, suggesting the potential negative consequences of an emphasis on external motives for marathon running.

The influence of motivation on marathon performance has been addressed in three other investigations. In the aforementioned study by Ogles and Masters (2003) participants characterized under the motivational cluster "competitive achievers" had the fastest average marathon finish times ($X$ = 208.12 min; $SD$ = 29.84) while the "lifestyle managers" had the slowest average finishing times ($X$ = 235.6 min; 33.77 = $SD$). Consistent with these findings, Ogles and Masters (2000) found that runners who emphasized competitive reasons for running tended to train more miles per week, participate in more marathons, and had faster personal best finishing times. Similarly, like the "lifestyle managers", runners endorsing general fitness as a primary motive for running in Ogles and Masters (2000) study also had the slowest running times.

Relationships between motivation for running and running performance were also revealed in a third investigation. Given the competitive nature of sport, Lange and Crusius (2015) reasoned that feelings of envy or jealousy might provide an important source of motivation driving running participation. Applying this logic, the researchers sought to examine the impact of two types of envy—benign envy and malicious envy—on marathon running performance. Benign envy was defined as "the motivation to move upward", whereas malicious envy was related to "pulling superior others down" (p. 284). According to Lange and Crusius (2015), benign envy increases the motivation to invest more effort to enhance one's own standing whereas malicious envy increases the motivation to diminish the success of envied others. Analysis of 370 marathon participants (208 = half marathon and

162 full marathon) results revealed that dispositional benign envy predicted higher goal setting, which in turn predicted faster marathon race performance. In contrast, dispositional malicious envy predicted the avoidance of setting a concrete time goal for the race. Collectively, results from studies in this section, indicate that external motives such as weight-related preoccupations, a desire for recognition, and an interest in "pulling" superior others down may be detrimental towards marathon completion or completion time. Such a contention is consistent with motivational research highlighting the negative influence of external motives for task completion, persistence, and performance (Ryan and Deci 2000).

Although the authors are not aware of any other studies examining the implications of various motivations on marathon performance, one other study examined outcomes associated with different participative motives. Loughran et al. (2013) investigated whether the motives of non-elite marathon runners were related to any perceived benefits associated with their participation. Results revealed that individuals often perceived benefits that were similar to their initial motivations for running. For instance, those motivated to run for health reasons also reported physical benefits associated with their marathon running. This result suggests that marathoners may get what they seek from their marathon involvement. Furthermore, in some cases, perceived benefits extended to other domains. For example, health motivations for marathon running predicted perceived psychological and relationship benefits outside the sport realm. Given the increased popularity of marathon running among individuals of all ages and athletic backgrounds, it seems likely that a multitude of physical, psychological and social benefits may be derived from marathon running. Further research examining the impact of different running motives on a variety of health and well-being benefits (e.g., vitality, general happiness) and performance indicators is needed to extend research in this area.

## 6.3 Can the Motivation to Train Be Maladaptive?

In describing the definition of motivation, we suggested that a key component of motivation relates to the intensity of one's goal directed behavior. While an intense motivation to train might generally be perceived of as desirable quality, research suggests that there are instances, when one's motivation towards a target activity can become excessive and compulsive. Excessive motivation may result in deleterious psychosocial and health consequences for the individual (Hall et al. 2007; Stephan et al. 2009). The response to the question "is there such thing as too much of a good thing?" appears to be "yes". As described below, research on compulsive exercise behavior and passion indicate that motivation-related constructs appear to predict a number of adverse outcomes associated with involvement in marathon/long distance running.

### 6.3.1 Compulsive Exercise Behavior

The exercise literature contains numerous terms that have been used to describe compulsive exercise behavior, such as exercise dependence, exercise addiction, and obligatory exercise. While it is important to note that the profusion of nomenclature surrounding this phenomenon, limits progress in better understanding compulsive exercise behavior (Hall et al. 2007), a detailed discussion of terms used to examine compulsive exercise behavior is beyond the scope of this chapter. Rather, the focus here is to highlight research examining key psychological characteristics of compulsive runners and outcomes associated with it. As the term "obligatory running" seems to be most commonly used, we will employ it in the discussion below.

Results from several investigations suggest a number of common features characterizing obligatory runners (Coen and Ogles 1993; Hall et al. 2007; Karr et al. 2013; Ogles et al. 1995). Ogles et al. (1995) defined obligatory runners as those who run at all costs, often despite negative consequences such as injuries or damaging effects on interpersonal relationships. Such individuals have been found to be more motivated to train out of a desire to achieve personal goals, to beat competition, and to attain recognition for their accomplishments, in relation to their non-obligatory counterparts (Ogles et al. 1995). Obligatory runners have also reported training more miles, days, and hours per week, than non-obligatory runners (Coen and Ogles 1993) and suggested a greater willingness to run while injured and to continue running if they became injured in the future.

Several other psychological attributes appear to characterize obligatory runners including trait anxiety, perfectionist tendencies, a high exercise identity, and internalization of the thin/athletic-ideal body shape (Coen and Ogles 1993; Hall et al. 2007; Karr et al. 2013). For instance, obligatory runners have been found to have heightened preoccupations over organization, a fear of making mistakes, and doubts regarding the quality of their training (Coen and Ogles 1993; Hall et al. 2007). Furthermore, exercise identity, and internalization of the thin/athletic-ideal body shape have been positively associated with obligatory exercise (Karr et al. 2013). Karr and colleagues found that when controlling for body mass index, age, and race distance, the interaction of exercise identity, gender, and internalization of an athletic-ideal body shape predicted obligatory exercise. Specifically, women who valued an athletic physique and who highly identified with exercise appeared more susceptible to obligatory exercise. The aforementioned research on obligatory exercise suggests that a cluster of psychological factors may characterize the compulsive runner including high external motivation, trait anxiety, perfectionist tendencies, a high exercise identity, and internalization of Western ideals about an athletic/thin body.

### *6.3.2 Passion*

A motivation-related construct, which has been found to predict both adaptive and maladaptive outcomes in a variety of life domains, is passion. Passion has been defined as "a strong inclination toward a self-defining activity that one loves, values, and devotes a significant amount of time and energy to" (Vallerand 2012, p. 205). Vallerand (2003) distinguished passion from the concept of motivation suggesting that not all forms of motivation (e.g., extrinsic motivation) entail an aspect of liking the activity, an inherent feature of passion. In his dualistic model of passion, Vallerand et al. (2003) outlined two types of passion—harmonious and obsessive—the major difference between these two being how the individual internalizes an activity into their identity. Harmoniously passionate individuals engage in an activity of their own volition and accept the activity as important for them without any contingencies attached to it. In this instance, the passion underlining the performance of an activity occupies a significant but not overpowering aspect of the persons' identity and is in harmony with other aspects of the persons' life. Obsessively passionate people, on the other hand, feel compelled to engage in a particular pursuit because they feel controlled by internal or external contingencies such as feelings of social acceptance, self-esteem or an uncontrollable excitement derived from the activity (Vallerand 2012). Unlike harmonious passion, obsessive passion is characterized by a rigid persistence in an activity that comes to control the individual, eventually occupying a disproportionate amount of importance in the person's life and causing conflict with other aspects of their life (Vallerand 2012).

A review of passion research in sport and exercise suggests that harmonious and obsessive forms of passion lead to distinct cognitive, affective, behavioral, social, and performance outcomes (see Vallerand 2012). For example, harmonious passion has been associated with positive affect, concentration and flow (Vallerand et al. 2003), while obsessive passion has been linked to a variety of mostly maladaptive outcomes such as increased negative affect (Vallerand et al. 2006), performance avoidance goal-pursuits (Vallerand et al. 2008), and aggressive behaviors (Donahue et al. 2009). Moreover, as obsessive passion leads to inflexible persistence, (Vallerand et al. 2003), it is not surprising that it has been found to be a risk factor for both acute and chronic injuries (Rip et al. 2006). In a study of long distance runners involved in structured training regimens, Stephan et al. (2009) found that obsessive passion predicted perceived susceptibility to running-related injuries and was positively related to the number of past injuries. Harmonious passion, on the other hand, was not related to the number of past injuries and negatively predicted perceived susceptibility to running-related injury. Consistent with past research (e.g., Vallerand et al. 2003), these results suggest that despite their awareness of the risk of injury, obsessively passionate individuals rigidly persist in their running because they are controlled by the need to run. While an intense adoration towards an activity is not inherently negative, findings from the passion research suggest that passion may be problematic when the marathoner becomes controlled by a compulsive need to run. For such persons, a more rigid and pressured sense of engagement may mitigate the experience of full absorption and enjoyment in one's running and lead to a number of detrimental outcomes such as injury.

## 6.4 Directions for Future Research

Despite advances in knowledge of motivation and marathon running, there remain numerous areas for further inquiry. With the creation of the MOMS, Masters et al. (1993) provided a means for developing a more comprehensive understanding of the motivations of marathon runners. Using the MOMS, researchers have found differences in motivation across various experience levels, ages, genders, and family status. While these studies provide important descriptive information regarding the nature of athletes' motives for marathon running, a number of limitations are evident. First, as mentioned, the cross-sectional nature of most studies limits the ability to draw causal conclusions, and suggests the need for longitudinal studies examining changes in motivation over the lifespan. Second, all of the studies cited in this chapter were conducted on a general marathon running population. Although some studies (e.g., Ogles and Masters 2003) included participants who might be considered "elite", researchers have yet to examine potential motivational differences between elite and non-elite marathoners. Along such lines, it would be interesting to examine how the motivations of either elite or non-elite marathoners compare to athletes' of similar levels in other sports.

Other fruitful avenues for further inquiry are also evident. As much of the research on motivation among marathon runners has been atheoretical, employing various motivational theories—social cognitive theory, expectancy-value theory, attribution theory, achievement goal theory, self-determination theory—would facilitate a better understanding of motivation in marathoners as well as its antecedents and outcomes. For example, a range of personal (self-efficacy beliefs, expectations, self-regulation skills) and environmental factors (social support, reinforcements, organizational/social environment) emphasized in social cognitive theory may reciprocally interact to influence the development of motivation across individuals or within persons across time. Likewise, further research addressing potential outcomes associated with different motives for marathon running is needed. Few investigators have examined whether different motivations predict various behavioral, performance, and psychosocial outcomes or how motivation might play a mediating or moderating role between training, performance, or well-being variables. As suggested, employing existing theories will provide researchers with a theoretical rationale for selecting variables that likely influence the development of and outcomes associated with motivation for marathon running. Finally, research testing the value of different motivational interventions would be beneficial. Given the physical and psychological challenges associated with marathon running, examination of empirically validated interventions for optimizing motivation seems worthwhile. Testing theory based interventions, using experimental designs would be beneficial towards this end.

## 6.5 Summary

With dramatic increases in marathon participation rates over the past 35 years, it is evident that marathon running has become a popular vehicle for exercising one's competitive, social and fitness needs across the lifespan (Buman et al. 2008). Given the popularity of marathon running, we sought to address the issue of what motivates individuals to undertake such an endeavor and how one's motivation might impact important well-being and performance outcomes. We defined motivation as a process relating to the direction, intensity, and persistence one displays in their goal directed behavior (Roberts 2012). In defining motivation, we also suggested that the reasons or motives underpinning one's actions could have differential consequences for individuals', health, well-being and sport performance (Ryan and Deci 2000). In order to capture the specific participation motives of marathon runners, Masters et al. (1993) developed the MOMS scale, an inventory used in subsequent research examining individual differences and cluster profiles of motivation among marathon runners. In particular, research highlighting differences in motivation as a function of experience levels, age, gender, and family status was described. Overall, findings from this body of research suggest a plethora of motives for marathon running ranging from concerns about health and fitness, to social interests, and achieving certain performance standards or race times. The relative salience of these motives appears to vary depending upon the aforementioned demographic variables. Findings also suggested that running a marathon in order to address a social issue (e.g., cancer) has become increasingly popular in recent years. In the section on motivation and marathon performance, we found motivation also influenced important outcomes, namely marathon completion versus non-completion and marathon running times. Runners endorsing motives such as weight concern, social recognition, and malicious envy ("pulling superior others down") may be susceptible for pre-race dropout and poorer marathon times. Conversely, those motivated by competitive aspirations appear to achieve faster running times. We also highlighted research suggesting that individuals who feel compelled to run or controlled by the need to run—as is the case with obligatory runners or obsessively passionate runners—may be prone to maladaptive outcomes such as injury. Finally in providing suggestions for further research, we encouraged scholars to adopt theoretically based approaches that consider the antecedents and outcomes of motivation for marathon running as well as the utility of motivational interventions.

## References

Biddle SJH (1995) Exercise motivation across the life span. In: Biddle SJH (ed) European perspectives on exercise and sport psychology. Human Kinetic Publishers, Champaign, pp 3–25
Buman MP, Omli JW, Giacobbi PR, Brewer BW (2008) Experiences and coping responses of "hitting the wall" for recreational marathon runners. J Appl Sport Psychol 20:282–300
Carmack MA, Martens R (1979) Measuring commitment to running: a survey of runners' attitudes and mental states. J Sports Psychol 1:25–42
Clough P, Shepherd J, Maughan R (1989) Motives for participation in recreational running. J Leisure Res 21:297–309
Coen SP, Ogles BM (1993) Psychological characteristics of the obligatory runner: a critical examination of the anorexia analogue hypothesis. J Sport Exerc Psychol 15:338–354
Curtis J, McTeer W (1981). The motivation for running. Can Runner 18–19
Donahue DG, Rip B, Vallerand RJ (2009) When winning is everything: on passion, identity, and aggression in sport. Psychol Sport Exerc 10:526–534
Gillet N, Vallerand RJ, Amoura S, Baldes B (2010) Influence of coaches' autonomy support on athletes' motivation and sport performance: a test of the hierarchical model of intrinsic and extrinsic motivation. J Sport Exerc Psychol 11:155–161
Goodsell TL, Harris BD, Bailey BW (2013) Family status and motivations to run: a qualitative study of marathon runners. Leisure Sci 35:337–352
Hall HK, Kerr AW, Kozub SA, Finnie SB (2007) Motivational antecedents of obligatory exercise: the influence of achievement goals and multidimensional perfectionism. Psychol Sport Exerc 8:297–316
Havenar J, Lochbaum M (2007) Differences in participation motives of first-time marathon finishers and pre-race dropouts. J Sport Behav 30:270–279
Jeffery KA, Butryn TM (2012) The motivations of runners in a cause-based marathon-training program. J Sport Behav 35:300–319
Johnsgard K (1985a) The motivation of the long distance runner: I. J Sports Med Phys Fitness 25:135–139
Johnsgard K (1985b) The motivation of the long distance runner: II. J Sports Med Phys Fitness 25:140–143
Johnsgard KW (1989) The exercise prescription for depression and anxiety. Plenum, New York
Karr TM, Zunker C, Thompson RA, Sherman RT, Erickson A, Cao L, Crosby RD, Mitchell JE (2013) Moderators of the association between exercise identity and obligatory exercise among participants of an athletic event. Body Image 10:70–77
Lange J, Crusius J (2015) Dispositional envy revisited: unraveling the motivational dynamics of benign and malicious envy. Pers Soc Psychol Bull 41:284–294
Leedy G (2009) "I can't cry and run at the same time": women's use of distance running. Affilia J Women Soc Work 24:80–93
Londsdale C, Hodge K, Rose E (2009) Athlete burnout in elite sport: a self-determination perspective. J Sports Sci 27:785–795
Loughran MJ, Hamilton D, McGinley M (2013) Motivation and perceived benefits of marathoning: an exploratory study. Athletic Insight 5:113–127
Martinez-Gonzalez MA, Varo JJ, Santos JL, De Irala J, Gibney M, Kearney J et al (2001) Prevalence of physical activity during leisure time in the European Union. Med Sci Sports Exerc 33:1142–1146
Masters KS, Lambert MJ (1989) The relations between cognitive coping strategies, reasons for running, injury, and performance of marathon runners. J Sport Exercise Psychol 11:161–170
Masters KS, Ogles BM (1995) An investigation of the different motivations of marathon runners with varying degrees of experience. J Sport Behav 18:69–79
Masters KS, Ogles BM (1998) The relations of cognitive strategies with injury, motivation, and performance among marathon runners: results from two studies. J Appl Sport Psychol 10:281–296

Masters KS, Ogles BM, Jolton JA (1993) The development of an instrument to measure motivation for marathon running: the motivations of marathoners scales (MOMS). Res Q Exerc Sport 64:134–143

Ogles BM, Masters KS (2000) Older vs. younger adult male marathon runners: participative motives and training habits. J Sport Behav 23:130–143

Ogles BM, Masters KS (2003) A typology of marathon runners based on cluster analysis of motivations. J Sport Behav 26:69–85

Ogles BM, Masters KS, Richardson SA (1995) Obligatory running and gender: an analysis of participative motives and training habits. Int J Sport Psychol 26:233–248

Pelletier LG, Fortier MS, Vallerand RJ, Brière NM (2001) Associations among perceived autonomy support, forms of self-regulation, and persistence: a prospective study. Motiv Emot 25:279–306

Podlog L, Eklund RC (2005) Return to sport after serious injury: a retrospective examination of motivation and psychological outcomes. J Sport Rehabil 14:20–34

Rip B, Fortin S, Vallerand RJ (2006) The relationship between passion and injury in dance students. J Dance Med Sci 10:14–20

Roberts GC (2012) Motivation in sport and exercise from an achievement goal theory perspective: after 30 years, where are we? In: Roberts GC, Treasure DC (eds) Advances in motivation in sport and exercise, 3rd edn. Human Kinetics, Champaign, pp 5–58

Running USA (2015) 2014 Running USA annual marathon report. Retrieved 15 Oct 2015, from http://www.runningusa.org

Ryan RM, Deci EL (2000) Intrinsic and extrinsic motivations: classic definitions and new directions. Contemp Educ Psychol 25:54–67

Shin M, Kim I, Kwon S (2014) Effect of intrinsic motivation on affective response during and after exercise: latent curve model analysis. Percept Mot Skills 119(3):717–730

Stephan Y, Deroche T, Brewer BW, Caudroit J, Le Scanff C (2009) Predictors of perceived susceptibility to sport-related injury among competitive runners: the role of previous experience, neuroticism, and passion for running. Appl Psychol Int Rev 58:672–687

Summers JJ, Sargent GI, Levey AJ, Murray KD (1982) Middle-aged, non- elite marathon runners: a profile. Percept Mot Skills 54:963–969

Summers JJ, Machin VJ, Sargent GI (1983) Psychosocial factors related to marathon running. J Sport Psychol 5:314–331

Vallerand RJ (2012) The dualistic model of passion in sport and exercise. In: Roberts GC, Treasure DC (eds) Advances in motivation in sport and exercise, 3rd edn. Human Kinetics, Champaign, pp 169–206

Vallerand RJ, Blanchard C, Mageau GA, Koestner R, Ratelle C, Léonard M, Gagné M, Marsolais J (2003) Les passions de l'ame: On obsessive and harmonious passion. J Pers Soc Psychol 85:756–767

Vallerand RJ, Rousseau FL, Grouzet F, Dumais A, Grenier S, Blanchard CM (2006) Passion in sport: a look at determinants and affective experiences. J Sport Exerc Psychol 28:454–478

Vallerand RJ, Mageau GA, Elliot AJ, Dumais A, Demers MC, Rousseau F (2008) Passion and performance attainment in sport. Psychol Sport Exerc 9:373–392

# Chapter 7
# Marathon Training: Gender and Age Aspects

**Jennifer L. Reed and Jenna C. Gibbs**

**Abstract** No presentation of marathon running would be complete without a discussion of gender and age aspects. Marathon running is one of the world's oldest sports dating back to the ancient Greeks. However, it is only in the last 40 years that women and older runners have begun training for and competing in these 42 km (marathon distance) foot races. In the pages that follow, we will provide a brief history of several notable women and older runners that have shaped the history of marathon running. We will review the physiological differences such as body composition and oxygen carrying capacity between men and women as it relates to marathon training and performance. We will discuss the performance differences such as finishing time and pace strategy between men and women as well as comment on gender-specific training and injury characteristics. Specific to female runners, we will report on menstrual disturbances that may result from high exercise energy expenditure and/or low dietary energy intake frequently observed among runners, and training and running considerations during pregnancy. As apparent and highly researched are the physiological considerations of marathon running, the equally important musculoskeletal and psychological factors such as bone loss and disordered eating will be discussed. We will briefly review the cardiovascular, pulmonary and neuromuscular changes that occur with aging, and the impact of these changes on marathon training and performance. Finally, we will discuss the risk of medical problems and running-related injuries in older marathon runners and the emerging trend of younger marathon runners (<18 years of age).

**Keywords** Aging · Marathon · Running · Women

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C. Zinner and B. Sperlich (eds.), *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*, DOI 10.1007/978-3-319-29728-6_7

## 7.1 Introduction

It was once believed that women were not physically capable of running a marathon due to the strenuous nature of the event and thus were forbidden from doing so. A woman who was caught, even as a spectator, at the Olympic Games in Athens could face execution. Today, more than 500 marathons are held annually worldwide, with the vast majority of competitors being male and female recreational athletes. Several notable women have been central to the sports development. In 1923, Frances Hayward was the first woman, although an unofficial entrant, to complete the Comrades Marathon, with a time of 11:35:00 (Burfoot 2007). The Comrades Marathon is arguably the greatest ultra marathon in the world held annually in the KwaZulu-Natal Province of South Africa. Athletes worldwide combine muscle and mental strength to compete in this uphill 87 km or downhill 89 km race (the direction of the race alternates each year). In 1966, Roberta “Bobbi” Gibb was the first woman, although also an unofficial entrant, to run the Boston Marathon. She disguised herself under a hooded sweatshirt and hid behind bushes near the starting pen until the race began. When the starting gun fired, she emerged from the bushes and began running, wearing men’s running shoes. During the race she removed the sweatshirt at which point it became apparent that she was a woman. She finished the marathon in 3:21:40 to place 126th overall. In 1978, a Norwegian track star named Grete Waitz was the first woman to run the New York City Marathon in a world record time of 2:32:30. After several other marathons worldwide also proved that women could safely run 42 km, the women’s marathon was introduced at the 1984 Summer Olympics (Los Angeles, USA) and was won by Joan Benoit Samuelson of the United States with a time of 2:24:52 (Burfoot 2007). Notable accomplishments in the women’s marathon have continued since the addition of the women’s Olympic Marathon in 1984. In 2002, Paula Radcliffe became the first woman to break 2:18:00 with a finishing time of 2:17:18 in the Chicago Marathon. In 2003, she ran the London Marathon in an outstanding 2:15:25, a world record that still stands. These women were the first to break the sport’s gender barrier and have been consistently among the world’s leading performers.

In the 1970s it was uncommon to find an older runner (>40 years of age) competing in a marathon, with the exception of John A. Kelley who finished 58 Boston Marathons, the last at 84 years of age. Since 1976, the marathon running population has aged to a remarkable extent; we now see remarkable performances by men and women at all ages (Burfoot 2007).

## 7.2 Gender Differences in Marathon Running

### *7.2.1 Training, Performance and Injury Differences Between Men and Women*

In the early 1990s, scientists predicted that women would outperform men in the marathon event within the decade based on world record progression, expressed as mean running velocity versus historical time, in women's favour (Stray-Gundersen et al. 2001). However, the gap in the fastest marathon finishing times between men and women remains approximately 9–10 %, with older and lower-placed female runners driving the deficit regardless of competition level (Hunter et al. 2011). The best finishing times of male marathon runners have gradually declined from 1980 (Gerard Nijboer—Amsterdam Marathon—2:09:01) to 2014 (Dennis Kimetto—Berlin Marathon—2:02:57) (International Association of Athletics Federation 2015). The best finishing times of female marathon runners have decreased more dramatically during the same time period from 2:31:23 (Joan Benoit—1980 Auckland Marathon) to 2:20:18 (Tirfi Tsegaye—2014 Berlin Marathon), with the best finishing time achieved by Paula Radcliffe at the 2003 London Marathon (2:15:25) (International Association of Athletics Federation 2015). Figure 7.1 depicts the progression patterns of the best marathon finishing times of American male and female marathon runners from 1976 to 2005.

Running economy, defined as the energy demand of sub-maximal running at a given velocity (Saunders et al. 2004), may contribute to differences in marathon running performance between men and women. However, to date, results from studies comparing running economy of elite male and female runners are inconclusive. In classic studies of male and female runners matched for $\dot{V}O_2max$ and performance, running economy was similar between sexes at slower running speeds (Hopkins and Powers 1982); yet, male runners demonstrated superior running economy at faster "race pace" speeds (Daniels and Daniels 1992). Helegrud (1994) alternatively reported that female runners may in fact compensate for lower $\dot{V}O_2max$ (compared to male runners) with superior running economy, greater training volume, and higher exercise intensity during the race. Therefore, the contribution of running economy to gender differences in marathon performance remains unclear.

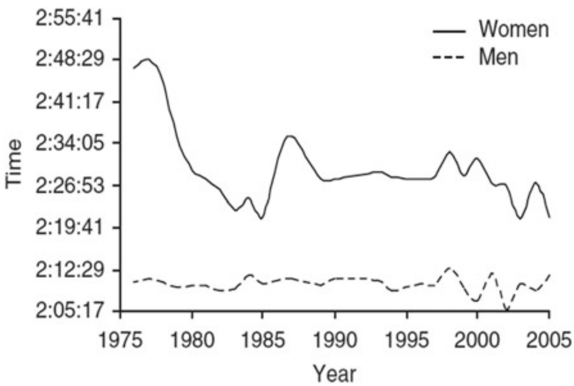


**Fig. 7.1** Best marathon finishing times of American male and female marathon runners, from 1976 to 2005. Reproduced from Pate and O'Neill (2007) with permission

Pace strategy is another important component of marathon performance. A marathon runner's pace may be characterized using a pacing profile (i.e. even/consistent, variable), the percentage change in pace in first versus second half of the race, or the mean velocity of last 9.7 km divided by first 32.5 km (March et al. 2011; Deaner et al. 2015; Santos-Lozano et al. 2014). In a study of 190,228 finishers of the New York City marathon, both male and female runners demonstrated an even pace across the marathon event (Santos-Lozano et al. 2014). Alternatively, findings from a study of 14 American marathons in 2011 (total of 91,929 performances) (Deaner et al. 2015) showed the mean change in second half marathon pace relative to the first half pace was 15.6 and 11.7 % for men and women, respectively. Similarly, female marathon runners have demonstrated less variable patterns in marathon finishing time in consecutive races across a competitive season when compared with their male counterparts (Hopkins and Hewson 2001). Trubee et al. (2014) found that non-elite female runners were better pacers than non-elite male runners, particularly in warmer race temperatures. Possible explanations for differences in pacing between sexes include differences in recovery patterns, training intensity, body temperature regulation, and substrate utilization during endurance exercise (Carter et al. 2001; Lamont 2005; Tarnopolsky 2000).

Marathon performance has been shown to peak at similar ages in men and women, with evidence of best marathon finishing times at mean ages of 27 and 29 years in men and women, respectively (Hunter et al. 2011). Gender differences in marathon performance similarly increase with advancing age due to the comparable effects of aging on cardiovascular and neuromuscular functions in men and women (Wiswell et al. 2000; Joyner 1993). Between 18 and 57 years of age, women have been shown to exhibit faster race times (19 % higher) when compared with men (Lara et al. 2014). However, after 57 years of age, gender differences exponentially increase, likely due to lower participation rates and lower number of elite or top-ranked athletes among female marathon runners (Hunter and Stevens 2013). As such, running pace for marathon world record performances have been similar between men and women until the age of 50 years, and thereafter, elite female marathon runners have demonstrated slower running pace when compared with elite male marathon runners (Fig. 7.2) (Trappe 2007). In addition to physiological factors, gender differences in marathon performance may be explained by socio-cultural determinants of sports participation, including socio-cultural expectations, social support, athletic opportunity, and early life sports and exercise participation (Hankonen et al. 2010; Seefeldt et al. 2002; Vrazel et al. 2008).

Training frequency, intensity, and duration strongly influence marathon running performance in men and women. Similar physiological responses to training programs are observed in men and women (Burke 1977). Therefore, similar approaches to conditioning can be utilized to achieve performance goals in the marathon in both sexes. No significant differences in training frequency and mileage have been reported between male and female marathon runners (Leyk et al. 2009); yet, male runners have demonstrated higher training speeds (Knechtle et al. 2010). Number of weekly training sessions and years of training are determinants of marathon performance in women (Bale et al. 1985); whereas, weekly training hours and mileage

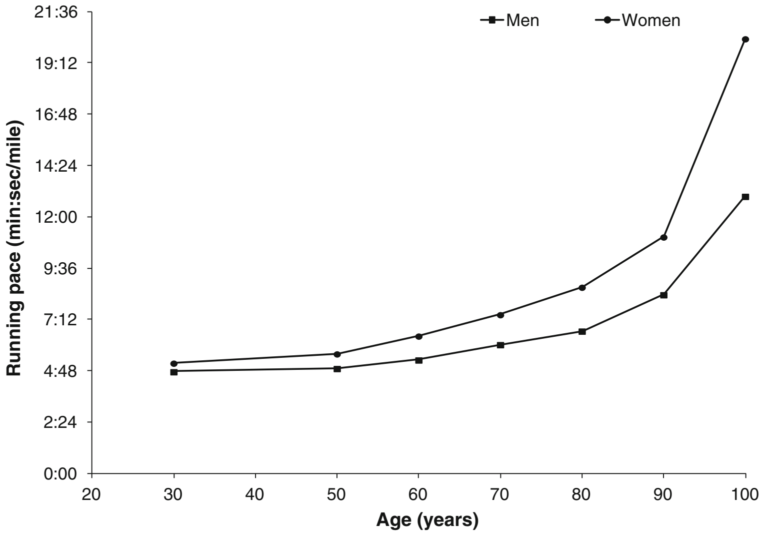


**Fig. 7.2** Running pace (min:sec/mile) for marathon world record performances in men and women with age (years). Men are represented by *lines* with *squares* and women are represented by *lines* with *circles*. Reproduced from Trappe (2007) with permission

and mean training speed contribute the most to marathon performance in men (Knechtle et al. 2010a, b). Prior evidence of the minimal or non-existent effects of menstruation on performance during training or competition in female marathon runners have been elucidated (De Souza and Metzger 1991). However, in the presence of dysmenorrhea (painful menstruation), a female marathon runner may decide to alter training for 1–3 days to avoid discomfort or seek medical attention from a physician to relieve symptoms and prevent interruptions in training (Hale 1984). Regardless of gender, marathon training programs should be individualized to the athlete, including their fitness level, age, and performance goals.

Injury patterns have been shown to differ between male and female runners due to individual (i.e. age, sex, genetics), running/training (i.e. running mileage, training frequency, gait patterns, running shoes), and health and lifestyle factors (i.e. history of injury, co-morbidities, smoking, diet) (van der Worp et al. 2015; Boles and Ferguson 2010). Findings from a prospective cohort study in novice runners demonstrated that men, particularly younger men (<40 years), have a higher risk of running-related injuries when compared with women (Buist et al. 2010). Women have been shown to be at a higher risk of postural hypotension and dermatological complications (Schwabe et al. 2014). In a recent systematic review in long-distance recreational or competitive runners, there is moderate-to-strong evidence to support that a history of previous injury and orthotic/inserts use were associated with an increased risk of running-related injuries in both men and women (van der Worp et al. 2015). Risk factors for running-related injury specific to women were older age, previous sports-related activity, running on a concrete surface, previous participation in a marathon, weekly running mileage (30–39 miles), and wearing running shoes for 4–6 months (van der Worp et al. 2015). Risk factors for running-related injury specific to men were history of injury, running experience (≤2 years), and weekly running mileage (20–29 miles or >40 miles/week) (van der Worp et al. 2015). Future prospective investigation is necessary to confirm the effect of gender differences on the incidence of injuries in runners across distance events and competition levels.

### 7.2.2 *Physiological Differences Between Men and Women*

Gender differences in marathon performance are thought to be primarily explained by physiological differences that allow men to run faster over the 42 km marathon distance than women. Men typically have a higher $\dot{V}O_2max$ (Wiswell et al. 2000; Pollock 1977; American College of Sports Medicine 2014; Pate and O'Neill 2007; Pate et al. 1987) greater muscle mass relative to body weight (Cheuvront et al. 2005), and superior hemoglobin content (Stray-Gundersen et al. 2001; Cureton et al. 1986) when compared with women, which are factors known to be associated with superior marathon running performance.

Women have a reduced oxygen carrying capacity as a result of lower hemoglobin concentrations when compared with men (Cureton et al. 1986). Hemoglobin is the protein molecule in red blood cells which carries oxygen from the lungs to the body's tissues and returns carbon dioxide from the tissues back to the lung. A reduced oxygen carrying capacity impairs muscle function and limits exercise performance. Iron is required for the formation of hemoglobin (Rodriguez et al. 2009). Iron depletion (low iron stores) has been observed among female marathon runners (Lampe et al. 1986). The recommended dietary allowance for iron for women aged 19–50 years is 18 mg per day (Thompson et al. 2005). The recommended dietary allowance for iron for men aged 19 years and older is 8 mg per day (Thompson et al. 2005). Elite runners and those who are vegetarian or regular blood donors should aim for an iron intake greater than the recommended dietary allowance (Rodriguez et al. 2009). The high incidence of iron depletion among athletes is usually attributed to inadequate dietary energy intake (Rodriguez et al. 2009). Other factors that can impact iron status include vegetarian diets that have poor iron availability, periods of rapid growth, training at high altitudes, increased iron losses in sweat, feces, urine, menstrual blood, intravascular hemolysis, regular blood donation or injury. In athletes who are iron-deficient, iron supplementation not only improves blood biochemical measures and iron status but also increases exercise performance as evidenced by increasing oxygen uptake and endurance, reducing heart rate, decreasing lactate concentration during exercise, and reducing muscle fatigue. Folate is required for the production of red blood cells. The recommended dietary allowance for folate for women and men aged 19 years and older is 400 μg per day (Thompson et al. 2005). Folate is frequently low in female athletes' diets, especially those who are vegetarian or have disordered eating patterns (Rodriguez et al. 2009). Severe deficiency of folate may result in anemia and reduced exercise performance (Rodriguez et al. 2009).

Despite a lower $\dot{V}O_2max$, smaller muscle mass relative, and lower hemoglobin content, there are some physiological factors which aid women in longer duration exercise such as marathon running. Marathon running is largely determined by the body's efficiency in converting substrates (i.e. glucose) into energy. Glycogen is a polysaccharide which is the principal storage form of glucose in humans. Glycogen is synthesized within muscle and liver cells by linking glucose molecules via the action of glycogen synthase. Cells store glycogen as a means of supplying carbohydrates as an energy source. During marathon training and running, individual muscle and liver cells break down glycogen into glucose and use the glucose as a source of energy for muscle contraction. The production of new glucose also occurs in the liver, with the free glucose being released into the bloodstream and transported to tissues throughout the body. Findings from several studies have shown that women oxidize a greater proportion of fat during submaximal endurance exercise when compared with men, resulting in the relative sparing of muscle glycogen (Carter et al. 2001; Tate and Holtz 1998). Sex hormones (specifically estrogen) show the strongest association with the observed sex-based differences in substrate metabolism (Maher and Tarnopolsky 2013). Findings from animal and human studies suggest that circulating estrogen plays a role in the preferential oxidization of fat during exercise (Tarnopolsky 2008). Oxidizing more fat and less carbohydrate and protein during exercise may be advantageous for female runners as it may delay 'hitting the wall' (i.e. depleting glycogen stores in muscle and liver) during long races such as marathons. It may also explain why ultra-running (>42 km) is one of the few sports where elite female and male athletes regularly compete together, and in which female athletes sometimes win (Speechly et al. 1996). The biological mechanisms for the higher fat use in women during endurance exercise are not fully understood and remain an intriguing area of research.

## 7.3 Women and the Marathon

### *7.3.1 Energy Availability and Reproductive Factors Associated with Marathon Running in Women*

Marathon running is characterized by high exercise energy expenditure given the substantial time spent training and competing (>2 h of continuous running during a marathon). Further to high exercise energy expenditure, the internal and external pressures placed on exercising women to maintain low body weight or lean physique to improve running performance may result in lower dietary energy intakes (Nattiv et al. 2007). The Female Athlete Triad refers to an interrelated syndrome of energy availability with or without disordered eating/eating disorder, bone mineral density (BMD), and menstrual function across a continuum of healthy/optimal conditions to subclinical and clinical disorders (Fig. 7.3) (Nattiv et al. 2007)

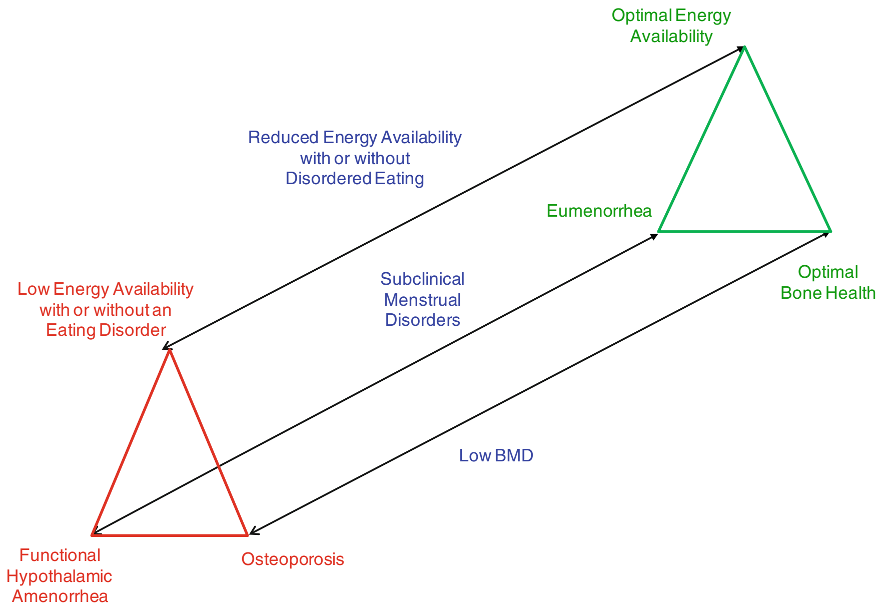


**Fig. 7.3** Model of the Female Athlete Triad characterizing an interrelated syndrome of energy availability with or without disordered eating/eating disorder, bone mineral density (BMD), and menstrual function across a continuum of healthy/optimal conditions to subclinical and clinical disorders. Reproduced from De Souza et al (2014) with permission

(for in-depth content on BMD and disordered eating/eating disorders see the *Musculoskeletal factors associated with marathon running in women* and *Psychological factors associated with marathon running in women* sections).

Energy availability is the amount of energy intake remaining after exercise training for all other metabolic processes and has been operationally defined by Loucks and Thuma (2003) as energy intake minus exercise energy expenditure relative to kilograms of lean body mass (LBM) (EI-EEE/kg LBM). Laboratory studies indicate that negative reproductive, bone and metabolic related changes occur when energy availability drops below 30 kcal/kg LBM (Loucks and Thuma 2003; Ihle and Loucks 2004). Specifically, Loucks and Thuma (2003) demonstrated that during short term manipulation of energy intake and exercise energy expenditure in a controlled laboratory setting in previously sedentary females, low energy availability (<30 kcal/kg LBM) conditions lead to the suppression of several metabolic hormones, including triiodothyronine, leptin, glucose, insulin, and insulin-like growth factor (Loucks and Thuma 2003), several bone markers, including estradiol, osteocalcin, and type 1 procollagen carboxy-terminal propeptide (Ihle and Loucks 2004), and luteinizing hormone pulsatility (Loucks and Thuma 2003). Under free-living conditions, Reed et al. (2015) recently demonstrated that energy availability, defined as energy intake minus exercise energy expenditure normalized to kilograms of LBM and assessed using conventional methods (i.e. self-reported diet logs, exercise logs and heart rate monitoring), discriminated clinical menstrual extremes; energy availability was significantly lower in exercising women with amenorrhea (no menses in past 90 days) when compared with exercising women with eumenorrhea (regular menstrual cycle intervals of 26–35 days in length) (Reed et al. 2015). Lower triiodothyronine concentrations and ratio of resting energy expenditure (REE) to predicted resting energy expenditure (pREE) (REE/pREE) were observed in the exercising amenorrheic women indicating that the women with amenorrhea were exhibiting adaptations to chronic energy deficiency.

Athletes at the greatest risk for low energy availability are those who restrict energy intake, exercise for long periods of time, and limit their food choices (Nattiv et al. 2007). These are frequently observed behaviours among a subset of female runners (Sundgot-Borgen 1994; Loucks et al. 2011). The monitoring of energy status (i.e. exercise energy expenditure vs. energy intake) is thus important for female marathon runners as it may help to prevent reproductive disturbances (Loucks and Thuma 2003; Bullen et al. 1985; Williams et al. 1995, 1999, 2001, 2010; De Souza et al. 1998, 2003, 2010; Reed et al. 2011; Cobb et al. 2003). De Souza and Williams (2004) propose that a continuum of reproductive disturbances exists ranging from ovulatory, subtle presentations of luteal phase defects and anovulation to the most severe disturbances, oligomenorrhea and amenorrhea. The prevalence of subtle menstrual disturbances is difficult to determine as they are characterized by subtle endocrine abnormalities that can only be detected with repeated hormonal measurements (De Souza et al. 1998, 2010) or careful monitoring of basal body temperatures (Vitzthum 2009). Recently, in a study of exercising women using daily hormone measurements of 274 menstrual cycles, approximately half (52 %) experienced subtle menstrual disturbances such as luteal phase defects and anovulation, and one third (37 %) were suggested to be amenorrheic depending on their sport (De Souza et al. 2010). Negative clinical outcomes such as lower BMD (De Souza et al. 2008), higher injury rates (Papanek 2003), disordered eating (Vescovi et al. 2008; Gibbs et al. 2011), altered vascular function (O'Donnell et al. 2009, 2011), reductions in resting metabolic rate (Lebenstedt et al. 1999; Myburgh et al. 1999), and suppressed metabolic hormones (De Souza et al. 2007) have all been documented in women with exercise associated menstrual disturbances.

Several studies in animals (Williams et al. 2001; Wade and Schneider 1992) and humans (Gentile et al. 2011; Golden et al. 1997; Misra et al. 2008; Dueck et al. 1996; Kopp-Woodroffe et al. 1999; Arimura et al. 2010; Mallinson et al. 2013) have documented the effectiveness of either improved energy intake, (Williams et al. 2001; Gentile et al. 2011; Golden et al. 1997; Misra et al. 2008; Mallinson et al. 2013) decreased exercise energy expenditure (Warren 1980), or the manipulation of both (Dueck et al. 1996; Kopp-Woodroffe et al. 1999) to improve indices of reproductive function. For example, resumption of menses occurred during times of rest from injury in female ballet dancers who were previously amenorrheic (Warren 1980). Resumption of menses also occurred in several amenorrheic female athletes following a 15–20 week diet and exercise intervention designed to improve energy balance. Athletes decreased exercise energy expenditure by adding 1 rest day to their training schedule and increased EI by adding one sport nutrition supplement to their total daily energy intake (Dueck et al. 1996; Kopp-Woodroffe et al. 1999). Using a non-human primate model, increases in gonadotropin hormones, ovarian steroids, and resumption of menses were documented in female cynomologus monkeys who increased energy intake while maintaining strenuous exercise training (Williams et al. 2001). While changes in body weight are generally concomitant with alterations in reproductive function resulting from changes in energy intake and or energy expenditure as observed in amenorrheic female athletes (Dueck et al. 1996; Kopp-Woodroffe et al. 1999; Warren 1980) and monkeys (Williams et al. 2001) who resumed menses, body weight is not always an accurate reflection of changes in energy balance (Williams et al. 2001, 2010) or energy availability.

The assessment of energy availability has been suggested as a practical method of monitoring energy status (Burke et al. 2006); however, even the most accessible and affordable tools such as the compendium of physical activities to estimate exercise energy expenditure (Ainsworth et al. 2000), online nutritional analysis programs to approximate energy intake, and bioelectrical impedance to measure lean body mass may be impractical.

### *7.3.2 Musculoskeletal Factors Associated with Marathon Running in Women*

Mechanical loading through external impact forces and internal muscle forces plays an important role in the regulation of bone strength in female athletes (Nattiv et al. 2007). Additionally, adequate menstrual function and nutrition are critical to the achievement of peak bone strength during adolescence and the preservation of bone strength during adulthood (Nattiv et al. 2007). Inadequate energy availability may negatively alter bone turnover, leading to bone loss and a deterioration of bone structure (Ihle and Loucks 2004; De Souza et al. 2008). Substantial research has linked low BMD in amenorrheic female athletes and women with anorexia nervosa to hypoestrogenism (Drinkwater et al. 1984; Myerson et al. 1992) based on the inhibitory effects of estrogen on osteoclast activity. Chronic undernutrition also contributes to changes in bone structure and density (independent of estrogen) via the dysregulation of metabolic hormones, such as insulin-like growth factor-1, leptin, triiodothyronine and cortisol, which are known to regulate bone turnover (Warren et al. 2002; Zanker and Swaine 1998; Christo et al. 2008; Grinspoon et al. 1996). Alterations in bone turnover have been documented in exercising women with estrogen and energy deficiency, such that there is an increase in bone resorption and a decrease in bone formation, leading to a net loss of bone (De Souza et al. 2008). Oligo/amenorrheic athletes have been shown to demonstrate compromised skeletal integrity (i.e. cortical porosity, thinner trabeculae and cortices), lower volumetric BMD, and reduced estimated bone strength compared with regularly menstruating athletes (Ackerman et al. 2011, 2012). As such, oligo/amenorrheic adolescent and young adult female athletes with low EA, particularly long-distance runners, may be at a greater risk of bone stress injuries (including stress fractures and stress reactions) compared with regularly, menstruating female athletes with adequate energy availability (Ackerman et al. 2011).

Marathon running involves repetitive, weight-bearing loads exposing bone to internal stresses and strains (Bennell et al. 1999). If the strain magnitude, rate, and number of loading cycles sustained to bone are above thresholds for normal remodelling, microcracks may develop and accumulate into macrocracks if adequate reparation does not occur, potentially leading to a bone stress injury (Bennell et al. 1999). Gender and hormonal factors contribute to a higher risk of bone stress injury in women than men, particularly female athletes participating in leanness and endurance-focused sports (i.e. long-distance running) (Ihle and Loucks 2004; Hilton and Loucks 2000; Lawson et al. 2009). Retrospective prevalence studies found that 8.3–52 % of female runners and track and field athletes had a history of bone stress injury (Nattiv 2000; Bennell et al. 1995). Prospective studies among female runners and military recruits reported an incidence of bone stress injury ranging from 3.3–28.9 % (Lappe et al. 2001; Rauh et al. 2010; Shaffer et al. 2006). In female long-distance runners with low energy availability and/or menstrual disturbances, skeletal adaptations occur that reduce the ability of bone to withstand loading forces and adequately repair microdamage (Warden et al. 2014). The majority of bone stress injuries in female long-distance runners occur at the tibia; however, other prevalent locations include the femur, metatarsals, calcaneus, fibula, and tarsals (Kelsey et al. 2007). Female long-distance runners with bone stress injury may present with pain, reduced training volume, greater injury incidence, more frequent training and competition breaks, and an overall shorter athletic career (Sundgot-Borgen and Torstveit 2007). Ackerman and colleagues found that oligo/amenorrheic athletes had a higher prevalence of stress fractures versus eumenorrheic athletes and non-athletic controls. (Ackerman et al. 2015). Additionally, oligo/amenorrheic athletes with a history of ≥2 stress fractures had lower lumbar spine and total body BMD Z-scores, trabecular volumetric BMD, stiffness, and failure load at the radius, and lower stiffness and failure load at the tibia compared with those with a history of <2 stress fractures (Ackerman et al. 2015).

As discussed above, several physiological adaptations occur in response to an energy deficiency in exercising women. These adaptations are summarized below in Box 1.

**Box 1. Summary of the Physiological Adaptations to Energy Deficiency in Exercising Women**

| Physiological adaptations |
|---|
| Weight loss |
| Loss of lean body mass |
| Menstrual disturbances |
| Lower areal and volumetric bone mineral density |
| Lower bone strength (failure load and stiffness) |
| Stress fracture |
| Vascular dysfunction |
| Reduced resting metabolic rate |
| Suppressed metabolic and reproductive hormone concentrations |

### *7.3.3 Psychological Factors Associated with Marathon Running in Women*

Disordered eating and exercise behaviours are observed in a subset of female athletes, often those participating in leanness-focused and endurance sports (i.e. long-distance running) (Sundgot-Borgen 1994). Female long-distance runners may restrict food intake and participate in strenuous, high-volume training to lose or control their body weight (Loucks et al. 2011). Risk factors for disordered eating and exercise behaviour in female long-distance runners include pressure from coaches to lose weight, early start of sport-specific training, weight cycling, overtraining, body dissatisfaction, and dieting (Sundgot-Borgen 1994). Disordered eating exists along a continuum ranging from subclinical to clinical eating disorders (i.e. anorexia nervosa, bulimia nervosa) (Sundgot-Borgen and Torstveit 2010). Clinical eating disorders are severe mental illnesses characterized by a pathological preoccupation with food, body weight, and shape that presents as starvation, purging, and fasting (American Psychiatric Association 2000). Subclinical eating disorders are characterized by restrictive eating, persistent dieting, and weight and body image concerns linked to less severe psychopathology than anorexia nervosa or bulimia nervosa (Beals and Manore 2000). Disordered exercise behaviour is characterized by compulsive and abnormal exercise training patterns for weight or appearance motives (Davis et al. 1997; Dalle Grave et al. 2008) or other reasons, such as mood regulation (Mond and Calogero 2009) or health and fitness/performance (Martinsen et al. 2010). Disordered eating (subclinical or clinical) may lead to lower energy availability and therefore, has been linked to the etiology of menstrual disturbances and bone loss in female athletes (Vescovi et al. 2008; Gibbs et al. 2011, 2013; Barrack et al. 2008). For more in-depth content on the mechanisms underlying low energy availability and reproductive disturbances, please see Sect. 7.3.1.

### *7.3.4 Marathon Running and Training During Pregnancy*

Pregnancy is a life event that is distinct to women. Substantial evidence exists in support of the positive effects of regular exercise during pregnancy and the post-partum period for both the woman and her baby (Beilock et al. 2001; Lokey et al. 1991; Sternfeld et al. 1995). However, all women are advised to consult their physician for safe and appropriate exercise guidance before starting or continuing a training program during pregnancy (Davies et al. 2003; Practice 2002). Recreational and competitive-level female long-distance runners with uncomplicated pregnancies can remain active and should appropriately modify their usual exercise training in consultation with a physician. For the majority of women, pregnancy is not the time for serious training and competition. Professional female marathon runners have received significant attention for training and competing while pregnant. However, evidence on the effects of strenuous exercise during pregnancy and the postpartum period are limited and even competitive-level female athletes who engage in intensive training regimens require close medical supervision. Notably, exercise intensity should be determined based on heart rate and perceived effort and should not exceed pre-pregnancy levels. Careful monitoring of body temperature during exercise is recommended and appropriate adjustments in nutritional intake are necessary for adequate weight gain and optimal fetus development. For more in-depth content on this topic, please consult resources from the American College of Obstetricians and Gynecologists and Society of Obstetricians and Gynecologists of Canada/Canadian Society for Exercise Physiology Guidelines for Exercise in Pregnancy and the Postpartum Period (Davies et al. 2003; American College of Obstetricians and Gynecologists 2002).

## 7.4 Marathon Running Across the Lifespan

### *7.4.1 Effects of Aging on Marathon Running*

The decline in the physiological capacity of humans is an inevitable consequence of the biological aging process. Reductions in functional capacity can generally be attributed to loss of cardiovascular, pulmonary, neuromuscular and metabolic functions that typically occur with aging. Despite these declines, marathon running during the older adult years is not only possible, but a successful feat for many!

#### 7.4.1.1 Cardiovascular

Adolf Eugen Fick defined $\dot{V}O_2max$ as the product of cardiac output (CO) and arteriovenous oxygen difference (a-v$O_2$ difference) ($\dot{V}O_2 = CO \times$ a-v$O_2$ difference) (American College of Sports Medicine 2014). CO is the product of heart rate and stroke volume (CO = heart rate × stroke volume). Heart rate is the speed of the heartbeat measured by the number of contractions of the heart per unit of time—typically beats per minute. Stroke volume is the amount of blood pumped out of the left ventricle of the heart to the body during each contraction, and is typically measured in mL/beat. Arteriovenous oxygen difference is the difference in the oxygen content of the blood between the arterial and venous blood. $\dot{V}O_2$max decreases with age in men and women, regardless of training status (Fig. 7.4).

$\dot{V}O_2$max decreases by approximately 1 % per year (10 % per decade) after 25 years of age (Taylor and Johnson 2008). Although $\dot{V}O_2$max declines with age, the extent to which such decreases occur largely depends on one's training status. Trappe (2007) reported that reductions in $\dot{V}O_2$max were 0.5 % per year in highly trained runners, compared with 1.0 % per year in fitness trained runners and 1.5 % per year in untrained and fit older men. Continuing to run at a high level during the older adult years can attenuate, but not prevent declines in $\dot{V}O_2$max. Former highly

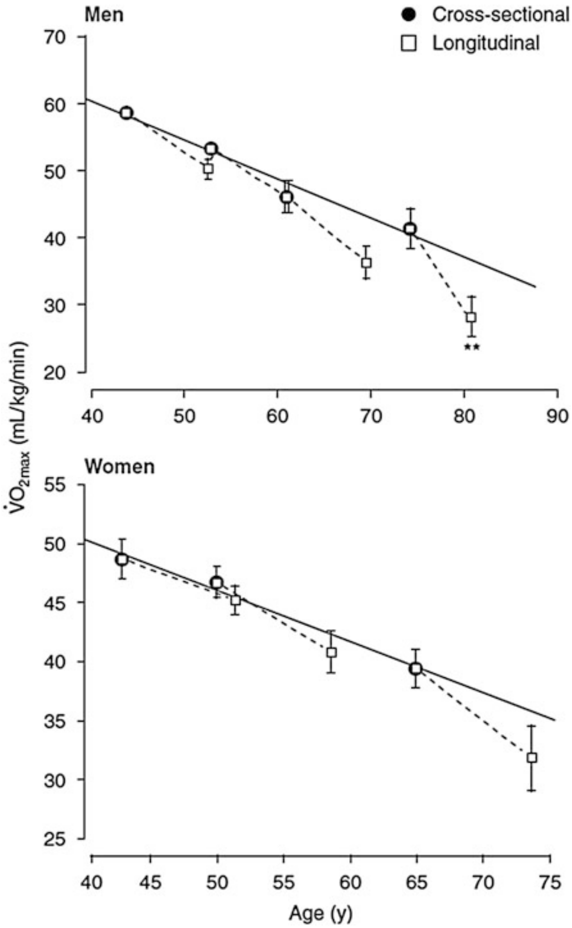


**Fig. 7.4** Decrease in VO2max (mL/kg/min) with age in men and women master athletes. ** indicates significantly different rate of loss compared with cross-sectional (reproduced from Hawkins and Wiswell (2003) with permission)

trained athletes who become sedentary and older runners (>70 years old) experience an even greater rate of loss in $\dot{V}O_2max$ with age (Trappe 2007). Beyond 60 years of age, there appears to be a substantial decline in $\dot{V}O_2max$, which greatly impacts one's performance and ability to tolerate high-level training.

The age-related decline in $\dot{V}O_2max$ has been attributed to decreases in CO, a-$vO_2$ difference, and a loss in muscle mass. Resting CO decreases by approximately 1 % per year after 30 years of age, and CO during maximal exercise decreases by approximately 30 % between 20 and 80 years of age (Taylor and Johnson 2008). These declines are attributed to a smaller stroke volume and slower heart rate. Stroke volume may decrease by as much as 30 % before 85 years of age (Taylor and Johnson 2008). The myocardium's increased relaxation time and decreased sensitivity to catecholamines (i.e. epinephrine, norepinephrine) can decrease maximum heart rate by as much as 30–50 % between the ages of 25 and 85 years (Taylor and Johnson 2008). Further, the decrease in the number of sinoatrial node, atrioventricular node, bundle of His and Purkinje network cells that occurs with aging leads to an increase in atrioventricular conduction time, thus slowing of heart rate (Kuga et al. 1993). Even though decreases in stroke volume, heart rate and a-$vO_2$ difference occurs with aging, the ability to sustain a relatively high intensity of aerobic exercise, such as marathon running, appears to be preserved.

It is well established that alterations in arterial structure and function occur with aging (Seals et al. 2008; Taddei et al. 1995; Avolio et al. 1985; Mitchell et al. 2004). Specifically, increases in vascular stiffening and endothelial dysfunction, most commonly measured by increased aortic pulse wave velocity (aPWV), are observed. Very little evidence exists to explain the mechanisms associated with increased arterial stiffness in aging. It is generally presumed that remodelling in the extracellular matrix molecules, including collagen and elastin, may play a role (Lakatta 2003; Lakatta and Levy 2003). Inflammation has been implicated as a trigger for these events (Vlachopoulos et al. 2005). Emerging evidence suggests that vascular aging can be reduced with regular endurance exercise. There is, however, ongoing debate regarding the effects of chronic extreme exercise (marathons and ultra-marathons) on cardiovascular health (O'Keefe and Lavie 2013). Findings from research studies have suggested that there may be no negative effects of extreme endurance training on vascular structure in individuals with normal blood pressure (Radtke et al. 2014). Conversely, endothelial dysfunction may be increased in marathon runners who experience exercise induced high blood pressure (Jee et al. 2013).

With respect to arterial structure in the aging process, middle-aged and older male and female endurance athletes have lower aPWV (Vaitkevicius et al. 1993; Tanaka et al. 1998) and increased carotid artery compliance (Tanaka et al. 2000; Moreau et al. 2003, 2006) when compared with sedentary or untrained middle-aged and older individuals, but are comparable to trained and untrained young adults (Vaitkevicius et al. 1993). This vascular maintenance may be explained by decreased oxidative stress-related suppression of arterial compliance (Moreau et al. 2006). There is a paucity of research examining the specific affects of long-term endurance training on women across the lifespan. With respect to vascular function, male endurance athletes' show preserved endothelial function, as measured by endothelial dependent dilation, with aging (DeSouza et al. 2000; Taddei et al. 2000; Black et al. 2009). The underlying mechanism may be attributed to a reduced vascular oxidative stress environment and therefore greater bioavailability of nitric oxide (Taddei et al. 2000). There is also a little data regarding older endurance trained women and endothelial function. The trend to date suggests greater endothelial dependent dilation in endurance trained versus untrained older women (Black et al. 2009; Hagmar et al. 2006). However, some research in this area shows no difference between trained and untrained women, yet a difference between trained and untrained men (Pierce et al. 2011).

#### 7.4.1.2 Pulmonary

Similar to the cardiovascular system, several changes in the pulmonary system occur with aging. Vital capacity, which represents the maximum amount of air a person can expel from the lungs after a maximum inhalation, decreases by approximately 40–50 % by 70 years of age (Taylor and Johnson 2008). The number of alveoli and corresponding capillaries which enable the exchange of oxygen and carbon dioxide in the bloodstream decreases with age. Further, a thickening of the larger pulmonary arteries, calcification of the rib cartilage and weakening of the respiratory muscles result in a reduced compliance of the thorax; such changes consequently lead to a 20 % increase in the work of the respiratory muscles. Increased ventilation thus becomes more dependent on increasing respiratory rate rather than increasing the depth of breathing. Despite these decrements, pulmonary function does not seem to be a limiting factor for exercise in healthy older runners. In fact, during moderate-intensity exercise, pulmonary ventilation and mechanical efficiency are similar between the old and young marathon runner.

#### 7.4.1.3 Neuromuscular

Significant losses in muscular strength occur with aging, although there appears to be substantial variation in the rate of loss among muscle groups (Rogers and Evans 1993). This decline in muscular strength can be attributed to either the loss of muscle mass and/or to alterations in the muscle's capacity to generate force. Muscle mass declines by approximately 40 % between 20 and 60 years, with the reported amount varying with the imaging technique, skeletal muscle site and gender (Lang et al. 2010). Loss of muscle mass is associated with a decrease in muscle function and strength, including muscle atrophy, reduced contractility, and reduced enzymatic changes (Trappe 2007). Muscle atrophy or decreased muscle cross-sectional area (contractile tissue) is caused by a loss of fast twitch muscle fibers in response to less explosive movements and a selective loss of motor neurons with age. Fat and connective tissue (non-contractile tissue) replace areas previously occupied by muscle mass, resulting in a reduction in muscle quality and lower contractility. After reaching a maximum at 20 years of age, fiber size decreases with age, with the major decrements in size occurring between 60 and 80 years of age (Taylor and Johnson 2008); regular exercise, however, maintains a high proportion of fiber size until approximately 60 years of age (Taylor and Johnson 2008). Further neuromuscular changes with aging include: decrease in adenosine triphosphate (ATP) activity; increase in length of contraction; lower muscle excitation threshold; increase in twitch tension; new axonal new branches; and, decrease in nerve conduction occur which collectively impair muscle contractility.

The activity of several enzymes has been measured in muscle from individuals of different ages to examine the effect of aging on the metabolic capacity of muscle. The following enzymes and pathways have received the most interest: glycogen phosphorylase (glycogenolysis), phosphofructokinase (glycolysis), succinate dehydrogenase or citrate synthase (Krebs cycle) and beta-hydroxyacyldehydrogenase (free fatty acid pathway). Other important enzymes measured to assess metabolic change in pathways associated with energy production include: hexokinase (indirect measure of the transport of glucose into the muscle cell from the circulation); lactic dehydrogenase (converts lactic acid to pyruvic acid); and, calcium activated ATPase (breaks off the phosphates from ATP to generate energy). The concentrations for these enzymes have been shown to decrease with aging, and thus offer a further explanation for reduced muscle function in older adults. Although several unfavorable neuromuscular changes occur with aging, findings from research in runners show that years of continued exercise training may preserve the oxidative capacity of muscle at high levels (Trappe 2007; Trappe et al. 1995). In a 20-year follow-up study, Trappe and colleagues reported that mitochondrial enzymes (i.e. citrate synthase and succinate dehydrogenase), capillary density, capillary-to-fibre ratio and the abundance of slow-twitch muscle-fibers were the highest in the best-conditioned veteran runners (Trappe et al. 1995).

**Box 2. Summary of the Cardiovascular, Pulmonary and Neuromuscular Changes that Occur With Aging**

| | Direction of aging-related changes |
|---|---|
| **Cardiovascular** | |
| $\dot{V}O_2$max | ↓ |
| Cardiac output | ↓ |
| Heart rate | ↓ |
| Stroke volume | ↓ |
| a-v$O_2$ difference | ↓ |
| Vascular stiffening | ↑ |
| Endothelial dysfunction | ↑ |

(continued)

(continued)

| | Direction of aging-related changes |
|---|---|
| **Pulmonary** | |
| Vital capacity | ↓ |
| Number of alveoli and capillaries | ↓ |
| Work of respiratory muscles | ↑ |
| **Neuromuscular** | |
| Muscle mass | ↓ |
| Body fat | ↑ |
| Muscle cross-sectional area | ↓ |
| Fiber size | ↓ |
| Number of fast twitch muscle fibers and motor neurons | ↓ |
| Muscle contractility | ↓ |
| ATP activity | ↓ |
| Length of contraction | ↑ |
| Muscle excitation threshold | ↓ |
| Twitch tension | ↑ |
| Nerve conduction | ↓ |
| Metabolic enzyme activities | ↓ |

### *7.4.2 Risk of Medical Problems and Running-Related Injuries in Older Marathon Runners*

The benefits of running on cardiovascular capacity, physical function, and survival regardless of age are well-documented (Wang et al. 2002); yet, older or master runners may be at a higher risk of medical complications and injuries when compared with younger runners. To date, few studies have evaluated the prevalence of medical complications and injuries and associated risk factors in master runners (McKean et al. 2006). In a retrospective study of 2,886 runners (McKean et al. 2006), master runners (≥40 years) reported more injuries, including a higher prevalence of soft tissue injuries (i.e. calf, achilles, and hamstrings), than younger runners. Previous studies have shown that older age represents a risk factor for overuse injury (Wen et al. 1997) and hamstring and achilles tendon injuries (Hirschmuller et al. 2012). In a prospective study in 39,511 runners competing in a 21 km race, older female runners (>50 years of age) were at a higher risk of medical complications (Schwabe et al. 2014), particularly those with less running experience and slower running pace. Marathons and half-marathons have a low overall risk of sudden cardiac arrest and related deaths (Kim et al. 2012). The incidence rate of cardiac arrest is 0.54 per 100,000 marathon participants, with older males being at a higher risk (Webner et al. 2012). Older runners, particularly those with a family history of heart disease and other coronary risk factors, should consult a physician for medical evaluation before starting a marathon training program (Noakes 1987).

Age-related changes in skeletal muscle strength and flexibility are associated with a higher risk of musculoskeletal injury in older runners (Trappe 2007). In addition, reductions in skeletal muscle cross sectional area and contractile ability contribute to a greater susceptibility of muscle fatigue and damage among men and women with age (Dill et al. 1967; Coggan et al. 1990). Classic animal experiments reported greater or similar magnitude of eccentric contraction-induced muscle damage in older versus younger animals (Brooks and Faulkner 1990; Brooks et al. 2001). Similar studies in humans have not shown any significant differences in exercise-induced muscle damage between age groups (Fielding et al. 1991; Dedrick and Clarkson 1990). However, slower muscle recovery has been demonstrated in older athletes due to increased oxidative stress and inflammation with aging, suggesting muscle damage may persist for longer periods in older athletes (Rader and Faulkner 2006a, b). Therefore, less effective muscle recovery may result in reduced training capacity in older marathon runners and limit marathon performance with advancing age. Age-related changes in running biomechanics, range of motion, and shock-absorbing capacity may also be linked to a greater risk of lower-extremity overuse injuries in older runners (Bus 2003; Fukuchi et al. 2014). As such, older runners are advised to seek expert evaluation of biomechanical characteristics prior to marathon training to inform gait retraining strategies and type of running shoes (i.e. cushioning, orthotics/insoles).

### *7.4.3 Marathon Running in Children and Adolescents*

In recent years, there has been an increase in the number of opportunities and youth training programs for younger marathon runners (<18 years of age) (Roberts 2007). Evidence exists in support of safe training and completion of marathon races in younger runners (Roberts and Nicholson 2010). However, the effects of marathon training and competition at younger ages on growth, development, and long-term health are not well-understood. A major concern of children and adolescents participating in marathon training is the possibility of musculoskeletal injury due to microtrauma associated with repetitive training. Growth cartilage is less resistant to mechanical stresses at younger ages, resulting in a greater risk of running-related injury in children and adolescents (Roberts 2007). There is evidence of stress-related injuries of the lower-extremity (i.e. proximal and distal tibia, first metatarsal, distal fibula) in younger long-distance runners (Demorest and Landry 2003); yet, the majority of studies have focused on injuries in younger athletes in general (Caine et al. 2006). Findings from a multi-sport injury surveillance program demonstrated a higher injury incidence per 1,000 athlete exposures in female high school cross-country runners compared with other sports (Rice 2000). Heat stress is also a major concern for younger marathon runners since children are less heat tolerant and are thought to be at greater risk of heat stroke compared with adults due to their surface area to mass ratio and premature ability to regulate sweat (Climatic heat stress and the exercising child and adolescent 2000). Fluid and electrolyte balance and proper hydration must be emphasized in younger runners as a means to prevent heat stress-related injury. Although, few studies have evaluated the scope of this problem. Psychological factors, such as self-esteem, body image, and confidence, are also important in younger marathon participants, particular since younger female athletes are more likely to drop-out of sport participation (American Academy of Pediatrics Committee on Sports Medicine 1990). Self-motivated younger athletes may be safe to train and compete in marathons (depending on race administration rules); yet, medical supervision, nutritional counselling, coaching, and family support are strongly advised to ensure optimal health, adequate growth and development, and social and psychological well-being (Mohtadi 2005). Prospective studies of junior age marathon runners would inform our understanding of the long-term health outcomes associated with long-distance running at younger ages (<18 years of age).

## 7.5 Conclusion

The growing popularity of marathon running in men and women across the lifespan is a testament to the appeal of this sport, its ability to ensure fitness, and the excitement that surrounds training and competition. Despite faster world-record marathon finishing times in men over women, no major differences in running economy and training characteristics have been documented between male and female marathon runners. However, female marathon runners have been shown to have better pacing strategies. Physiological differences including body composition and oxygen carrying capacity between men and women appear to provide men with a training and performance advantage; however, sex hormones, particularly estrogen, may prove helpful in delaying "hitting the wall" in long races for women due to greater fat oxidation. Female marathon runners must be diligent in matching their dietary energy intake with exercise energy expenditure to avoid negative reproductive, bone and metabolic changes associated with an energy deficiency. A subset of female runners has been shown to practice disordered eating and exercise behaviour, such as restrictive eating and excessive training, and therefore, are at a greater risk of energy deficiency-related reproductive disturbances, bone loss, and bone stress injuries. Despite the unfavourable changes in cardiovascular, pulmonary and neuromuscular functions with aging, older marathon runners are most certainly able to train for and compete in marathons, and should be encouraged to given the many health benefits associated with regular exercise (Warburton et al. 2006)! Special populations, such as pregnant or post-partum women, children, and adolescents, are advised to consult a physician regarding the safety of participating in long-distance running.

**Acknowledgements** We would like to sincerely thank Dr. Lisa Cote, a Postdoctoral Fellow in the Division of Prevention and Rehabilitation specifically associated with the Canadian Women's Heart Health Centre at the University of Ottawa Heart Institute, for providing her expertise and assistance in preparing the vascular health section.

## References

Ackerman KE, Nazem T, Chapko D et al (2011) Bone microarchitecture is impaired in adolescent amenorrheic athletes compared with eumenorrheic athletes and nonathletic controls. J Clin Endocrinol Metab 96:3123–3133

Ackerman KE, Putman M, Guereca G et al (2012) Cortical microstructure and estimated bone strength in young amenorrheic athletes, eumenorrheic athletes and non-athletes. Bone 51:680–687

Ackerman KE, Cano Sokoloff N, G Denm et al (2015) Fractures in relation to menstrual status and bone parameters in young athletes. Med Sci Sports Exerc 47:1577–1586

Ainsworth BE, Haskell WL, Whitt MC et al (2000) Compendium of physical activities: an update of activity codes and MET intensities. Med Sci Sports Exerc 32:S498–S504

American Academy of Pediatrics Committee on Sports Medicine (1990) Risks in distance running for children. Pediatrics 86:799–800

American College of Sports Medicine (2014) ACSM's guidelines for exercise testing and prescription, 9th edn. Lippincott Williams & Wilkins, Baltimore (MD)

American Psychiatric Association (2000) Diagnostic and statistical manual of mental disorders: American Psychiatric Association

Arimura C, Nozaki T, Takakura S et al (2010) Predictors of menstrual resumption by patients with anorexia nervosa. Eat Weight Disord 15:e226–e233

Avolio AP, Deng FQ, Li WQ et al (1985) Effects of aging on arterial distensibility in populations with high and low prevalence of hypertension: comparison between urban and rural communities in China. Circulation 71:202–210

Bale P, Rowell S, Colley E (1985) Anthropometric and training characteristics of female marathon runners as determinants of distance running performance. J Sports Sci 3:115–126

Barrack MT, Rauh MJ, Barkai HS et al (2008) Dietary restraint and low bone mass in female adolescent endurance runners. Am J Clin Nutr 87:36–43

Beals KA, Manore MM (2000) Behavioral, psychological, and physical characteristics of female athletes with subclinical eating disorders. Int J Sport Nutr Exerc Metab 10:128–143

Beilock SL, Feltz DL, Pivarnik JM (2001) Training patterns of athletes during pregnancy and postpartum. Res Q Exerc Sport 72:39–46

Bennell KL, Malcolm SA, Thomas SA et al (1995) Risk factors for stress fractures in female track-and-field athletes: a retrospective analysis. Clin J Sport Med 5:229–235

Bennell K, Matheson G, Meeuwisse W et al (1999) Risk factors for stress fractures. Sports Med 28:91–122

Black MA, Cable NT, Thijssen DH et al (2009) Impact of age, sex, and exercise on brachial artery flow-mediated dilatation. Am J Physiol Heart Circ Physiol 297:H1109–H1116

Boles CA, Ferguson C (2010) The female athlete. Radiol Clin North Am 48:1249–1266

Brooks SV, Faulkner JA (1990) Contraction-induced injury: recovery of skeletal muscles in young and old mice. Am J Physiol 258:C436–C442

Brooks SV, Opiteck JA, Faulkner JA (2001) Conditioning of skeletal muscles in adult and old mice for protection from contraction-induced injury. J Gerontol A Biol Sci Med Sci 56:B163–B171

Buist I, Bredeweg SW, Lemmink KA et al (2010) Predictors of running-related injuries in novice runners enrolled in a systematic training program: a prospective cohort study. Am J Sports Med 38:273–280

Bullen BA, Skrinar GS, Beitins IZ et al (1985) Induction of menstrual disorders by strenuous exercise in untrained women. N Engl J Med 312:1349–1353
Burfoot A (2007) The history of the marathon: 1976-present. Sports Med 37:284–287
Burke EJ (1977) Physiological effects of similar training programs in males and females. Res Q 48:510–517
Burke LM, Loucks AB, Broad N (2006) Energy and carbohydrate for training and recovery. J Sports Sci 24:675–685
Bus SA (2003) Ground reaction forces and kinematics in distance running in older-aged men. Med Sci Sports Exerc 35:1167–1175
Caine D, DiFiori J, Maffulli N (2006) Physeal injuries in children's and youth sports: reasons for concern? Br J Sports Med 40:749–760
Carter SL, Rennie C, Tarnopolsky MA (2001) Substrate utilization during endurance exercise in men and women after endurance training. Am J Physiol Endocrinol Metab 280:E898–E907
Cheuvront SN, Carter R, Deruisseau KC et al (2005) Running performance differences between men and women: an update. Sports Med 35:1017–1024
Christo K, Prabhakaran R, Lamparello B et al (2008) Bone metabolism in adolescent athletes with amenorrhea, athletes with eumenorrhea, and control subjects. Pediatrics 121:1127–1136
Climatic heat stress and the exercising child and adolescent (2000) American Academy of Pediatrics. Committee on Sports Medicine and Fitness. Pediatrics 106:158–159
Cobb KL, Bachrach LK, Greendale G et al (2003) Disordered eating, menstrual irregularity, and bone mineral density in female runners. Med Sci Sports Exerc 35:711–719
Coggan AR, Spina RJ, Rogers MA et al (1990) Histochemical and enzymatic characteristics of skeletal muscle in master athletes. J Appl Physiol 1985(68):1896–1901
Cureton K, Bishop P, Hutchinson P et al (1986) Sex difference in maximal oxygen uptake. Effect of equating haemoglobin concentration. Eur J Appl Physiol Occup Physiol 54:656–660
Dalle Grave R, Calugi S, Marchesini G (2008) Compulsive exercise to control shape or weight in eating disorders: prevalence, associated features, and treatment outcome. Compr Psychiatry 49:346–352
Daniels J, Daniels N (1992) Running economy of elite male and elite female runners. Med Sci Sports Exerc 24:483–489
Davies GA, Wolfe LA, Mottola MF et al (2003) Joint SOGC/CSEP clinical practice guideline: exercise in pregnancy and the postpartum period. Can J Appl Physiol 28:330–341
Davis C, Katzman DK, Kaptein S et al (1997) The prevalence of high-level exercise in the eating disorders: etiological implications. Compr Psychiatry 38:321–326
De Souza MJ, Metzger DA (1991) Reproductive dysfunction in amenorrheic athletes and anorexic patients: a review. Med Sci Sports Exerc 23:995–1007
De Souza MJ, Williams NI (2004) Physiological aspects and clinical sequelae of energy deficiency and hypoestrogenism in exercising women. Hum Reprod Update 10:433–448
De Souza MJ, Miller BE, Loucks AB et al (1998) High frequency of luteal phase deficiency and anovulation in recreational women runners: blunted elevation in follicle-stimulating hormone observed during luteal-follicular transition. J Clin Endocrinol Metab 83:4220–4232
De Souza CA, Shapiro LF, Clevenger CM et al (2000) Regular aerobic exercise prevents and restores age-related declines in endothelium-dependent vasodilation in healthy men. Circulation 102:1351–1357
De Souza MJ, Van Heest J, Demers LM et al (2003) Luteal phase deficiency in recreational runners: evidence for a hypometabolic state. J Clin Endocrinol Metab 88:337–346
De Souza MJ, Lee DK, VanHeest JL et al (2007) Severity of energy-related menstrual disturbances increases in proportion to indices of energy conservation in exercising women. Fertil Steril 88:971–975
De Souza MJ, West SL, Jamal SA et al (2008) The presence of both an energy deficiency and estrogen deficiency exacerbate alterations of bone metabolism in exercising women. Bone 43:140–148

De Souza MJ, Toombs RJ, Scheid JL et al (2010) High prevalence of subtle and severe menstrual disturbances in exercising women: confirmation using daily hormone measures. Hum Reprod 25:491–503

De Souza et al (2014) Clin J Sports Med 24(2):96–119

Deaner RO, Carter RE, Joyner MJ et al (2015) Men are more likely than women to slow in the marathon. Med Sci Sports Exerc 47:607–616

Dedrick ME, Clarkson PM (1990) The effects of eccentric exercise on motor performance in young and older women. Eur J Appl Physiol Occup Physiol 60:183–186

Demorest RA, Landry GL (2003) Prevention of pediatric sports injuries. Curr Sports Med Rep 2:337–343

Dill DB, Robinson S, Ross JC (1967) A longitudinal study of 16 champion runners. J Sports Med Phys Fitness 7:4–27

Drinkwater BL, Nilson K, Chesnut CH 3rd et al (1984) Bone mineral content of amenorrheic and eumenorrheic athletes. N Engl J Med 311:277–281

Dueck CA, Matt KS, Manore MM et al (1996) Treatment of athletic amenorrhea with a diet and training intervention program. Int J Sport Nutr 6:24–40

Fielding RA, Meredith CN, O'Reilly KP et al (1991) Enhanced protein breakdown after eccentric exercise in young and older men. J Appl Physiol 1985(71):674–679

Fukuchi RK, Stefanyshyn DJ, Stirling L et al (2014) Flexibility, muscle strength and running biomechanical adaptations in older runners. Clin Biomech (Bristol, Avon) 29:304–310

Gentile MG, Manna GM, Pastorelli P et al (2011) Resumption of menses after 32 years in anorexia nervosa. Eat Weight Disord 16:e223–e225

Gibbs JC, Williams NI, Scheid JL et al (2011) The association of a high drive for thinness with energy deficiency and severe menstrual disturbances: confirmation in a large population of exercising women. Int J Sport Nutr Exerc Metab 21:280–290

Gibbs JC, Williams NI, Mallinson RJ et al (2013) Effect of high dietary restraint on energy availability and menstrual status. Med Sci Sports Exerc 45:1790–1797

Golden NH, Jacobson MS, Schebendach J et al (1997) Resumption of menses in anorexia nervosa. Arch Pediatr Adolesc Med 151:16–21

Grinspoon S, Baum H, Lee K et al (1996) Effects of short-term recombinant human insulin-like growth factor I administration on bone turnover in osteopenic women with anorexia nervosa. J Clin Endocrinol Metab 81:3864–3870

Hagmar M, Eriksson MJ, Lindholm C et al (2006) Endothelial function in post-menopausal former elite athletes. Clin J Sport Med 16:247–252

Hale R (1984) Factors important to women engaged in vigorous physical activity. In: Strauss R (ed) Sports Medicine. W. B. Saunders, Philadelphia, pp 1–441

Hankonen N, Absetz P, Ghisletta P et al (2010) Gender differences in social cognitive determinants of exercise adoption. Psychol Health 25:55–69

Hawkins SA, Wiswell RA (2003) Rate and mechanism of maximal oxygen consumption decline with aging: implications for exercise training. Sports Med 33(12):877–888

Helgerud J (1994) Maximal oxygen uptake, anaerobic threshold and running economy in women and men with similar performances level in marathons. Eur J Appl Physiol Occup Physiol 68:155–161

Hilton LK, Loucks AB (2000) Low energy availability, not exercise stress, suppresses the diurnal rhythm of leptin in healthy young women. Am J Physiol Endocrinol Metab 278:E43–E49

Hirschmuller A, Frey V, Konstantinidis L et al (2012) Prognostic value of Achilles tendon Doppler sonography in asymptomatic runners. Med Sci Sports Exerc 44:199–205

Hopkins WG, Hewson DJ (2001) Variability of competitive performance of distance runners. Med Sci Sports Exerc 33:1588–1592

Hopkins P, Powers SK (1982) Oxygen uptake during submaximal running in highly trained men and women. Am Correct Ther J 36:130–132

Hunter SK, Stevens AA (2013) Sex differences in marathon running with advanced age: physiology or participation? Med Sci Sports Exerc 45:148–156

Hunter SK, Stevens AA, Magennis K et al (2011) Is there a sex difference in the age of elite marathon runners? Med Sci Sports Exerc 43:656–664

Ihle R, Loucks AB (2004) Dose-response relationships between energy availability and bone turnover in young exercising women. J Bone Miner Res 19:1231–1240

International Association of Athletics Federation (2015). Available from: http://www.iaaf.org/records/toplists/road-running/marathon/outdoor/men/senior. 18 Nov 2015

International Association of Athletics Federation (2015). Available from: http://www.iaaf.org/records/toplists/road-running/marathon/outdoor/women/senior. 18 Nov 2015

Jee H, Park J, Oh JG et al (2013) Effect of a prolonged endurance marathon on vascular endothelial and inflammation markers in runners with exercise-induced hypertension. Am J Phys Med Rehabil 92:513–522

Joyner MJ (1993) Physiological limiting factors and distance running: influence of gender and age on record performances. Exerc Sport Sci Rev 21:103–133

Kelsey JL, Bachrach LK, Procter-Gray E et al (2007) Risk factors for stress fracture among young female cross-country runners. Med Sci Sports Exerc 39:1457–1463

Kim JH, Malhotra R, Chiampas G et al (2012) Cardiac arrest during long-distance running races. N Engl J Med 366:130–140

Knechtle B, Knechtle P, Rosemann T et al (2010a) Sex differences in association of race performance, skin-fold thicknesses, and training variables for recreational half-marathon runners. Percept Mot Skills 111:653–668

Knechtle B, Knechtle P, Rosemann T (2010b) Race performance in male mountain ultra-marathoners: anthropometry or training? Percept Mot Skills 110:721–735

Kopp-Woodroffe SA, Manore MM, Dueck CA et al (1999) Energy and nutrient status of amenorrheic athletes participating in a diet and exercise training intervention program. Int J Sport Nutr 9:70–88

Kuga K, Yamaguchi I, Sugishita Y (1993) Age-related changes of sinus node function and autonomic regulation in subjects without sinus node disease–assessment by pharmacologic autonomic blockade. Jpn Circ J 57:760–768

Lakatta EG (2003) Arterial and cardiac aging: major shareholders in cardiovascular disease enterprises: Part III: cellular and molecular clues to heart and arterial aging. Circulation 107:490–497

Lakatta EG, Levy D (2003) Arterial and cardiac aging: major shareholders in cardiovascular disease enterprises: Part I: aging arteries: a "set up" for vascular disease. Circulation 107:139–146

Lamont LS (2005) Gender differences in amino acid use during endurance exercise. Nutr Rev 63:419–422

Lampe JW, Slavin JL, Apple FS (1986) Poor iron status of women runners training for a marathon. Int J Sports Med 7:111–114

Lang T, Streeper T, Cawthon P et al (2010) Sarcopenia: etiology, clinical consequences, intervention, and assessment. Osteoporos Int 21:543–559

Lappe JM, Stegman MR, Recker RR (2001) The impact of lifestyle factors on stress fractures in female army recruits. Osteoporos Int 12:35–42

Lara B, Salinero JJ, Del Coso J (2014) The relationship between age and running time in elite marathoners is U-shaped. Age (Dordr) 36:1003–1008

Lawson EA, Donoho D, Miller KK et al (2009) Hypercortisolemia is associated with severity of bone loss and depression in hypothalamic amenorrhea and anorexia nervosa. J Clin Endocrinol Metab 94:4710–4716

Lebenstedt M, Platte P, Pirke KM (1999) Reduced resting metabolic rate in athletes with menstrual disorders. Med Sci Sports Exerc 31:1250–1256

Leyk D, Erley O, Gorges W et al (2009) Performance, training and lifestyle parameters of marathon runners aged 20–80 years: results of the PACE-study. Int J Sports Med 30:360–365

Lokey EA, Tran ZV, Wells CL et al (1991) Effects of physical exercise on pregnancy outcomes: a meta-analytic review. Med Sci Sports Exerc 23:1234–1239

Loucks AB, Thuma JR (2003) Luteinizing hormone pulsatility is disrupted at a threshold of energy availability in regularly menstruating women. J Clin Endocrinol Metab 88:297–311
Loucks AB, Kiens B, Wright HH (2011) Energy availability in athletes. J Sports Sci 29(Suppl 1): S7–S15
Maher AC, Tarnopolsky MA (2013) Substrate utilization in female athletes implications for fuel selection and macronutrient requirements. In: Beals KA (ed) Nutrition and the female athlete: from research to practice. CRC Press Taylor & Francis Group, Boca Raton, FL
Mallinson RJ, Williams NI, Olmsted MP et al (2013) A case report of recovery of menstrual function following a nutritional intervention in two exercising women with amenorrhea of varying duration. J Int Soc Sports Nutr 10:34
March DS, Vanderburgh PM, Titlebaum PJ et al (2011) Age, sex, and finish time as determinants of pacing in the marathon. J Strength Cond Res 25:386–391
Martinsen M, Bratland-Sanda S, Eriksson AK et al (2010) Dieting to win or to be thin? A study of dieting and disordered eating among adolescent elite athletes and non-athlete controls. Br J Sports Med 44:70–76
McKean KA, Manson NA, Stanish WD (2006) Musculoskeletal injury in the masters runners. Clin J Sport Med 16:149–154
Misra M, Prabhakaran R, Miller KK et al (2008) Weight gain and restoration of menses as predictors of bone mineral density change in adolescent girls with anorexia nervosa-1. J Clin Endocrinol Metab 93:1231–1237
Mitchell GF, Parise H, Benjamin EJ et al (2004) Changes in arterial stiffness and wave reflection with advancing age in healthy men and women: the Framingham heart study. Hypertension 43:1239–1245
Mohtadi N (2005) Rehabilitation of anterior cruciate ligament injuries: a review. Clin J Sport Med 15:287–288
Mond JM, Calogero RM (2009) Excessive exercise in eating disorder patients and in healthy women. Aust N Z J Psychiatry 43:227–234
Moreau KL, Donato AJ, Seals DR et al (2003) Regular exercise, hormone replacement therapy and the age-related decline in carotid arterial compliance in healthy women. Cardiovasc Res 57:861–868
Moreau KL, Gavin KM, Plum AE et al (2006) Oxidative stress explains differences in large elastic artery compliance between sedentary and habitually exercising postmenopausal women. Menopause 13:951–958
Myburgh KH, Berman C, Novick I et al (1999) Decreased resting metabolic rate in ballet dancers with menstrual irregularity. Int J Sport Nutr 9:285–294
Myerson M, Gutin B, Warren MP et al (1992) Total body bone density in amenorrheic runners. Obstet Gynecol 79:973–978
Nattiv A (2000) Stress fractures and bone health in track and field athletes. J Sci Med Sport 3:268–279
Nattiv A, Loucks AB, Manore MM et al (2007) American College of Sports Medicine position stand. The female athlete triad. Med Sci Sports Exerc 39:1867–1882
Noakes TD (1987) Heart disease in marathon runners: a review. Med Sci Sports Exerc 19:187–194
O'Donnell E, Harvey PJ, De Souza MJ (2009) Relationships between vascular resistance and energy deficiency, nutritional status and oxidative stress in oestrogen deficient physically active women. Clin Endocrinol (Oxf) 70:294–302
O'Donnell E, Goodman JM, Harvey PJ (2011) Clinical review: Cardiovascular consequences of ovarian disruption: a focus on functional hypothalamic amenorrhea in physically active women. J Clin Endocrinol Metab 96:3638–3648
O'Keefe JH, Lavie CJ (2013) Run for your life … at a comfortable speed and not too far. Heart 99:516–519
Papanek PE (2003) The female athlete triad: an emerging role for physical therapy. J Orthop Sports Phys Ther 33:594–614
Pate RR, O'Neill JR (2007) American women in the marathon. Sports Med 37(4–5):294–298

Pate RR, Sparling PB, Wilson GE et al (1987) Cardiorespiratory and metabolic responses to submaximal and maximal exercise in elite women distance runners. Int J Sports Med 8(Suppl 2):91–95

Pierce GL, Eskurza I, Walker AE et al (2011) Sex-specific effects of habitual aerobic exercise on brachial artery flow-mediated dilation in middle-aged and older adults. Clin Sci (Lond) 120:13–23

Pollock ML (1977) Submaximal and maximal working capacity of elite distance runners. Part I: cardiorespiratory aspects. Ann N Y Acad Sci 301:310–322

American College of Obstetricians and Gynecologists (2002) ACOG Committee opinion. Number 267, January 2002: exercise during pregnancy and the postpartum period. Obstet Gynecol 99:171–173

Rader EP, Faulkner JA (2006a) Recovery from contraction-induced injury is impaired in weight-bearing muscles of old male mice. J Appl Physiol 1985(100):656–661

Rader EP, Faulkner JA (2006b) Effect of aging on the recovery following contraction-induced injury in muscles of female mice. J Appl Physiol 1985(101):887–892

Radtke T, Schmidt-Trucksass A, Brugger N et al (2014) Ultra-endurance sports have no negative impact on indices of arterial stiffness. Eur J Appl Physiol 114:49–57

Rauh MJ, Nichols JF, Barrack MT (2010) Relationships among injury and disordered eating, menstrual dysfunction, and low bone mineral density in high school athletes: a prospective study. J Athl Train 45:243–252

Reed JL, Bowell JL, Hill BR et al (2011) Exercising women with menstrual disturbances consume low energy dense foods and beverages. Appl Physiol Nutr Metab 36:382–394

Reed JL, De Souza MJ, Mallinson RJ et al (2015) Energy availability discriminates clinical menstrual status in exercising women. J Int Soc Sports Nutr 12:11

Rice SG (2000) Development of an injury surveillance system: results from a longitudinal study of high school athletes. In: Ashare AB (ed) Safety in ice hockey. American Society for Testing and Materials, West Conshohocken, PA, pp 3–18

Roberts WO (2007) Can children and adolescents run marathons? Sports Med 37:299–301

Roberts WO, Nicholson WG (2010) Youth marathon runners and race day medical risk over 26 years. Clin J Sport Med 20:318–321

Rodriguez NR, Di Marco NM, Langley S (2009) American college of sports medicine position stand. Nutrition and athletic performance. Med Sci Sports Exerc 41:709–731

Rogers MA, Evans WJ (1993) Changes in skeletal muscle with aging: effects of exercise training. Exerc Sport Sci Rev 21:65–102

Santos-Lozano A, Collado PS, Foster C et al (2014) Influence of sex and level on marathon pacing strategy. Insights from the New York City race. Int J Sports Med 35:933–938

Saunders PU, Pyne DB, Telford RD et al (2004) Factors affecting running economy in trained distance runners. Sports Med 34:465–485

Schwabe K, Schwellnus M, Derman W et al (2014a) Medical complications and deaths in 21 and 56 km road race runners: a 4-year prospective study in 65 865 runners–SAFER study I. Br J Sports Med 48:912–918

Schwabe K, Schwellnus MP, Derman W et al (2014b) Less experience and running pace are potential risk factors for medical complications during a 56 km road running race: a prospective study in 26 354 race starters–SAFER study II. Br J Sports Med 48:905–911

Seals DR, Desouza CA, Donato AJ et al (2008) Habitual exercise and arterial aging. J Appl Physiol 105:1323–1332

Seefeldt V, Malina RM, Clark MA (2002) Factors affecting levels of physical activity in adults. Sports Med 32:143–168

Shaffer RA, Rauh MJ, Brodine SK et al (2006) Predictors of stress fracture susceptibility in young female recruits. Am J Sports Med 34:108–115

Speechly DP, Taylor SR, Rogers GG (1996) Differences in ultra-endurance exercise in performance-matched male and female runners. Med Sci Sports Exerc 28:359–365

Sternfeld B, Quesenberry CP Jr, Eskenazi B et al (1995) Exercise during pregnancy and pregnancy outcome. Med Sci Sports Exerc 27:634–640

Stray-Gundersen J, Chapman RF, Levine BD (2001) "Living high-training low" altitude training improves sea level performance in male and female elite runners. J Appl Physiol 1985 (91):1113–1120
Sundgot-Borgen J (1994) Risk and trigger factors for the development of eating disorders in female elite athletes. Med Sci Sports Exerc 26:414–419
Sundgot-Borgen J, Torstveit MK (2007) The female football player, disordered eating, menstrual function and bone health. Br J Sports Med 41(Suppl 1):i68–i72
Sundgot-Borgen J, Torstveit MK (2010) Aspects of disordered eating continuum in elite high-intensity sports. Scand J Med Sci Sports 20(Suppl 2):112–121
Taddei S, Virdis A, Mattei P et al (1995) Aging and endothelial function in normotensive subjects and patients with essential hypertension. Circulation 91:1981–1987
Taddei S, Galetta F, Virdis A et al (2000) Physical activity prevents age-related impairment in nitric oxide availability in elderly athletes. Circulation 101:2896–2901
Tanaka H, DeSouza CA, Seals DR (1998) Absence of age-related increase in central arterial stiffness in physically active women. Arterioscler Thromb Vasc Biol 18:127–132
Tanaka H, Dinenno FA, Monahan KD et al (2000) Aging, habitual exercise, and dynamic arterial compliance. Circulation 102:1270–1275
Tarnopolsky MA (2000) Gender differences in substrate metabolism during endurance exercise. Can J Appl Physiol 25:312–327
Tarnopolsky MA (2008) Sex differences in exercise metabolism and the role of 17-beta estradiol. Med Sci Sports Exerc 40:648–654
Tate CA, Holtz RW (1998) Gender and fat metabolism during exercise: a review. Can J Appl Physiol 23:570–582
Taylor AW, Johnson MJ (2008) Physiology of exercise and healthy aging. Human Kinetics, Champaign, IL
Thompson J, Manore M, Sheeshka J (2005) Nutrition: a functional approach. Second Canadian edn. Pearson, Toronto, Ontario
Trappe S (2007) Marathon runners: how do they age? Sports Med 37(4–5):302–305
Trappe SW, Costill DL, Fink WJ et al (1995) Skeletal muscle characteristics among distance runners: a 20-yr follow-up study. J Appl Physiol 1985(78):823–829
Trubee NW, Vanderburgh PM, Diestelkamp WS et al (2014) Effects of heat stress and sex on pacing in marathon runners. J Strength Cond Res 28:1673–1678
Vaitkevicius PV, Fleg JL, Engel JH et al (1993) Effects of age and aerobic capacity on arterial stiffness in healthy adults. Circulation 88:1456–1462
van der Worp MP, ten Haaf DS, van Cingel R et al (2015) Injuries in runners; a systematic review on risk factors and sex differences. PLoS One 10:e0114937
Vescovi JD, Scheid JL, Hontscharuk R et al (2008) Cognitive dietary restraint: impact on bone, menstrual and metabolic status in young women. Physiol Behav 95:48–55
Vitzthum VJ (2009) The ecology and evolutionary endocrinology of reproduction in the human female. Am J Phys Anthropol 140(Suppl 49):95–136
Vlachopoulos C, Dima I, Aznaouridis K et al (2005) Acute systemic inflammation increases arterial stiffness and decreases wave reflections in healthy individuals. Circulation 112:2193–2200
Vrazel J, Saunders RP, Wilcox S (2008) An overview and proposed framework of social-environmental influences on the physical-activity behavior of women. Am J Health Promot 23:2–12
Wade GN, Schneider JE (1992) Metabolic fuels and reproduction in female mammals. Neurosci Biobehav Rev 16:235–272
Wang BW, Ramey DR, Schettler JD et al (2002) Postponed development of disability in elderly runners: a 13-year longitudinal study. Arch Intern Med 162:2285–2294
Warburton DE, Nicol CW, Bredin SS (2006) Health benefits of physical activity: the evidence. CMAJ 174:801–809
Warden SJ, Davis IS, Fredericson M (2014) Management and prevention of bone stress injuries in long-distance runners. J Orthop Sports Phys Ther 44:749–765

Warren MP (1980) The effects of exercise on pubertal progression and reproductive function in girls. J Clin Endocrinol Metab 51:1150–1157

Warren MP, Brooks-Gunn J, Fox RP et al (2002) Osteopenia in exercise-associated amenorrhea using ballet dancers as a model: a longitudinal study. J Clin Endocrinol Metab 87:3162–3168

Webner D, DuPrey KM, Drezner JA et al (2012) Sudden cardiac arrest and death in United States marathons. Med Sci Sports Exerc 44:1843–1845

Wen DY, Puffer JC, Schmalzried TP (1997) Lower extremity alignment and risk of overuse injuries in runners. Med Sci Sports Exerc 29:1291–1298

Williams NI, Young JC, McArthur JW et al (1995) Strenuous exercise with caloric restriction: effect on luteinizing hormone secretion. Med Sci Sports Exerc 27:1390–1398

Williams NI, Bullen BA, McArthur JW et al (1999) Effects of short-term strenuous endurance exercise upon corpus luteum function. Med Sci Sports Exerc 31:949–958

Williams NI, Helmreich DL, Parfitt DB et al (2001a) Evidence for a causal role of low energy availability in the induction of menstrual cycle disturbances during strenuous exercise training. J Clin Endocrinol Metab 86:5184–5193

Williams NI, Caston-Balderrama AL, Helmreich DL et al (2001b) Longitudinal changes in reproductive hormones and menstrual cyclicity in cynomolgus monkeys during strenuous exercise training: abrupt transition to exercise-induced amenorrhea. Endocrinology 142:2381–2389

Williams NI, Reed JL, Leidy HJ et al (2010) Estrogen and progesterone exposure is reduced in response to energy deficiency in women aged 25–40 years. Hum Reprod 25:2328–2339

Wiswell RA, Jaque SV, Marcell TJ et al (2000) Maximal aerobic power, lactate threshold, and running performance in master athletes. Med Sci Sports Exerc 32:1165–1170

Zanker CL, Swaine IL (1998) Bone turnover in amenorrhoeic and eumenorrhoeic women distance runners. Scand J Med Sci Sports 8:20–26

# Chapter 8
# Training Aspects of Marathon Running

**Christoph Zinner**

**Abstract** Training for long distance running events such as marathon races need a well-designed training plan. The aim of this training should be to enhance physiological parameters which have been shown to influence long distance running performance. These important physiological parameters mainly include: maximal oxygen uptake ($\dot{V}O_{2max}$), % of $\dot{V}O_{2max}$ at lactate threshold, and the running economy. The structure of applying training with different loads and/or intensities in series of training cycles seems to be critical to the final performance outcome of a runner. For successful marathon training a high amount of prolonged high-volume training is crucial. With a combination of prolonged high-volume training and low-volume high-intensity interval training important adaptations in essential physiological parameters can be reached and finally running performance enhancements. Therefore, a structured periodization of the content of training as well as the load of training over a longer period of time with a certain goal is mandatory for long term developments.

**Keywords** Intensity distribution · Maximal oxygen uptake · Periodization · Training zones

## 8.1 Introduction

Numerous factors and determinants have been shown to influence long distance running performance including: physiological factors, hydration and fuel supplementation, environmental conditions, and genetic predispositions to name only a few (Joyner et al. 2011). Important physiological factors contributing to marathon performance include: maximal oxygen uptake ($\dot{V}O_{2max}$) (Billat et al. 2001a; Foster 1983; Noakes et al. 1990), % of $\dot{V}O_{2max}$ at lactate threshold (Noakes et al. 1990;

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C. Zinner and B. Sperlich (eds.), *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*, DOI 10.1007/978-3-319-29728-6_8

Farrell et al. 1993; Tanaka and Matsuura 1984), and the running economy (Noakes et al. 1990; Conley and Krahenbuhl 1980; Morgan et al. 1989). These three physiological factors are relatively "easy" to develop using different training methods.

The remainder of the chapter describes the main points for periodization of training as well as the known stimuli for improving the key factors contributing to marathon performance. Acute responses and chronic adaptations of measurable determinants occur when biological structures are exposed to a training induced stress which results in increased performance (Viru 1984). Phrased in simpler terms, stimuli generated by training are a combination of the intensity and duration of the exercise. To elicit acute reactions and later chronic adaptations, a stimulus (i.e. the product of intensity and duration) must exceed a certain threshold. The level of a stimulus required to elicit adaptation depends on various factors within an individual, namely, genetics, training status, training history, and nutrition.

## 8.2 Periodization

A periodization plan helps structure the content of training and training loads over a longer period of time such as a competitive season, with a certain goal in mind, for example, a competition or improvement of a particular skill. The structure of applying training with different loads and/or intensities in series of training blocks seems to be critical to the final performance outcome of a runner. Several concepts of periodization are important in optimizing the training structure for a competitive event. The most well-known periodization model is described by Bompa (1999). In the model, a training year is divided into large, medium, and small training phases, entitled macro- (12–16 weeks), meso- (3–5 weeks), and micro-cycles (training sessions). Another model is the so-called "block periodization" described by Issurin (2008). The aim of periodization is to achieve a high level of performance at a certain time point at the end of a macrocycle, for instance, an important competition. Training goals are set within every meso-cycle. The fundamental idea of periodization is that training should start with general exercises and lead to specific training, with peak performance occurring at the time of competition. Therefore, the aims of every mesocycle within a macrocycle change from general to specific training goals. This means for example, the portion of high-intensity interval training sessions will be higher in the later meso-cycles within a season compared to the beginning.

During the different cycles, runners vary their training intensity and/or duration on a frequent, if not daily basis. The goal of such variation is to enhance runners' physiological capacities without maladaptation and overtraining (McKenzie 1999). Within a periodization framework, the frequency of training has to be considered and is fairly constant for elite and sub-elite runners, who train 10–14 sessions per week (Billat et al. 2002; Tanaka et al. 1986). Younger endurance athletes exercise less often, typically 5–8 sessions per week (Seiler and Tønnessen 2009). Consequently, for young recreational athletes who already include prolonged high-volume training sessions in their workouts and who want to increase their total annual training hours, the best way to do so is to increase the number of sessions rather than to lengthen the duration of each session.

## 8.3 Definition of Exercise Intensity

Typically, training intensity is prescribed in zones based on maximal heart rate (HR), oxygen uptake, blood lactate levels, or ratings of perceived exertion (e.g. Borg scale). Examples of such zones are shown in Fig. 8.1 and Table 8.1 with typical zones highlighted for the "aerobic"/endurance part of the training. Additional zones for the "anaerobic" training content (e.g. sprints, strength training etc.) can be added. In the following, the three zone model (Fig. 8.1) will be applied to describe the training which is needed to elicit changes in important physiological parameters.

On the molecular level, there are several overlapping effects between increased exercise duration and increased exercise intensity. Therefore, an important part of training periodization is to be sensitive to changes in the athlete's health, training tolerance, and performance when adjustments in training are made. Training adjustments seem to be an important factor discriminating between moderately capable and highly successful athletes; the latter integrate feedback experiences into planning daily training activities in order to avoid negative outcomes (e.g. infection, injuries, overtraining etc.) and improve training benefits.

A typical error of less experienced runners during training is the "drift between the intensity zones". This drift means athletes tend to run harder on the days with

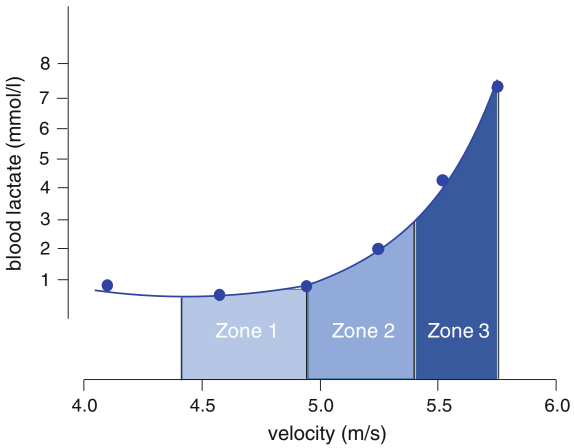


**Fig. 8.1** Intensity Zones *Model 1*. The end of *zone 1* is approximately at the lactate threshold/ventilatory threshold 1, the end of *zone 2* at the second ventilatory threshold according to Seiler (2010)

low-intensity training and do not run hard enough on days with high-intensity training (Foster et al. 2001) (Fig. 8.2). The result of this error is a higher number of training sessions performed near or at threshold intensity.

Total training stress is mainly altered by changes in duration and intensity of the training. Five different training models can be used to improve running endurance performance (Stoggl and Sperlich 2014): (a) Prolonged high-volume training with low intensity (HVT); (b) low-volume high-intensity interval training (HIIT); (c) a combined training regimen based on the three aforementioned models, also termed "polarized training" (POL); (d) training near or at the lactate threshold (THR); and (e) an equal distribution between all intensity zones, or "uniform" training (Fig. 8.3). In the training process for long distance running events, such as a marathon, both HIIT and HVT are supposed to be important components (Laursen 2010). Most retrospective studies on well-trained to elite endurance athletes show that large proportions of their training distribution are spent in HVT with some time spent in HIIT. In this case, a polarized distribution has been proven to be an

**Table 8.1** Intensity Zones *Model 2*. Five zones to describe the training intensity of marathon runners

| Zone | Heart rate (%max) | Lactate (mmol·l$^{-1}$) | RPE | % $\dot{V}O_{2max}$ | Training duration |
|---|---|---|---|---|---|
| 1 | 55–75 | 0.5–1.6 | 10–14 | 50–65 | 1–3 h |
| 2 | 75–85 | 1.6–2.6 | 14–16 | 65–80 | 1–2 h |
| 3 | 85–90 | 2.6–4.0 | 16–18 | 81–86 | 40–80 min |
| 4 | 90–95 | 4.0–6.3 | 18–19 | 87–93 | 30–60 min |
| 5 | 95–100 | 6.3–10.0 | 19–20 | 94–100 | 15–30 min |


**Fig. 8.2** Drift between the intensity zones

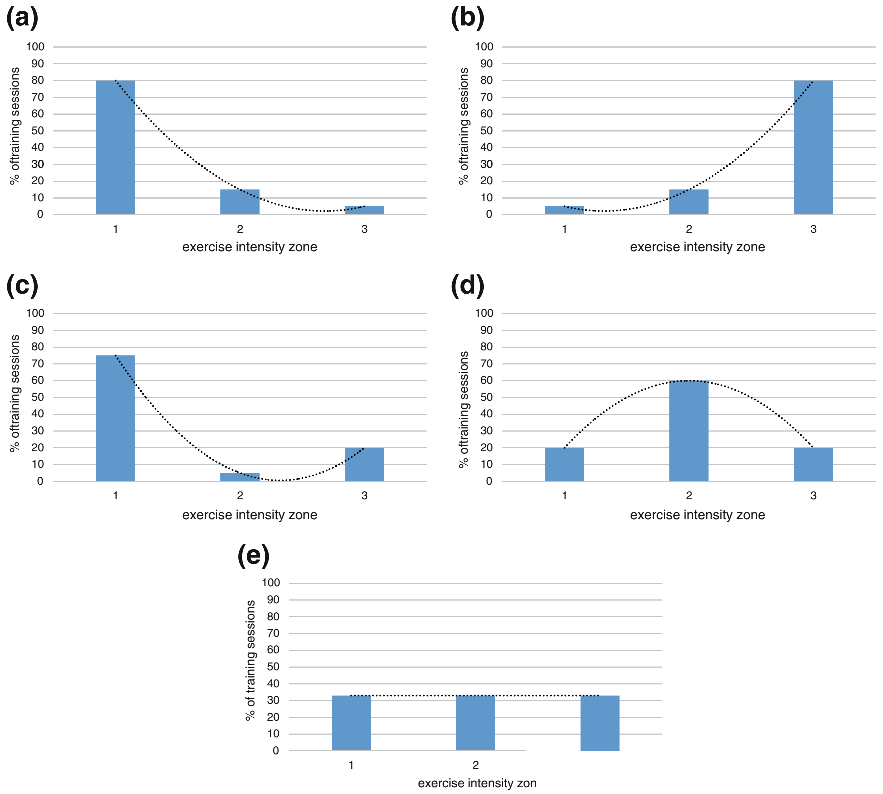


**Fig. 8.3** Different training models, with percentage of sessions within a certain zone (according to the three-zone model as shown in Fig. 8.1). **a** Prolonged high-volume training with low intensity (HVT); **b** low-volume high-intensity interval training (HIIT); **c** a combined training regimen based on the three aforementioned models, also termed "polarized training" (POL); **d** training near or at the lactate threshold (THR); and **e** an equal distribution between all intensity zones, or "uniform" training

effective stimulus for elite athletes during certain phases of the season (Stoggl and Sperlich 2015).

Prolonged training with high volume and low intensities (HVT) comprises a large part of a marathoners training program. HVT is thought to be a fundamental training concept in the preparation for marathon events and is usually performed at 65–75 % of $\dot{V}O_{2max}$ (Laursen and Jenkins 2002), <80 % of $HR_{max}$ (Laursen and Jenkins 2002), or <2 mmol $l^{-1}$ of blood lactate (Seiler and Kjerland 2006; Laursen and Jenkins 2002). HVT consists of long duration training sessions lasting ≥60 min (Seiler and Kjerland 2006).

In comparison with the plethora of studies investigating the effects of endurance training with high intensities (e.g. Buchheit and Laursen 2013; Gibala and Jones 2013), only a small number of investigations have examined the underlying effects of performance improvements with increases in HVT (Costill et al. 1991). One difference in the investigation of effects of HVT might be the time course of adaptations following an increase in training volume. Following HVT training, performance improvements occur slower than after training with high intensities (Costill et al. 1991; Laursen and Jenkins 2002). Aside from the challenges of investigating HVT, there are many unrecognizable positive adaptations of high-volume low intensity training (Esteve-Lanao et al. 2005, 2007; Seiler and Kjerland 2006).

In recreational athletes, HVT leads to a number of functional and morphological adaptations at peripheral and central levels. In untrained individuals, HVT increases stroke volume (Green et al. 1990) and plasma volume (Green et al. 1987) as well as muscular blood flow (Coyle 1999) within the first few days (Green et al. 1987). To provoke further increases like an enhanced $\dot{V}O_{2max}$ or a higher number of capillaries and mitochondria a longer time frame (3–5 weeks) with more training sessions (3–5 sesssions/week) is needed (Hickson et al. 1981; Hoppeler and Weibel 2000). Additionally, over the long term, HVT leads to a decrease in glycose and muscle glycogen utilization (Coggan et al. 1995; Karlsson et al. 1974) as well as an enhanced buffer capacity and a lower blood lactate concentration at submaximal intensities (Green et al. 1991). Muscle fiber characteristics of trained athletes demonstrate threefold increases in capillary density, a 3–4 times higher aerobic enzyme activity, and higher amounts of type I muscle fibers compared to untrained athletes' muscles (Henriksson 1992).

Cardiorespiratory adaptations to HVT seem to be limited. Once an athlete has "achieved" the potential adaptations associated with HVT, a further increase in training volume fails to provide any additional enhancements to cardiorespiratory fitness (Costill et al. 1988, 1991; Londeree 1997; Lake and Cavanagh 1996). Long term training studies on adaptations to HVT are however, rare. Scholars have suggested that adaptations to HVT may take a substantial period of time before they manifest, and hence most studies have failed to detect changes to HVT—particularly considering the fact that the performance tests are often in close proximity to the intervention period (Laursen 2010). Although it is insufficient to include only HVT in the periodization of marathon runners, this type of training is extremely important for successful training (Laursen 2010; Seiler et al. 2007; Yeo et al. 2008; Seiler and Kjerland 2006).

On the basis that HVT is not an adequate stimulus to provoke an athlete's best performance, it seems reasonable to include training sessions with higher intensities in a marathon runner's training plan. It is important to note, that high volumes of HIIT dramatically increase the training stress. If HIIT is performed too often, the training stress leads to overreaching, overtraining, maladaptation, and an eventual decrease in functional capacity (McKenzie 1999). In well trained marathon runners with a high frequency of training sessions, two HIIT sessions per week are performable (Billat et al. 1999). In conclusion, one or two sessions of HIIT per week with at least 48 h between the sessions is recommended. Before HIIT sessions are included in the training program, a preparatory training period with low intensity training is mandatory.

In retrospective analyses of the distribution of training intensities in well-trained and elite runners as well as other elite endurance athletes (cross country skiers, rowers etc.) an extremely high percentage of high volume training (zone 1) was evident (Fig. 8.3a, c) (Stoggl and Sperlich 2015). Although HIIT is important for further enhancements in endurance athletes, the higher number of training sessions should be low in intensity. The high amount of training at low intensities is needed in order to create a tolerance to higher training volumes (Hartmann et al. 1990), while avoiding the negative symptoms of overtraining. The implementation of a high amount of HVT in order to achieve physiological adaptations among marathon runners has been established by several scientists (Zapico et al. 2007; Esteve-Lanao et al. 2005, 2007; Ingham et al. 2008). Furthermore, the amount of HVT is positively correlated with increases in performance (Esteve-Lanao et al. 2005; Steinacker 1993; Seiler and Kjerland 2006; Hagerman and Staron 1983).

Training at marathon race pace, which has been suggested to improve running economy (Wilkinson 1999) does not appear to be the strategy of top-class marathoners. This finding, highlights that a common training strategy in which large amounts of training are performed at lactate threshold is in strong contrast to the training strategies adopted by world class runners. The training distribution of high performance athletes is above and below the lactate threshold intensity (polarized training) (Fig. 8.3c) and not at threshold intensity (Stoggl and Sperlich 2015). With this type of distribution, important training adaptations at central and peripheral levels are apparently achieved while minimizing the risk of overtraining (Foster 1998). Adopting the preceding mesocycle prior to a marathon ($\sim$3 months) has been shown to be highly beneficial for marathon performance (Hagan et al. 1981; Sjodin and Jacobs 1981).

Although the intensity during HVT is clearly lower than during a marathon race, and despite the fact that acute effects of HVT on exercise performance are difficult to investigate, it is clear that low-intensity training sessions have a positive impact on performance. HVT seems to provide the aerobic foundation which is important for facilitating adaptations to high-intensity interval training (Laursen 2010).

## 8.4 Training to Enhance Maximal Oxygen Uptake

Typically, distance runners have favored training with low intensities [50–70 % of $\dot{V}O_{2max}$ (Poole and Gaesser 1985; Branch et al. 2000)] and long durations to improve their $\dot{V}O_{2max}$ (Robinson et al. 1991; Fohrenbach et al. 1987; Basset et al. 2003; Hewson and Hopkins 1995). Among beginners commencing endurance training, fast improvements in $\dot{V}O_{2max}$ occur (Smith and Wenger 1981; Rodas et al. 2000). Therefore, HVT is an effective method to enhance $\dot{V}O_{2max}$ in less fit persons (Milanovic et al. 2015), however the minimal training intensity required to increase $\dot{V}O_{2max}$ is highly dependent on the initial $\dot{V}O_{2max}$ (Swain and Franklin 2002). In recent years, empirical evidence has mounted that the $\dot{V}O_{2max}$ of already well-trained athletes cannot be further enhanced with high volume training alone (Laursen and Jenkins 2002). Therefore, training intensity seems to be the important parameter for enhancing $\dot{V}O_{2max}$ in already well trained athletes.

The most effective training for enhancing $\dot{V}O_{2max}$ appears to be at intensities of 90–100 % $\dot{V}O_{2max}$ (Wenger and Bell 1986; Hill and Rowell 1997; Daniels and Scardina 1984; Laursen et al. 2002; Tabata et al. 1997; Wenger and Macnab 1975). By including these high intensities, the $\dot{V}O_{2max}$ of well-trained distance runners can be increased by ~5.4 %, despite a 10 % decrease in training volume (Billat et al. 2002). Other studies reported comparable increases in $\dot{V}O_{2max}$ following implementation of training intensities of 90–100 % $\dot{V}O_{2max}$ (Smith et al. 1999, 2003; Laffite et al. 2003; Mikesell and Dudley 1984).

Endurance training at very high intensities (90–100 % $\dot{V}O_{2max}$) maximally stresses physiological processes and structures that limit $\dot{V}O_{2max}$, and therefore provides an optimal stimulus for adaptations. To elicit enhancements in capillarisation, which is an important factor of $\dot{V}O_{2max}$ (Saltin and Rowell 1980), shear stress and capillary pressure have to be augmented by an increase in blood flow velocity (Hudlicka et al. 1992). Furthermore, in trained individuals the maximal stroke volume seems to be the major limitation of $\dot{V}O_{2max}$ (Saltin and Rowell 1980; Ouellet et al. 1969). In well trained athletes, the stroke volume increases until intensities of 100 % $\dot{V}O_{2max}$ and the myocardial pressures are maximal at this point (Zhou et al. 2001; Gledhill et al. 1994). A combination of increased stroke volume and myocardial pressures lead to high blood volumes in the heart and this mechanical overlord is the most important stimulus for myocardial adaptations (e.g. increases in stroke volume) (Helgerud et al. 2007; Clausen 1977; Cooper 1997).

The aim of training designed to improve $\dot{V}O_{2max}$ with intensities ranging from 90 to 100 % $\dot{V}O_{2max}$, should be to stress the cardiovascular system as long and as high as possible. In this scenario, training with "repeated short-to-long bouts of rather high intensity exercise interspersed with recovery periods" (Billat 2001) is the most appropriate way to structure training sessions. The question regarding the most effective interval intensities and durations to enhance $\dot{V}O_{2max}$ remains unclear. Figure 8.4 provides an overview of the possible nomenclature and ways to describe intensities during HIIT.

Franch et al. found a greater increase in $\dot{V}O_{2max}$ in an interval training group with 106 % $\dot{V}O_{2max}$ compared to a group training with 136 % $\dot{V}O_{2max}$ (Franch et al. 1998). Although it appears likely that extreme supra-$\dot{V}O_{2max}$ intensities are not as effective as lower high intensities, this supra-maximal training has other beneficial effects, for example, improvements attributed to muscle power (Buchheit and Laursen 2013). With interval training performed at intensities of 100 % $\dot{V}O_{2max}$, it appears that distance runners are able to run 9–9.5 min at this intensity (Billat et al. 2000, 2001b). For intervals with higher intensities, it is only possible to use shorter durations (see Fig. 8.4). The optimal work to rest ratio between intervals are still uncertain (Milanovic et al. 2015).

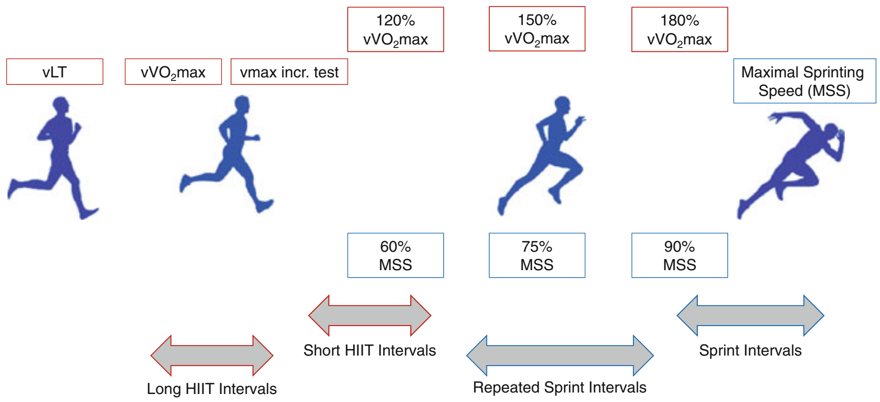


**Fig. 8.4** Different high intensity training nomenclatures and intensities. Modified according to Buchheit and Laursen (2013). vLT velocity at the lactate threshold, $v\dot{V}O_{2peak}$ running speed required to achieve $\dot{V}O_{2peak}$, vmax incr. test maximal velocity during an incremental test

In summary, determining the best training program for enhancing $\dot{V}O_{2max}$, primarily depends on the fitness level of the runner. First, the volume of HVT should be increased until a plateau in $\dot{V}O_{2max}$ enhancement is achieved. Thereafter, implementation of HIIT in various forms should be added, knowing that a high number of HIIT sessions per week (>2) without adequate recovery periods will lead to overtraining. From a scientific point of view, resistance training does not appear to be effective in enhancing $\dot{V}O_{2max}$ (Paavolainen et al. 1999; Spurrs et al. 2003; Johnston 1997; Turner et al. 2003).

## 8.5 Training to Enhance the Velocity at Lactate Threshold and % of $\dot{V}O_{2max}$ at Lactate Threshold

Although it is clear that lactate is not a cause of fatigue during exercise (Cairns 2006), scientists and coaches apply lactate measurements as practical indicators of improved performance. The lactate threshold (LT) is the intensity of work or $\dot{V}O_2$ where the blood lactate concentration starts to rise during continuous exercise (di Prampero et al. 1986). The lactate concentration measured in the capillary blood (i.e. earlobe or finger) reflects the balance of lactate production in the muscles, the transport rates of lactate from the muscles to the blood, and the clearance of lactate from the blood. An increase of the blood lactate concentration does not indicate that exercise has become more “anaerobic” (Gladden 2004). Typically, the lactate threshold is between 50 and 75 % of $\dot{V}O_{2max}$, but it can be increased to 80–85 % of $\dot{V}O_{2max}$ in highly trained marathon and ultra-marathon runners (Sjodin and Svedenhag 1985). Exercise close to the LT can be sustained for approximately 2 h whereby blood lactate concentration does not accumulate over time.

In endurance athletes it has been demonstrated that the velocity at the lactate threshold (vLT) is closely linked to performance (Midgley et al. 2007; Bassett and Howley 2000). Performance at the LT changes in response to training and furthermore, the % of $\dot{V}O_{2max}$ at LT changes as well (Helgerud et al. 2001; McMillan et al. 2005; Pate and Kriska 1984). As a result, the vLT and fractional utilization of $\dot{V}O_2$ at vLT (% of $\dot{V}O_{2max}$) seem to be good indicators of endurance performance. Trained runners are able to run the marathon at an intensity of ~80 % of $\dot{V}O_{2max}$, whereas untrained and less trained athletes achieve only 50–70 % of their $\dot{V}O_{2max}$.

There is no doubt that long-distance runners typically have higher lactate thresholds than middle-distances runners. This fact suggests that high training volumes of low intensity (below threshold levels) are effective in enhancing the lactate threshold (MacDougall 1977). Natural selection however, can also potentially explain this phenomenon. An athlete with an excess overweight of slow twitch fibers, who possesses a high lactate threshold, may potentially perform better in longer events (Ivy et al. 1980; Noakes et al. 1990; Tanaka and Matsuura 1984; Farrell et al. 1993). Training adaptations associated with improvements in lactate threshold seem mainly to be related to skeletal muscle adaptations (Midgley et al. 2007). Concerning these improvements in lactate threshold, the mitochondrial content of the muscles—measured by mitochondrial enzyme activity—is one variable associated with lactate production. Therefore, increases in performance at the LT after training are potentially linked to adaptations in the mitochondrial enzyme activity (Coyle 1999). The process here is the following. Endurance training leads to a high increase in the quantity of mitochondria in the trained muscles (up to +100 %). Subsequently, during exercise at submaximal intensities, the oxygen inhaled is "used" by a higher number of mitochondria. Thus, following training, the concentration of ADP does not increase to the same level as prior to the training, to achieve the same rate of oxidative phosphorylation. The aforementioned process leads to lower phosphofructokinase activity and a lower carbohydrate turnover with more mitochondria using fat for energy production, resulting in a lower lactate production rate (Bassett and Howley 2000).

Training at intensities slightly above LT, appears to be an optimal training strategy for improving LT for sedentary people (Henritze et al. 1985; Weltman et al. 1992). Training at ~59 % $\dot{V}O_{2max}$ (slightly above LT) increased the $\dot{V}O_2$ at LT by 48 % in untrained women (Henritze et al. 1985) while the group that trained at LT (~44 % $\dot{V}O_{2max}$) did not improve their $\dot{V}O_2$ at LT. In an extended training intervention, the performance at LT plateaued after four months in the group training at LT, whereas the group which trained above LT continued to improve their LT performance for 8 months (Weltman et al. 1992). A further study showed no advantages of training at or above LT (Belman and Gaesser 1991). Marathon runners who include a high amount of HVT in their training demonstrate a plateau in LT performance changes (Laursen and Jenkins 2002). Elite cross country skiers demonstrated an increase in performance at the LT after HIIT (80–90 % $\dot{V}O_{2max}$) compared to HVT (60–70 % $\dot{V}O_{2max}$) (Evertsen et al. 2001).

Knowledge regarding the most advantageous training for enhancing LT is limited and conflicting. It seems that HVT is beneficial for increasing performance at the LT until a certain plateau is reached.

## 8.6 Training to Enhance the Runner's Economy

Achieving low energy costs during constant submaximal running speeds—as is the case during a marathon race—is highly important for marathon runners. Therefore, one aim of marathon training is to reduce the energy costs per kilometer, that is, to improve one's running economy (RE). The RE is measured in oxygen uptake in relation to body mass ($\dot{V}O_2$ in ml/min/kg) or as absolute oxygen uptake per kilometer ($\dot{V}O_2$ in ml/kg/km) during constant velocities of <85 % $\dot{V}O_{2max}$ (Morgan et al. 1989). During the same submaximal velocities, trained athletes show a lower $\dot{V}O_2$ compared to untrained athletes (Saunders et al. 2004; Barnes and Kilding 2015). World class male marathon runners with a $\dot{V}O_{2max}$ of 83 ml/min/kg show a $\dot{V}O_2$ at 16 km/h of approximately 40 ml/min/km (Lucia et al. 2008) and female runners ($\dot{V}O_{2max}$: 75 ml/min/kg) of approximately 44 ml/min/kg (Jones 2006). Untrained male sport students at 10.1 km/h show a $\dot{V}O_2$ of 35.6 ± 7.6 ml/min/kg with their female counterparts having a $\dot{V}O_2$ of 34.7 ± 5.6 ml/min/kg (mean ± SD; own data). Theoretical calculations predict that an improvement in RE of 5 % leads to an improvement of running performance of approximately 4 % (di Prampero et al. 1986). In several studies different training regimes and their influences on running economy have been investigated.

In interventions with durations between 4 to 10 weeks, HIIT seemed to improve RE by 2–8 % (Billat et al. 1999; Denadai et al. 2006; Franch et al. 1998; Laffite et al. 2003; Sjödin et al. 1982; Slawinski et al. 2001). Intensities between 93 and 120 % $\dot{V}O_{2max}$ were used in these interventions. Other studies investigating the effect of HIIT on the RE did not find any changes (Smith et al. 2003; Yoshida et al. 1990; Franch et al. 1998). It has to be mentioned, that most of the studies incorporated HIIT into the normal training schedule of the runners participating in these studies. It seems that longer intervals (4 min at 94 % $\dot{V}O_{2max}$) have a higher impact on the enhancement of the RE (+3 %) compared to shorter intervals (15 s at 92 % $\dot{V}O_{2max}$) (Franch et al. 1998). The greatest enhancements in RE were found for intervals lasting 3–4 min at an intensity of 90–100 % $\dot{V}O_{2max}$ (Billat et al. 1999; Denadai et al. 2006; Laffite et al. 2003). Running uphill intervals as a special form of HIIT, has shown contradictory results concerning changes in RE (Barnes et al. 2013a; Ferley et al. 2014).

Strength training seems to have an indirect effect on RE in distance runners. Studies which added different forms of strength training to normal running found improvements in RE for recreational (Albracht and Arampatzis 2013; Berryman et al. 2010; Paavolainen et al. 1999; Piacentini et al. 2013; Skovgaard et al. 2014; Taipale et al. 2010) and elite (Millet et al. 2002; Saunders et al. 2006; Sedano et al. 2013) athletes in the range of 3–7 %. Nevertheless, some studies found only slight changes in RE after maximal strength training (Barnes et al. 2013b; Ferrauti et al. 2010; Mikkola et al. 2011; Taipale et al. 2013). Potential reasons suggested for the changes in RE are adjustments in recruitment patterns as well as an improved synchronization of motoneurons (Kraemer et al. 1996). Plyometric and explosive strength training performed with running specific movements (e.g. jumps and sprints) at maximal intensities show positive (Mikkola et al. 2011; Cheng et al. 2012; Paavolainen et al. 1999; Piacentini et al. 2013; Stanton et al. 2004; Taipale et al. 2010, 2013) or no changes in RE in their sub groups. One study showed a 5 % improvement in RE in well-trained runners after plyometric training (Sedano et al. 2013). It is assumed that plyometric training should increase the stiffness of the tendons involved in running, thereby reducing ground contact times, and minimizing energy expenditure (Anderson 1996; Spurrs et al. 2003). The "strength endurance" training often performed by marathon runners involves numerous repetitions (>20) with a low or complete lack of additional weight. Only two studies found an increase in RE by 2.4–4 % after "strength endurance" training (Johnston 1997; Sedano et al. 2013), with many studies finding no changes in RE (Cheng et al. 2012; Mikkola et al. 2011; Paavolainen et al. 1999; Piacentini et al. 2013; Stanton et al. 2004; Taipale et al. 2010, 2013).

Taken together, different training interventions support various forms of endurance and strength which can contribute to enhanced RE. The available literature regarding different forms of altitude training and the impact on the RE is contradictory (Sperlich et al. 2015). However, the improvements are subject to high inter-individual variability. The most important factor in enhancing RE seems to be the accumulation of training over several years (Nelson and Gregor 1976). Among elite athletes in particular, and in less trained runners as well, the training age and accumulated training volume of several years shows the highest correlation with improved running economy (Conley et al. 1984; Jones 2006; Svedenhag and Sjödin 1985). It is noteworthy that studies with female runners concerning training influences on RE are completely absent.

## 8.7 Conclusions

It is the aim of every coach, scientist and athlete to find the "optimal" training method for successful marathon training. To draw conclusions from training studies with mainly short intervention times and which focus their investigations on a few number of parameters makes the optimization of training very challenging. Some conclusions seem to be assured based on recent studies and experiences from successful runners:

- HVT is the most important part in the training of a marathon runner.
- Total training volume shows a high correlation with improvements in running performance.
- A well-developed endurance foundation achieved by high volumes of training is crucial in the preconditioning to tolerate and respond optimally to an increase in training intensity.
- HIIT should be included in the training plan of marathon runners of every performance level.
- Even though HIIT is an important part of a marathoners training and shows rapid improvements in performance, two HIIT sessions per week are sufficient to achieve performance enhancements without inducing excessive stress.
- To ensure long term development and avoid stagnation, the overall training amount (volume + intensity) should be increased carefully over several years.
- A training zone distribution of approximately 80–5–15 % (Fig. 8.3c) seems to be the most effective training distribution for marathon runners.

## References

Albracht K, Arampatzis A (2013) Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans. Eur J Appl Physiol 113(6):1605–1615. doi:10.1007/s00421-012-2585-4

Anderson T (1996) Biomechanics and running economy. Sports Med 22(2):76–89

Barnes KR, Kilding AE (2015) Strategies to improve running economy. Sports Med 45(1):37–56. doi:10.1007/s40279-014-0246-y

Barnes KR, Hopkins WG, McGuigan MR, Kilding AE (2013a) Effects of different uphill interval-training programs on running economy and performance. Int J Sports Physiol Perform 8(6):639–647

Barnes KR, Hopkins WG, McGuigan MR, Northuis ME, Kilding AE (2013b) Effects of resistance training on running economy and cross-country performance. Med Sci Sports Exerc 45 (12):2322–2331. doi:10.1249/MSS.0b013e31829af603

Basset FA, Chouinard R, Boulay MR (2003) Training profile counts for time-to-exhaustion performance. Can J Appl Physiol 28(4):654–666

Bassett DR Jr, Howley ET (2000) Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc 32(1):70–84

Belman MJ, Gaesser GA (1991) Exercise training below and above the lactate threshold in the elderly. Med Sci Sports Exerc 23(5):562–568

Berryman N, Maurel D, Bosquet L (2010) Effect of plyometric vs. dynamic weight training on the energy cost of running. J Strength Cond Res 24(7):1818–1825. doi:10.1519/JSC.0b013e3181def1f5

Billat LV (2001) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. Sports Med 31(1):13–31

Billat VL, Flechet B, Petit B, Muriaux G, Koralsztein JP (1999) Interval training at $VO_{2max}$: effects on aerobic performance and overtraining markers. Med Sci Sports Exerc 31(1):156–163

Billat VL, Slawinski J, Bocquet V, Demarle A, Lafitte L, Chassaing P, Koralsztein JP (2000) Intermittent runs at the velocity associated with maximal oxygen uptake enables subjects to

remain at maximal oxygen uptake for a longer time than intense but submaximal runs. Eur J Appl Physiol 81(3):188–196. doi:10.1007/s004210050029
Billat VL, Demarle A, Slawinski J, Paiva M, Koralsztein JP (2001a) Physical and training characteristics of top-class marathon runners. Med Sci Sports Exerc 33(12):2089–2097
Billat VL, Slawinksi J, Bocquet V, Chassaing P, Demarle A, Koralsztein JP (2001b) Very short (15 s–15 s) interval-training around the critical velocity allows middle-aged runners to maintain $VO_{2max}$ for 14 minutes. Int J Sports Med 22(3):201–208. doi:10.1055/s-2001-16389
Billat V, Demarle A, Paiva M, Koralsztein JP (2002) Effect of training on the physiological factors of performance in elite marathon runners (males and females). Int J Sports Med 23(5):336–341. doi:10.1055/s-2002-33265
Bompa TO (1999) Periodization training: theory and methodology, 4th edn. Human Kinetics, Champaign
Branch JD, Pate RR, Bourque SP (2000) Moderate intensity exercise training improves cardiorespiratory fitness in women. J Womens Health Gend Based Med 9(1):65–73. doi:10.1089/152460900318984
Buchheit M, Laursen PB (2013) High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. Sports Med 43(5):313–338. doi:10.1007/s40279-013-0029-x
Cairns SP (2006) Lactic acid and exercise performance: culprit or friend? Sports Med 36(4):279–291
Cheng C-F, Cheng K-H, Lee Y-M, Huang H-W, Kuo Y-H, Lee H-J (2012) Improvement in running economy after 8 weeks of whole-body vibration training. J Strength Conditioning Res/Nat Strength Conditioning Assoc 26(12):3349–3357. doi:10.1519/JSC.0b013e31824e0eb1
Clausen JP (1977) Effect of physical training on cardiovascular adjustments to exercise in man. Physiol Rev 57(4):779–815
Coggan AR, Raguso CA, Williams BD, Sidossis LS, Gastaldelli A (1995) Glucose kinetics during high-intensity exercise in endurance-trained and untrained humans. J Appl Physiol 78 (3):1203–1207
Conley DL, Krahenbuhl GS (1980) Running economy and distance running performance of highly trained athletes. Med Sci Sports Exerc 12(5):357–360
Conley DL et al (1984) Following Steve Scott: physiological changes accompanying training. Physician Sportsmed 12(1):103–106
Cooper G (1997) Basic determinants of myocardial hypertrophy: a review of molecular mechanisms. Annu Rev Med 48:13–23. doi:10.1146/annurev.med.48.1.13
Costill DL, Flynn MG, Kirwan JP, Houmard JA, Mitchell JB, Thomas R, Park SH (1988) Effects of repeated days of intensified training on muscle glycogen and swimming performance. Med Sci Sports Exerc 20(3):249–254
Costill DL, Thomas R, Robergs RA, Pascoe D, Lambert C, Barr S, Fink WJ (1991) Adaptations to swimming training: influence of training volume. Med Sci Sports Exerc 23(3):371–377
Coyle EF (1999) Physiological determinants of endurance exercise performance. J Sci Med Sport 2(3):181–189
Daniels J, Scardina N (1984) Interval training and performance. Sports Med 1(4):327–334
Denadai BS, Ortiz MJ, Greco CC, de Mello MT (2006) Interval training at 95 % and 100 % of the velocity at $VO_{2\ max}$: effects on aerobic physiological indexes and running performance. Appl Physiol Nutr Metab (Physiologie appliquée, nutrition et métabolisme) 31(6):737–743. doi:10.1139/h06-080
di Prampero PE, Atchou G, Bruckner JC, Moia C (1986) The energetics of endurance running. Eur J Appl Physiol 55(3):259–266
Esteve-Lanao J, San Juan AF, Earnest CP, Foster C, Lucia A (2005) How do endurance runners actually train? Relationship with competition performance. Med Sci Sports Exerc 37(3):496–504
Esteve-Lanao J, Foster C, Seiler S, Lucia A (2007) Impact of training intensity distribution on performance in endurance athletes. J Strength Cond Res 21(3):943–949. doi:10.1519/R-19725.1

Evertsen F, Medbo JI, Bonen A (2001) Effect of training intensity on muscle lactate transporters and lactate threshold of cross-country skiers. Acta Physiol Scand 173(2):195–205. doi:10.1046/j.1365-201X.2001.00871.x

Farrell PA, Wilmore JH, Coyle EF, Billing JE, Costill DL (1993) Plasma lactate accumulation and distance running performance. 1979. Med Sci Sports Exerc 25(10):1091–1097 (discussion 1089–1090)

Ferley DD, Osborn RW, Vukovich MD (2014) The effects of incline and level-grade high-intensity interval treadmill training on running economy and muscle power in well-trained distance runners. J Strength Conditioning Res/Nat Strength Conditioning Assoc 28(5):1298–1309. doi:10.1519/jsc.0000000000000274

Ferrauti A, Bergermann M, Fernandez-Fernandez J (2010) Effects of a concurrent strength and endurance training on running performance and running economy in recreational marathon runners. J Strength Conditioning Res/Nat Strength Conditioning Assoc 24(10):2770–2778. doi:10.1519/JSC.0b013e3181d64e9c

Fohrenbach R, Mader A, Hollmann W (1987) Determination of endurance capacity and prediction of exercise intensities for training and competition in marathon runners. Int J Sports Med 8 (1):11–18. doi:10.1055/s-2008-1025633

Foster C (1983) $VO_{2max}$ and training indices as determinants of competitive running performance. J Sports Sci 1:13–22

Foster C (1998) Monitoring training in athletes with reference to overtraining syndrome. Med Sci Sports Exerc 30(7):1164–1168

Foster C, Heiman KM, Esten PL, Brice G, Porcari J (2001) Differences in perceptions of training by coaches and athletes. S Afr J Sports Med 8:3–7

Franch J, Madsen K, Djurhuus MS, Pedersen PK (1998) Improved running economy following intensified training correlates with reduced ventilatory demands. Med Sci Sports Exerc 30 (8):1250–1256

Gibala MJ, Jones AM (2013) Physiological and performance adaptations to high-intensity interval training. Nestle Nutr Inst Workshop Ser 76:51–60. doi:10.1159/000350256

Gladden LB (2004) Lactate metabolism: a new paradigm for the third millennium. J Physiol 558 (Pt 1):5–30. doi:10.1113/jphysiol.2003.058701

Gledhill N, Cox D, Jamnik R (1994) Endurance athletes' stroke volume does not plateau: major advantage is diastolic function. Med Sci Sports Exerc 26(9):1116–1121

Green HJ, Jones LL, Hughson RL, Painter DC, Farrance BW (1987) Training-induced hypervolemia: lack of an effect on oxygen utilization during exercise. Med Sci Sports Exerc 19(3):202–206

Green HJ, Jones LL, Painter DC (1990) Effects of short-term training on cardiac function during prolonged exercise. Med Sci Sports Exerc 22(4):488–493

Green HJ, Jones S, Ball-Burnett M, Fraser I (1991) Early adaptations in blood substrates, metabolites, and hormones to prolonged exercise training in man. Can J Physiol Pharmacol 69 (8):1222–1229

Hagan RD, Smith MG, Gettman LR (1981) Marathon performance in relation to maximal aerobic power and training indices. Med Sci Sports Exerc 13(3):185–189

Hagerman FC, Staron RS (1983) Seasonal variables among physiological variables in elite oarsmen. Can J Appl Sport Sci 8(3):143–148

Hartmann U, Mader A, Hollmann W (1990) Heart rate and lactate during endurance training programs in rowing and its relation to the duration of exercise by top elite rowers. FISA Coach 1:1–4

Helgerud J, Engen LC, Wisloff U, Hoff J (2001) Aerobic endurance training improves soccer performance. Med Sci Sports Exerc 33(11):1925–1931

Helgerud J, Hoydal K, Wang E, Karlsen T, Berg P, Bjerkaas M, Simonsen T, Helgesen C, Hjorth N, Bach R, Hoff J (2007) Aerobic high-intensity intervals improve $VO_{2max}$ more than moderate training. Med Sci Sports Exerc 39(4):665–671. doi:10.1249/mss.0b013e3180304570

Henriksson J (1992) Effects of physical training on the metabolism of skeletal muscle. Diabetes Care 15(11):1701–1711

Henritze J, Weltman A, Schurrer RL, Barlow K (1985) Effects of training at and above the lactate threshold on the lactate threshold and maximal oxygen uptake. Eur J Appl Physiol Occup Physiol 54(1):84–88

Hewson DJ, Hopkins WG (1995) Prescribed and self-reported seasonal training of distance runners. J Sports Sci 13(6):463–470. doi:10.1080/02640419508732263

Hickson RC, Hagberg JM, Ehsani AA, Holloszy JO (1981) Time course of the adaptive responses of aerobic power and heart rate to training. Med Sci Sports Exerc 13(1):17–20

Hill DW, Rowell AL (1997) Responses to exercise at the velocity associated with $VO_{2max}$. Med Sci Sports Exerc 29(1):113–116

Hoppeler H, Weibel ER (2000) Structural and functional limits for oxygen supply to muscle. Acta Physiol Scand 168(4):445–456

Hudlicka O, Brown M, Egginton S (1992) Angiogenesis in skeletal and cardiac muscle. Physiol Rev 72(2):369–417

Ingham SA, Carter H, Whyte GP, Doust JH (2008) Physiological and performance effects of low-versus mixed-intensity rowing training. Med Sci Sports Exerc 40(3):579–584. doi:10.1249/MSS.0b013e31815ecc6a

Issurin V (2008) Block periodization versus traditional training theory: a review. J Sports Med Phys Fitness 48(1):65–75

Ivy JL, Withers RT, Van Handel PJ, Elger DH, Costill DL (1980) Muscle respiratory capacity and fiber type as determinants of the lactate threshold. J Appl Physiol Respir Environ Exerc Physiol 48(3):523–527

Johnston QTJKRVNB (1997) Strength training in female distance runners: impact on running economy. J Strength Conditioning Res 11(4):224–229

Jones AM (2006) The physiology of the women's world record holder for the women's marathon. Int J Sports Sci Coaching 1(2):101–116

Joyner MJ, Ruiz A, Lucia A (2011) Last word on viewpoint: the two-hour marathon: who and when? J Appl Physiol 110 (1)

Karlsson J, Nordesjo LO, Saltin B (1974) Muscle glycogen utilization during exercise after physical training. Acta Physiol Scand 90(1):210–217

Kraemer WJ, Fleck SJ, Evans WJ (1996) Strength and power training: physiological mechanisms of adaptation. Exerc Sport Sci Rev 24:363–397

Laffite LP, Mille-Hamard L, Koralsztein JP, Billat VL (2003) The effects of interval training on oxygen pulse and performance in supra-threshold runs. Arch Physiol Biochem 111(3):202–210. doi:10.1076/apab.111.3.202.23455

Lake MJ, Cavanagh PR (1996) Six weeks of training does not change running mechanics or improve running economy. Med Sci Sports Exerc 28(7):860–869

Laursen PB (2010) Training for intense exercise performance: high-intensity or high-volume training? Scand J Med Sci Sports 20:1–10. doi:10.1111/j.1600-0838.2010.01184.x

Laursen PB, Jenkins DG (2002) The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. Sports Med 32(1):53–73

Laursen PB, Shing CM, Peake JM, Coombes JS, Jenkins DG (2002) Interval training program optimization in highly trained endurance cyclists. Med Sci Sports Exerc 34(11):1801–1807. doi:10.1249/01.MSS.0000036691.95035.7D

Londeree BR (1997) Effect of training on lactate/ventilatory thresholds: a meta-analysis. Med Sci Sports Exerc 29(6):837–843

Lucia A, Olivan J, Bravo J, Gonzalez-Freire M, Foster C (2008) The key to top-level endurance running performance: a unique example. Br J Sports Med 42(3):172–174 (discussion 174). doi:10.1136/bjsm.2007.040725

MacDougall JD (1977) The anaerobic threshold: its significance for the endurance athlete. Can J Appl Sport Sci 2:137–140

McKenzie DC (1999) Markers of excessive exercise. Can J Appl Physiol 24(1):66–73

McMillan K, Helgerud J, Macdonald R, Hoff J (2005) Physiological adaptations to soccer specific endurance training in professional youth soccer players. Br J Sports Med 39(5):273–277. doi:10.1136/bjsm.2004.012526

Midgley AW, McNaughton LR, Jones AM (2007) Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? Sports Med (Auckland, NZ) 37 (10):857–880

Mikesell KA, Dudley GA (1984) Influence of intense endurance training on aerobic power of competitive distance runners. Med Sci Sports Exerc 16(4):371–375

Mikkola J, Vesterinen V, Taipale R, Capostagno B, Häkkinen K, Nummela A (2011) Effect of resistance training regimens on treadmill running and neuromuscular performance in recreational endurance runners. J Sports Sci 29(13):1359–1371. doi:10.1080/02640414.2011.589467

Milanovic Z, Sporis G, Weston M (2015) Effectiveness of high-intensity interval training (HIT) and continuous endurance training for $VO_{2max}$ improvements: a systematic review and meta-analysis of controlled trials. Sports Med 45(10):1469–1481. doi:10.1007/s40279-015-0365-0

Millet GP, Jaouen B, Borrani F, Candau R (2002) Effects of concurrent endurance and strength training on running economy and $VO_2$ kinetics. Med Sci Sports Exerc 34(8):1351–1359

Morgan DW, Martin PE, Krahenbuhl GS (1989) Factors affecting running economy. Sports Med (Auckland, NZ) 7(5):310–330

Nelson RC, Gregor RJ (1976) Biomechanics of distance running: a longitudinal study. Res Q 47 (3):417–428

Noakes TD, Myburgh KH, Schall R (1990) Peak treadmill running velocity during the $VO_{2max}$ test predicts running performance. J Sports Sci 8(1):35–45. doi:10.1080/02640419008732129

Ouellet Y, Poh SC, Becklake MR (1969) Circulatory factors limiting maximal aerobic exercise capacity. J Appl Physiol 27(6):874–880

Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, Rusko H (1999) Explosive-strength training improves 5-km running time by improving running economy and muscle power. J Appl Physiol 86(5):1527–1533

Pate RR, Kriska A (1984) Physiological basis of the sex difference in cardiorespiratory endurance. Sports Med 1(2):87–98

Piacentini MF, De Ioannon G, Comotto S, Spedicato A, Vernillo G, La Torre A (2013) Concurrent strength and endurance training effects on running economy in master endurance runners. J Strength Cond Res 27(8):2295–2303. doi:10.1519/JSC.0b013e3182794485

Poole DC, Gaesser GA (1985) Response of ventilatory and lactate thresholds to continuous and interval training. J Appl Physiol 58(4):1115–1121

Robinson DM, Robinson SM, Hume PA, Hopkins WG (1991) Training intensity of elite male distance runners. Med Sci Sports Exerc 23(9):1078–1082

Rodas G, Ventura JL, Cadefau JA, Cusso R, Parra J (2000) A short training programme for the rapid improvement of both aerobic and anaerobic metabolism. Eur J Appl Physiol 82(5–6):480–486. doi:10.1007/s004210000223

Saltin B, Rowell LB (1980) Functional adaptations to physical activity and inactivity. Fed Proc 39 (5):1506–1513

Saunders PU, Pyne DB, Telford RD, Hawley JA (2004) Factors affecting running economy in trained distance runners. Sports Med (Auckland, NZ) 34(7):465–485

Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, Hawley JA (2006) Short-term plyometric training improves running economy in highly trained middle and long distance runners. J Strength Conditioning Res/Nat Strength Conditioning Assoc 20(4):947–954. doi:10.1519/r-18235.1

Sedano S, Marín PJ, Cuadrado G, Redondo JC (2013) Concurrent training in elite male runners: the influence of strength versus muscular endurance training on performance outcomes. J Strength Conditioning Res/Nat Strength Conditioning Assoc 27(9):2433–2443. doi:10.1519/JSC.0b013e318280cc26

Seiler S (2010) What is best practice for training intensity and duration distribution in endurance athletes? Int J Sports Physiol Perform 5(3):276–291

Seiler KS, Kjerland GO (2006) Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? Scand J Med Sci Sports 16(1):49–56. doi:10.1111/j.1600-0838.2004.00418.x

Seiler S, Tønnessen E (2009) Intervals, thresholds, and long slow distance: the role of intensity and duration in endurance training. Sportscience 13:32–54

Seiler S, Haugen O, Kuffel E (2007) Autonomic recovery after exercise in trained athletes: intensity and duration effects. Med Sci Sports Exerc 39(8):1366–1373. doi:10.1249/mss.0b013e318060f17d

Sjodin B, Jacobs I (1981) Onset of blood lactate accumulation and marathon running performance. Int J Sports Med 2(1):23–26. doi:10.1055/s-2008-1034579

Sjodin B, Svedenhag J (1985) Applied physiology of marathon running. Sports medicine 2(2):83–99

Sjödin B, Jacobs I, Svedenhag J (1982) Changes in onset of blood lactate accumulation (OBLA) and muscle enzymes after training at OBLA. Eur J Appl Physiol 49(1):45–57

Skovgaard C, Christensen PM, Larsen S, Andersen TR, Thomassen M, Bangsbo J (2014) Concurrent speed endurance and resistance training improves performance, running economy, and muscle NHE1 in moderately trained runners. J Appl Physiol 117(10):1097–1109. doi:10.1152/japplphysiol.01226.2013 [pii]

Slawinski J, Demarle A, Koralsztein JP, Billat V (2001) Effect of supra-lactate threshold training on the relationship between mechanical stride descriptors and aerobic energy cost in trained runners. Arch Physiol Biochem 109(2):110–116. doi:10.1076/apab.109.2.110.4270

Smith DJ, Wenger HA (1981) The 10 day aerobic mini-cycle: the effects of interval or continuous training at two different intensities. J Sports Med Phys Fitness 21(4):390–394

Smith TP, McNaughton LR, Marshall KJ (1999) Effects of 4-wk training using Vmax/Tmax on $VO_{2max}$ and performance in athletes. Med Sci Sports Exerc 31(6):892–896

Smith TP, Coombes JS, Geraghty DP (2003) Optimising high-intensity treadmill training using the running speed at maximal $O_2$ uptake and the time for which this can be maintained. Eur J Appl Physiol 89(3–4):337–343. doi:10.1007/s00421-003-0806-6

Sperlich B, Engel F, Zinner C (2015) Interventions to modify running economy in middle and long distance runners. Dt Zeitschr Sportmed 66:229–234

Spurrs RW, Murphy AJ, Watsford ML (2003) The effect of plyometric training on distance running performance. Eur J Appl Physiol 89(1):1–7. doi:10.1007/s00421-002-0741-y

Stanton R, Reaburn PR, Humphries B (2004) The effect of short-term Swiss ball training on core stability and running economy. J Strength Conditioning Res/Nat Strength Conditioning Assoc 18(3):522–528. doi:10.1519/1533-4287(2004)18<522:teossb>2.0.co;2

Steinacker JM (1993) Physiological aspects of training in rowing. Int J Sports Med 14(Suppl 1): S3–10

Stoggl T, Sperlich B (2014) Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. Front Physiol 5:33. doi:10.3389/fphys.2014.00033

Stoggl TL, Sperlich B (2015) The training intensity distribution among well-trained and elite endurance athletes. Front Physiol 6:295. doi:10.3389/fphys.2015.00295

Svedenhag J, Sjödin B (1985) Physiological characteristics of elite male runners in and off-season. Can J Appl Sport Sci (Journal canadien des sciences appliquées au sport) 10(3):127–133

Swain DP, Franklin BA (2002) $VO_2$ reserve and the minimal intensity for improving cardiorespiratory fitness. Med Sci Sports Exerc 34(1):152–157

Tabata I, Irisawa K, Kouzaki M, Nishimura K, Ogita F, Miyachi M (1997) Metabolic profile of high intensity intermittent exercises. Med Sci Sports Exerc 29(3):390–395

Taipale RS, Mikkola J, Nummela A, Vesterinen V, Capostagno B, Walker S, Gitonga D, Kraemer WJ, Hakkinen K (2010) Strength training in endurance runners. Int J Sports Med 31 (7):468–476. doi:10.1055/s-0029-1243639

Taipale RS, Mikkola J, Vesterinen V, Nummela A, Häkkinen K (2013) Neuromuscular adaptations during combined strength and endurance training in endurance runners: maximal versus explosive strength training or a mix of both. Eur J Appl Physiol 113(2):325–335. doi:10.1007/s00421-012-2440-7

Tanaka K, Matsuura Y (1984) Marathon performance, anaerobic threshold, and onset of blood lactate accumulation. J Appl Physiol Respir Environ Exerc Physiol 57(3):640–643

Tanaka K, Watanabe H, Konishi Y, Mitsuzono R, Sumida S, Tanaka S, Fukuda T, Nakadomo F (1986) Longitudinal associations between anaerobic threshold and distance running performance. Eur J Appl Physiol Occup Physiol 55(3):248–252

Turner AM, Owings M, Schwane JA (2003) Improvement in running economy after 6 weeks of plyometric training. J Strength Conditioning Res/Nat Strength Conditioning Assoc 17(1):60–67

Viru A (1984) The mechanism of training effects: a hypothesis. Int J Sports Med 5(5):219–227. doi:10.1055/s-2008-1025909

Weltman A, Seip RL, Snead D, Weltman JY, Haskvitz EM, Evans WS, Veldhuis JD, Rogol AD (1992) Exercise training at and above the lactate threshold in previously untrained women. Int J Sports Med 13(3):257–263. doi:10.1055/s-2007-1021263

Wenger HA, Bell GJ (1986) The interactions of intensity, frequency and duration of exercise training in altering cardiorespiratory fitness. Sports Med 3(5):346–356

Wenger HA, Macnab RB (1975) Endurance training: the effects of intensity, total work, duration and initial fitness. J Sports Med Phys Fitness 15(3):199–211

Wilkinson DM (1999) Training for middle and long-distance running. In: Fallowfield JL, Wilkinson DM (eds) Improving sports performance in middle and long-distance running. Wiley, Chichester, pp 69–98

Yeo WK, Paton CD, Garnham AP, Burke LM, Carey AL, Hawley JA (2008) Skeletal muscle adaptation and performance responses to once a day versus twice every second day endurance training regimens. J Appl Physiol 105(5):1462–1470. doi:10.1152/japplphysiol.90882.2008

Yoshida T, Udo M, Chida M, Ichioka M, Makiguchi K, Yamaguchi T (1990) Specificity of physiological adaptation to endurance training in distance runners and competitive walkers. Eur J Appl Physiol 61(3–4):197–201

Zapico AG, Calderon FJ, Benito PJ, Gonzalez CB, Parisi A, Pigozzi F, Di Salvo V (2007) Evolution of physiological and haematological parameters with training load in elite male road cyclists: a longitudinal study. J Sports Med Phys Fitness 47(2):191–196

Zhou B, Conlee RK, Jensen R, Fellingham GW, George JD, Fisher AG (2001) Stroke volume does not plateau during graded exercise in elite male distance runners. Med Sci Sports Exerc 33(11):1849–1854