MAXIMAL AEROBIC CAPACITY, RUNNING ECONOMY, AND PERFORMANCE IN HIGHLY TRAINED MARATHON RUNNERS AND MASTER LONG-DISTANCE RUNNERS

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Dedication

I dedicate this thesis to all of my study participants, who helped me remember that running is a gift.

Abstract

Maximal aerobic capacity (VO_{2max}) and running economy (RE) are key predictors of distance-running performance. Whether VO_{2max} and RE change with marathon-specific training in competitive sub-elite runners is unclear. While VO_{2max} is known to decline with age, RE may be maintained in older runners. PURPOSE: The purpose of this study was to evaluate VO_{2max} and RE at the beginning and end of a marathon training block in highly trained runners. Furthermore, master athletes training for a long-distance running event were evaluated shortly prior to their goal race to investigate relationships between age and running performance variables. Physiological and training factors were assessed to determine predictors of race performance in master runners. Several measures of RE were used. METHODS: In the study of younger competitive runners, participants were studied ~10 and 1-2 weeks before their goal marathons. They logged their workouts throughout a 12-week training period. The study on master athletes was cross-sectional. These runners were surveyed about recent and long-term training patterns. All participants completed a treadmill marathon-intensity effort (MIE) and VO_{2max} test. RESULTS: Among the sub-elite runners, VO_{2max} increased across the training period, while the percent of VO_{2max} used during the MIE decreased. Race performance, quantified using a temperature-converted VDOT score, was negatively correlated with MIE allometrically scaled oxygen consumption (alloVO_2). Among master runners, age was negatively associated with VO_{2max} and alloVO_2. Age was positively related to the MIE energy cost (EC) of running in females and to MIE oxygen consumption (VO_2) in males. The most important predictors of converted VDOT in master runners were VO_{2max} and three-year peak weekly training distance (3YP). Other significant predictors of VDOT were alloVO_2 and EC. CONCLUSION: Experienced open-age marathon runners may experience an increase in VO_{2max} with a block of marathon training. Age is negatively associated with VO_{2max} and alloVO_2 in fit master runners. Long-distance race performance in master athletes is positively associated with VO_{2max}, 3YP, and alloVO_2, and negatively associated with EC. Allometrically scaled MIE VO_2 may therefore be a useful and performance-related measure of RE in trained runners of all ages.

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CHAPTER 1: Introduction

Background

Between 1990 and 2013, marathon popularity has increased greatly: The annual number of marathon finishers in the United States rose over 140%, from 224,000 to 541,000 (Running USA, 2014). Studies on marathon running have tended to focus on novice and/or slower runners, resulting in a dearth of research on highly trained, competitive racers. Experienced runners may continue to improve their marathon times with repeated cycles of marathon-specific training, but the mechanisms that underlie such improvement are unclear. Meanwhile, the increase in participation of older athletes in endurance events has outpaced that of younger counterparts (Lepers & Cattagni, 2012; H. Tanaka & Seals, 2008). However, factors associated with running performance in master long-distance runners is not as well understood as in younger athletes.

Importance of the study

Endurance training improves maximal aerobic capacity (VO_{2max}), enhancing the body's ability to deliver oxygen to exercising tissues (Cornelissen & Fagard, 2005; Hawley & Spargo, 2007; Holloszy & Booth, 1976; Holloszy & Coyle, 1984; Holloszy, Rennie, Hickson, Conlee, & Hagberg, 1977; Jones & Carter, 2000). While this process has been extensively documented in untrained individuals, highly trained athletes may not experience VO_{2max} increases with training, possibly having reached the peak capacity their bodies can attain (Billat, 2001; Davies & Knibbs, 1971). However, using periodized, marathon-specific training, elite marathon runners have been shown to increase their VO_{2max} following high-intensity preparation for a marathon in a previous research study (Billat, Demarle, Paiva, & Koralsztein, 2002).

Other factors besides VO_{2max} may contribute to enhanced performance in competitive runners. Improvements in running economy (RE) are linked to faster running times (Barnes & Kilding, 2015a). In contrast to VO_{2max}, evidence suggests that even highly trained runners can develop better RE through incorporation of plyometrics (Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 2003; Paavolainen, Häkkinen, Hämäläinen, Nummela, & Rusko, 1999; Spurrs, Murphy, & Watsford, 2003) or heavy resistance training (Johnston, Quinn, Kertzer, & Vroman, 1997; Støren, Helgerud, Støa, & Hoff, 2008). Because enhancements in RE are related to faster race times (Saunders, Pyne, Telford, & Hawley, 2004), examining changes in RE that may occur with marathon-specific training may elucidate processes that underlie the improvements in running performance that can come with a marathon-specific training block.

Running economy, the energy required to run at a certain submaximal intensity, has traditionally been measured in VO_2, with units of $ml\,kg^{-1}\,min^{-1}$. Because oxygen cost does not increase linearly with body mass, some have proposed allometric scaling—i.e. body mass to the -0.66 – -0.75 power—has been proposed as a more valid means of evaluating submaximal VO_2 in groups heterogeneous for body size (Barnes & Kilding, 2015a; Berg, 2003). Energy-cost (EC) models may also prove more meaningful than simple VO_2, as they account for the entire caloric cost of running. Such models use respiratory exchange ratio (RER) to determine caloric equivalents and have units of kcal kg^{-1} min^{-1} or kcal km^{-1} min^{-1} (Berg, 2003). A further advantage of EC models is that they can account for speed, enabling comparison of runners of different abilities at the same relative intensity.

With age, VO_{2max} inevitably declines (Reed & Gibbs, 2016), resulting in diminished performance. Running economy, measured as VO_2 at submaximal intensities, may be preserved as runners age and thus not contribute to age-related slowing (Allen, Seals, Hurley, Ehsani, & Hagberg, 1985; Evans, Davy, Stevenson, & Seals, 1995; Quinn, Manley, Aziz, Padham, & MacKenzie, 2011). The relationship between age and other measures of RE, such as allometrically scaled VO_2 or an EC model, has not yet been established. In addition, the majority of running research has studied male runners, meriting an exploration of sex differences in running performance variables among master athletes.

No studies to date have examined physiological changes that occur across a marathon training cycle in sub-elite, experienced marathon runners. Furthermore, the existing body of literature does not include cross-sectional VO_{2max} and RE data from master runners who are near the end of their training for a long-distance goal race. The present study is novel in that it will investigate the physiology and training of competitive younger and older runners and will evaluate RE using more valid measures than appear in the vast majority of prior running research.

Summary and objectives

Competitive runners can continually improve their marathon times, implying that some adaptations must occur, whether from increases in VO_{2max} or from other changes. The nature of these adaptations in highly trained athletes completing a period of marathon-specific training remains to be characterized.

Master runners are a large and growing part of long-distance running events, but relatively little is known about the associations between age and running performance variables in this group, especially in athletes who are in peak shape for a race. The application of alternative models of RE may provide insights into whether older runners truly do not lose economy as they age, or whether decreased efficiency may play a role in diminished performance.

The present study will pursue the following aims:

Chapter one: Characterize the physiological changes that occur across a marathon-training cycle in competitive, experienced runners.

Chapter two: Evaluate the relationships between age and VO_{2max}, and between age and several measures of RE, in master runners who are training for a long-distance race (between 10 miles and a marathon in length).

Chapter three: Determine the most important predictors, including physiological and training factors, of long-distance race performance among master runners.

Significance

Little prior research has been conducted regarding adaptations to marathon training in competitive runners. The present study will investigate physiological changes that may provide the basis for improvement in times that may occur in this population despite extensive previous endurance training. In addition, this study will characterize running performance and training in master athletes of both sexes.

CHAPTER 2: Review of Literature

Variability in physiological and endurance running parameters in response to training

An athlete’s performance in endurance sports depends on the interactions between many and wide-ranging components, from the ambient temperature to his or her mental state to whether his or her equipment is suitable for the terrain. However, physiological aspects of endurance performance largely fall into two overarching categories: the maximal aerobic capacity, and the ability to sustain the highest possible proportion of that capacity for the longest possible time while using the least amount of energy (Barnes & Kilding, 2015b; Basset & Howley, 2000; Costill, Thomason, & Roberts, 1973; Coyle, 2007). While environment certainly plays a role in performance, an athlete’s response to that environment depends largely on physiological factors. Physiology also sets the limits for an endurance athlete’s aerobic power and its translation into training and competition. Training can influence parameters related to speed, power, and economy, but responses to training stimuli can vary greatly between individuals. Therefore, even athletes undertaking identical training programs show differences in performance. The discussion that follows will primarily examine variability in long-distance running but will include examples from other endurance sports where appropriate.

Maximal aerobic capacity

Maximal aerobic capacity, or VO_{2max}, is the maximal rate at which the body can take up oxygen. It has long been recognized as key to performance in endurance exercise, which is primarily aerobic (e.g. (Billat, 2001; Brooks, Fahey, & White, 2005)). Exercise at low to relatively high intensities requires adequate oxygen to maintain aerobic metabolism and provide adenosine triphosphate (ATP) to working muscles (Basset & Howley, 2000; A. V. Hill, Long, & Lupton, 1924; Joyner & Coyle, 2008; Saltin & Astrand, 1967). The highest values of VO_{2max} have been reported in cross country skiers and middle- to long-distance runners (Ingjer, 1991; Saltin & Astrand, 1967), and elite endurance athletes typically have VO_{2max} values of ~70-85 ml kg^{-1} min^{-1} in males and 60-75 ml kg^{-1} min^{-1} in females (Jones, 2006). Improvements in this parameter are often used to show a training program's effectiveness because of its relationship to exercise performance (Basset & Howley, 2000; Timothy D. Noakes, 1988). Possessing a high VO_{2max} is important because competitive distance running requires use of a high fraction of one's maximal capacity, e.g. 90-100% of VO_{2max} in a 10 km race and 75-85% in a marathon (Basset & Howley, 2000; Costill et al., 1973).

Physiological factors affecting maximal aerobic capacity

Maximal aerobic capacity depends on both oxygen transport and extraction and is described by the formula $VO_{2max} = HR_{max} * SV_{max} * (a – v)O_{2max}$, where HR_{max} is maximal heart rate, SV_{max} is maximal stroke volume, and $(a – v)O_{2max}$ is the maximal difference in arterial and venous oxygen content (Powers & Howley, 2009). The cardiovascular and pulmonary systems exert large influences on VO_{2max} through their role in oxygen transport. Cardiac output (Q), the product of heart rate (HR) and stroke volume (SV), is a major determinant of VO_{2max} (A. V. Hill et al., 1924; Jones & Carter, 2000). An athlete with a higher Q will be able to deliver more blood at a faster rate to exercising muscles, thereby enhancing oxygen delivery to and extraction by peripheral tissues. Cardiac output increases with the intensity of exercise to meet the oxygen demands of skeletal muscle. The Q-VO_2 relationship is curvilinear in fit subjects, approaching an asymptotic Q, i.e. an upper limit to exercise intensity (Beck et al., 2006). In less fit and even in highly trained individuals, the augmentation of Q at high intensities is driven largely by increases in HR, while SV plateaus. In a graded treadmill run to exhaustion, a SV plateau occurred in both untrained subjects and Division I distance runners, while SV continued to increase in a group of professional male distance runners (Zhou et al., 2001). Additionally, these professional runners had greater increases in Q than the Division I distance runners, who would certainly be considered high-level athletes. These findings imply that having a high Q during intense exercise, due primarily to the capacity to raise SV, is associated with top-class endurance status. Endurance athletes at the top of their fields may have a mechanism by which their hearts can continually increase SV even at very high intensities, thereby separating them from other highly trained competitors.

Maximal aerobic capacity has both heritable and training-related components. A wealth of information about the heritability of fitness parameters comes from the HERITAGE (HEalth, RIsk factors, exercise Training And GEnetics) Family Study. This study tracked changes in numerous health and fitness outcomes in family units over 20 weeks of endurance training. While these individuals were initially sedentary, not elite athletes, the findings from these studies still provides insight into what separates the good endurance athletes from the best. Before the training intervention, the authors found that approximately 40% of VO_{2max} (i.e. VO_{2max} in a sedentary state) is determined by genetic factors (Bouchard et al., 1998). After training, most subjects improved their VO_{2max} by ~300-500 ml min^{-1}, while some showed a decrease in VO_{2max}; within-family changes in

VO_{2max} had 2.5 times less variance than between-family changes, and the overall heritability of VO_{2max} response in the study cohort was 47% (Bouchard et al., 1999). Thus, untrained aerobic capacity and the response to training are both greatly affected by one's genes. Due to the multifactorial nature of VO_{2max}, many genes are likely involved. However, an athlete whose parents have high VO_{2max} values might also be expected to enjoy a great aerobic capacity, while offspring of parents who respond well to training have a high probability of exhibiting similar improvements.

The HERITAGE studies also showed that changes in Q occur with endurance training. Subjects completed submaximal cycling at a fixed intensity before and after training. Post-training HR decreased and SV increased relative to pre-training, resulting in an overall drop in Q due to the greater magnitude of training-induced change in HR (Wilmore et al., 2001). Sedentary Q and SV were found to be approximately 42 and 41% heritable, while the training responses in Q and SV had 38 and 29% heritability, respectively (An et al., 2000). Other studies have confirmed that VO_{2max} and Q improve with training. For example, after one year of endurance training, previously sedentary subjects experienced a drop in maximal HR and increases in VO_{2max}, Q, SV, and $(a – v)O_2$, with SV increasing proportionately more than Q (Arbab-Zadeh et al., 2014). A meta-analysis of endurance training interventions found that such programs tend to improve VO_{2max} and Q and that these measures are correlated (Montero, Diaz-Cañestro, & Lundby, 2015).

Variability in pulmonary function can also explain some discrepancies in endurance exercise performance. Oxygen from the lungs must diffuse across alveolar membranes into capillaries to reach circulation and be carried to exercising skeletal muscles.

Diffusing capacity of the lung (DL) is related to D_M, the alveolar-capillary membrane conductance, and to V_C, the pulmonary capillary blood volume (Guenard, Varene, & Vaida, 1987; Olson, Snyder, Beck, & Johnson, 2006). Although fitter people tend to have better lung function than unfit people, DL and V_C do not change meaningfully with training (Dempsey & Johnson, 1992), so an athlete may not be able to improve his or her pulmonary function to boost performance. Lung function can limit one's exercise performance: athletes with a high VO_{2max} who exercise at an intensity great enough to meet the full capacity of their pulmonary systems can reach low blood oxygen saturation with exercise. Blood transit time through the lungs drops while blood flow rises, and maximal V_C may not be adequate to supply enough oxygen to the blood to meet muscular demands, thereby limiting VO_{2max} (Dempsey, Hanson, & Henderson, 1984; Dempsey & Johnson, 1992; Joyner, 1993). (Note that it is not airway function but rather gas exchange that causes this limitation on exercise capacity.) Having a strong, large heart is vital for aerobic capacity, but the lungs must be able to keep up with myocardial ability to take advantage of this feature.

Once oxygen from the lungs reaches the blood, it must be transported effectively to working muscles. With endurance training, hemoglobin (Hb) and 2,3-diphosphoglycerate (2,3-DPG) levels increase in the blood (Jones & Carter, 2000). Hemoglobin carries oxygen in erythrocytes, and 2,3-DPG shifts the oxygen-binding curve of Hb to facilitate oxygen release at the tissues (Nelson, Lehninger, & Cox, 2008). Altitude exposure raises levels of 2,3-DPG to ensure that tissues do not become hypoxic due to the low partial pressure of oxygen in the air (Nelson et al., 2008), but 2,3-DPG can also be elevated in other circumstances, e.g. in cystic fibrosis, a disease that causes deterioration of pulmonary function (Orzalesi & Motoyama, 1973). Evidence that blood hemoglobin content affects endurance ability comes from studies of individuals with anemia (low Hb levels), who exhibit decreased aerobic capacity, and of blood doping (taking injections of erythrocytes), which raises VO_{2max} (Gledhill, 1982, 1985). Thus, athletes with high Hb levels, whether from altitude dwelling, blood doping, or inheritance, have an advantage in endurance sports.

Training-related improvements in VO_{2max} are approximately equally related to increased Q and to increased oxygen extraction by muscles (Holloszy & Booth, 1976). Endurance training increases mitochondrial density and oxidative enzyme content in skeletal muscle. Enzymes involved in the tricyclic acid cycle (e.g. succinate dehydrogenase, citrate synthase, and aconitase), the electron transport chain (cytochrome c, cytochrome oxidase), and oxidation of fatty acids (carnitine palmityltransferase, β-hydroxyacylcoA dehydrogenase) all show greater activity in muscle after training (Holloszy & Booth, 1976; Holloszy et al., 1977). Greater levels of these enzymes raise the ability of the mitochondria to take in oxygen during exercise and produce ATP through oxidative metabolism. This evidence suggests that athletes who have relatively large amounts of mitochondria and the enzymes needed for aerobic metabolism should consume more oxygen at peak exercise than others. However, some authors assert that the transport of oxygen to muscles contributes more to VO_{2max} than does mitochondrial consumption of oxygen in skeletal muscle (Basset & Howley, 2000); that is, oxygen supply constrains VO_{2max} more than does oxygen extraction (Jones & Carter, 2000).

Running economy

It would seem as though two athletes with the same VO_{2max} and similar training programs should have equivalent performance in competition: they have experienced the same training stimuli, and their cardiorespiratory systems take in, transport, and use the same volume of oxygen during maximal exercise. However, among elite athletes, VO_{2max} is not the gold standard for predicted performance in the field. Maximal aerobic capacity is negatively correlated with race time in heterogeneous groups (Costill et al., 1973; Mello, Murphy, & Vogel, 1988), but it does not explain variability in performance among athletes with similar VO_{2max} (Assumpção, Lima, Oliveira, Greco, & Denadai, 2013; Costill et al., 1973; Daniels & Daniels, 1992; Don W. Morgan et al., 1995). Instead, running economy (RE) and the speed at lactate threshold dictate the application of aerobic capacity to training and competition. Endurance races do not occur at 100% of VO_{2max} (Basset & Howley, 2000); therefore, the percent of VO_{2max} at which an athlete can exercise for a given distance or time delimits his or her top speed for that setting (Barnes & Kilding, 2015a; Basset & Howley, 2000; Costill et al., 1973). Running economy largely determines this proportion.

Running economy is typically defined as the oxygen cost of running (VO_2), in ml kg^{-1} min^{-1}, for a given submaximal speed, and is used as a proxy for the energy cost of running (Assumpção et al., 2013; Basset & Howley, 2000; Berg, 2003; Don W. Morgan et al., 1995). A runner with a lower energy cost of running will have a higher speed at VO_{2max} and be able to sustain a given pace for longer or run faster for a given duration. Faster runners have better RE on average than slower runners (Joyner & Coyle, 2008; Don W. Morgan et al., 1995), but in runners of similar ability, RE may vary 30-40% at a given submaximal speed (Daniels, 1985; Farrell, Wilmore, Coyle, Billing, & Costill, 1979; Svedenhag & Sjodin, 1985). Intraindividual variation in RE is small, with a coefficient of variance between 1.3 and 2% for moderately- to highly-trained runners (Pereira & Freedson, 1997; Pereira, Freedson, & Maliszewski, 1994), making it a reliable tool for assessment in the laboratory. However, the paradigm of RE is beginning to shift away from the traditional measurement of VO_2. Because VO_2 does not represent the true energy cost of running, a definition including energy is probably more appropriate, e.g. kcal kg^{-1} min^{-1} or $kcal^{-1}$ kg^{-1} km^{-1} (Barnes & Kilding, 2015a; Berg, 2003). Furthermore, VO_2 does not scale linearly with body mass, which should be adjusted with an exponent of -0.67 to -0.75 rather than -1 to account for this allometric relationship (Barnes & Kilding, 2015a; Berg, 2003). Nevertheless, most studies continue to report RE in terms of VO_2.

Several cases illustrate the significance of RE in accounting for variability in performance. In a study of highly-trained male distance runners, the authors note that several subjects had run a two-mile race faster than a previous world record holder at that distance despite having lower VO_{2max} values than he did (Costill et al., 1973). In another case study, two experienced ultramarathon racers were found to have the same VO_{2max}, yet one outperformed the other; he was likely faster because of his superior RE (Costill & Winrow, 1970). Further illustrating the interaction between VO_{2max}, RE, and the fractional use of VO_{2max} is a report on two runners with the same two-mile race times. One man had a high VO_{2max} and low RE, while the other had a low VO_{2max} but high RE (Daniels, 1974). In elite male distance runners, VO_2 at three submaximal speeds was highly correlated with 10 km race time ($r \geq 0.79$) and explained 65.4% of the variance in race time, while VO_{2max} was not significantly related to race time (Conley & Krahenbuhl, 1980). While it can be difficult to improve RE, especially in trained individuals (Jones &

Carter, 2000), a change in RE of 2.2-2.6% is enough to affect performance (Barnes & Kilding, 2015a), and elite athletes including Lance Armstrong and Paula Radcliffe have demonstrated positive development in RE over their careers (Coyle, 2005; Jones, 2006). These studies show that endurance athletes should not neglect a focus on increasing economy to advance their performance.

Physiological factors affecting running economy

Numerous physiological factors affect RE, which relies on multiple systems in the body (Barnes & Kilding, 2015a). The cardiopulmonary factors examined above in the context of VO_{2max} also apply to RE. An athlete who can more efficiently take in and transport oxygen can also employ a lower HR and breathing frequency during exercise, which is associated with lower VO_2 in maximal and submaximal exercise (Bailey & Pate, 1991; D. W. Morgan & Craib, 1992; R. R. Pate, Macera, Bartoli, & Maney, 1989). Stride length and frequency have been associated with RE, but most runners tend to use the most efficient running form for their bodies, making biomechanical generalizations about RE difficult (Barnes & Kilding, 2015a). Therefore, the following discussion of RE will focus primarily on metabolic and muscular contributions to RE. Unfortunately, as is common in the field of exercise science, many studies do not recruit highly trained subjects. It may be difficult to generalize findings from recreationally active or only moderately trained people to elite-level competitors. Nevertheless, it is possible to draw some conclusions about the relationship between RE and athletic performance.

Muscle fiber distribution may affect exercise economy. Type I, or slow-twitch, fibers are more efficient than type II, or fast-twitch, fibers: type II fibers require more ATP than type I due to their high contraction rate (Assumpção et al., 2013; Joyner &

Coyle, 2008; D. W. Morgan & Craib, 1992). Thus, some have postulated that an athlete's muscle fiber types may affect his or her economy. Among competitive male cyclists, those with a high percentage of type I fibers had a higher power output during a one-hour time trial at their maximum sustainable intensity than subjects with a low proportion of type I fibers (Horowitz, Sidossis, & Coyle, 1994). The same group found that the percentage of type I fibers was related to the amount of work done per unit of energy expenditure (Coyle, Sidossis, Horowitz, & Beltz, 1992). In young track and field athletes, submaximal VO_2 was positively related to the percent of type II muscle fibers in the vastus lateralis (Bosco et al., 1987). The authors postulated that the slower cross-bridge cycling in type I fibers allows them to store elastic energy better than type II fibers. Overall, however, there is little evidence to support a major role of fiber type distribution in economy specific to running (D. W. Morgan & Craib, 1992). Moreover, few changes in fiber type occur with endurance training (Holloszy & Coyle, 1984), so improvement in RE over time is likely not related to training-based alterations in fiber type.

Some controversy exists over whether muscle damage affects RE. Unaccustomed and, especially, eccentric exercise causes exercise-induced muscle damage (EIMD), which leads to force impairment and delayed-onset muscle soreness (DOMS) (Assumpção et al., 2013). Injury to myofibril contractile elements could diminish RE if athletes must recruit more motor units to compensate, thereby increasing VO_2 (Berg, 2003). Endurance athletes, particularly runners, experience potentially damaging training on a regular basis—for example, running down long hills. However, a wide range of studies, using subjects of all activity levels, diverse EIMD-inducing protocols, and various RE assessment methods have arrived at diverging conclusions regarding the influence of EIMD and DOMS on RE (W. Braun & Dutto, 2003; Burt, Lamb, Nicholas, & Twist, 2013; Chen, Nosaka, Lin, Chen, & Wu, 2009; Chen, Nosaka, & Tu, 2007; Hamill, Freedson, Clarkson, & Braun, 1991; Kyröläinen et al., 2000; Marcora & Bosio, 2007; Paschalis et al., 2005; Scott, Rozenek, Russo, Crussemeyer, & Lacourse, 2003; Vassilis et al., 2008; Wilcox, Climstein, Quinn, & Lawson, 1989). The literature suggests that if DOMS-associated RE impairments do occur, runners are more likely to have increased VO_2 only at high submaximal intensities (e.g. 90% of VO_{2max}) (Burt et al., 2013), and this increased VO_2 may be related to stride length (W. Braun & Dutto, 2003). The intensity-dependence of RE effects is logical given that type II fibers are more susceptible to EIMD than type I fibers (Assumpção et al., 2013). Considering these findings, two athletes with similar VO_{2max} and RE may perform differently if one has recently undertaken muscle-damaging exercise.

Physiology also mediates the influence of the environment on RE and endurance sport performance. Thermoregulation in hot and/or humid conditions requires energy, and athletes who can control their body temperature efficiently will benefit in such situations. Compared to larger people, smaller people theoretically have a thermoregulatory advantage: they have a larger body surface area-to-mass (BSA: M) ratio and can dissipate more heat through their skin in addition to producing less heat overall (Dennis & Noakes, 1999; Epstein, Shapiro, & Brill, 1983; Wright et al., 2002). It is recognized that elite athletes tend to be smaller than others, as is the case with East African athletes (Berg, 2003). Among elite South African distance runners, black runners were smaller than white runners and could sustain a higher percent of VO_{2max} even when corrected for body size (Coetzer et al., 1993). In athletes running at 15, 25, and 35° C, body mass correlated increasingly with core temperature as ambient temperature rose (Marino et al., 2000).

It is important for endurance athletes to avoid reaching the critical core temperature for fatigue of ~40° C (Nybo & Nielsen, 2001a, 2001b). As with muscle fiber type distribution and EIMD, results conflict regarding whether hyperthermic exercise actually impairs RE. A core temperature increase of 1° C was found to raise VO_2 by 6.2% in a 5 km race (Thomas, Fernhall, & Granat, 1999). In contrast, hyperthermic conditions did not affect VO_2 in other studies (Maron, Horvath, Wilkerson, & Gliner, 1976; Rowell, Brengelmann, Murray, Kraning, & Kusumi, 1969). A study tying together body size and RE found that heat-intolerant subjects had a smaller BSA: M as well as lower efficiency than heat-tolerant individuals (Epstein et al., 1983). In training and competition in warm conditions, smaller endurance athletes may outperform larger athletes, and this discrepancy may be due in part to thermoregulatory effects on RE.

Summary

While performance in endurance sports consists of innumerable elements, not all of them predictable, some physiological variables are useful in explaining the differences in outcomes between apparently similar athletes. Oxygen delivery and transport depend on optimal lung function along with efficient delivery through the blood and uptake in skeletal muscles. Genetic variation in cardiopulmonary function may account for aerobic capacity and the ability to use energy most efficiently. The response of an athlete to training and environment can limit his or her performance if he or she is vulnerable to muscle damage or heat stress. Psychological factors such as pacing strategy undoubtedly contribute to an athlete's success in distance events, and having the proper shoes and clothing can affect times in training and competition. However, the mind can only push the body to the limits of its capability. Therefore, differences in physiological function likely explain a large proportion of the variance in results among elite athletes in endurance sports.

The physiological components of distance running performance and training to improve them

Success in distance running depends on a complex interplay between multiple factors. Optimal nutrition and hydration practices ensure that an athlete can adequately thermoregulate, recover from workouts, and generate energy to fuel muscle contractions during exercise. Meeting training goals and developing appropriate pacing strategies challenge the connection between brain and body. Fundamentally, however, performance stems from an athlete's physiological characteristics. The most important physiological components of distance running performance are VO_{2max}, RE, and lactate threshold (LT)-associated parameters. Although the extent to which training may improve each component differs between athletes, these factors are critical for the long-distance runner and comprise the focus of most training programs.

Training plans are built on the principles of intensity, duration, and frequency (D. J. Smith, 2003). Runners may measure the duration of a workout in terms of length of time, total distance, or both. The intensity of a workout can be determined based on recent race performance, percent of VO_{2max} ($\%VO_{2max}$), percent of the speed at VO_{2max} ($\%vVO_{2max}$), percent of maximal heart rate ($\%HR_{max}$), rating of perceived exertion, blood lactate, or other measures (Midgley, McNaughton, & Jones, 2007). A somewhat more complex method of measuring training, called training impulse (TRIMP), monitors heart rate and performance (Calvert, Banister, Savage, & Bach, 1976). The TRIMP strategy aims to reach maximal performance through phases of more- and less-difficult training based on an athlete's fatigue and training responses. Some endurance athletes employ periodization, in which they undertake such planned periods of greater and lesser training loads to cause stress and recovery. However, Midgley et al. (2007) note that not all top distance runners periodize their training, so this approach may not be required for success in competitive running.

The most common goal of training for endurance runners is to increase the ability to run for longer at a certain speed or to take less time to cover a certain distance (Billat, 2001). To achieve this outcome, athletes must elicit training adaptations, which are beneficial physiological responses to training. To experience lasting training adaptations, athletes must meet or exceed an adaptation threshold. This threshold consists of minimum levels of intensity and duration and is determined by an athlete's prior training (Midgley et al., 2007). To improve VO_{2max}, RE, or LT selectively, an athlete may not need to surpass both intensity and duration thresholds; instead, training can be tailored to meet specific objectives.

Maximal aerobic capacity

The maximal aerobic capacity is the body's peak rate of oxygen uptake and is crucial for endurance exercise, which is primarily aerobic (Billat, 2001; Brooks et al., 2005). Having a high VO_{2max} allows the efficient delivery of a large volume of oxygen to peripheral tissues, facilitating the production of adenosine triphosphate (ATP), which provides energy to working muscles (Barnes & Kilding, 2015b). Since Hill and Lupton (1922) first collected data on oxygen uptake during exercise, VO_{2max} has been studied as a predictor of endurance sport performance (e.g. (Basset & Howley, 2000; A. V. Hill et al., 1924; Joyner & Coyle, 2008; Saltin & Astrand, 1967)). Cross country skiers and distance runners possess the highest values of VO_{2max} (Saltin & Astrand, 1967): 60-75 ml kg^{-1} min^{-1} for females (Jones, 2006) and 70-85 ml kg^{-1} min^{-1} for males (Joyner & Coyle, 2008). A high value of VO_{2max} does not guarantee top-level performance, but it is an important determinant of competitive results in endurance athletes nonetheless.

To review, the maximal aerobic capacity depends on four main factors: diffusing capacity of the lungs, cardiac output, the ability of the blood to carry oxygen, and skeletal-muscle oxygen uptake (Basset & Howley, 2000; A. V. Hill et al., 1924; Joyner & Coyle, 2008). Oxygen from the lungs must diffuse into alveolar capillaries to enter circulation. Once in the blood, oxygen binds hemoglobin (Hb), which carries it to the tissues. Endurance training (Jones & Carter, 2000), altitude acclimation (Assumpção et al., 2013), and blood doping (Gledhill, 1982, 1985) raise blood levels of Hb and thereby increase VO_{2max}. Cardiac output (Q), the product of heart rate (HR) and stroke volume (SV), determines the volume and rate of blood movement from the heart to the peripheral tissues. Because of the upper limit on HR, SV is the main contributor to rises in Q that occur during exercise (Basset & Howley, 2000). Stroke volume and Q increase with endurance training and are major contributors to improvements in VO_{2max} (Arbab-Zadeh et al., 2014; Wilmore et al., 2001). In skeletal muscle, mitochondrial enzymes use oxygen to generate ATP. Endurance training elevates skeletal-muscle oxidative enzyme content and mitochondrial density, increasing the amount of oxygen that muscles can take up (Holloszy & Booth, 1976; Holloszy & Coyle, 1984; Holloszy et al., 1977). According to Holloszy and Booth (1976), approximately half of a training-induced increase in VO_{2max} is due to an increased Q, and the other half comes from augmented muscular oxygen extraction. Evidence suggests that the pulmonary system is not trainable, and the airways that one is born with may therefore limit VO_{2max} (Dempsey, 1986), but training can improve the other factors.

Distance running demands the efficient transport of large volumes of oxygen. As such, VO_{2max} is a predictor of running performance. Among groups of athletes heterogeneous with regard to VO_{2max}, the maximal aerobic capacity can explain variation in race times. Maximal aerobic capacity was negatively related to 10-mile race time in male distance runners ($r = -0.91$) (Costill et al., 1973) and to 2-mile run time in males ($r = -0.91$) and females ($r = -0.89$) (Mello et al., 1988). In a cohort of runners who underwent a VO_{2max} test, ran races of distances from one to 26.2 miles, and provided training data, VO_{2max} was highly associated with race performance at all distances ($r \leq -0.91$), whereas training volume and intensity were not as important to performance (Foster, 1983). Training measures may still contribute to race times, however, as Hagan, Smith and Gettman (1981) found that marathon time in male runners was inversely associated with both VO_{2max} and training mileage, distance, and number of workouts. Among male distance runners with VO_{2max} values ranging from 46.3 to 73.7 ml kg^{-1} min^{-1}, their maximal aerobic capacity predicted race time at 3.2-, 9.7-, 15-, and 19.3-km races (Farrell et al., 1979). The time to complete a 4.7-mile race in a group of male collegiate cross country runners was negatively related to relative (ml kg^{-1} min^{-1}) and absolute (ml min^{-1}) VO_{2max} (Costill, 1967).

Others have suggested that VO_{2max}-related measures better predict performance than the maximal aerobic capacity alone. The percent of VO_{2max} at which a runner can exercise determines the speed at which he or she can complete a race (Barnes & Kilding, 2015b). As Costill (1972) notes, marathon runners tend to have a high VO_{2max} but exhibit a large degree of variation in race time. The ability to run using a large $\%VO_{2max}$ is therefore more important to race outcomes than only the value of an athlete's VO_{2max}. Notwithstanding a runner's $\%VO_{2max}$ for a given race distance, a high absolute VO_{2max} is still important: in a marathon race, top runners will use 75-85%VO_{2max}, and in a 10-km race, this fraction increases to 90-100% (Basset & Howley, 2000; Costill et al., 1973). Athletes with a deeper well from which to draw, so to speak, will have an advantage during competitions.

The speed associated with VO_{2max} is also related to running performance. A group of elite runners preparing to compete in an Olympic Trials Marathon completed a marathon-pace run and a VO_{2peak} test on a flat road (Billat, Demarle, Slawinski, Paiva, & Koralsztein, 2001). (The authors use the notation of "peak" rather than "max" because the test was undertaken on a flat road rather than using an inclined treadmill.) While VO_{2peak} differed between the faster and slower groups of males and was associated with a faster marathon race time, VO_{2peak} did not distinguish between the classes of female athletes. Furthermore, speed during the VO_{2peak} test was a better predictor of marathon time in this group than was VO_{2peak} alone. Noakes, Myburgh, and Schall (1990) have also found that maximal running speed during a treadmill VO_{2max} test is a good predictor of distance running performance.

Regardless of the relative importance of $\%VO_{2max}$ and vVO_{2max} to running performance, increasing VO_{2max} will also increase these measures. To improve VO_{2max}, an athlete needs to reach or supersede and sustain the intensity associated with VO_{2max}. This stress on the cardiorespiratory system can cause adaptations. Reaching a high volume and pressure in the heart can cause a lasting increase in SV, which is the main factor resulting in improvement in VO_{2max} in trained people (Midgley et al., 2007). Both maximal and supramaximal (i.e. above VO_{2max} intensity) exercise may increase VO_{2max}. A common method used to improve VO_{2max} is interval training (IT). This type of training alternates periods of exercise at or above the LT (which will be discussed below) with periods of recovery (either rest or light activity) (Billat, 2001). Intervals may be short (15-30 seconds) or long (one minute or more). Interval training allows athletes to spend more time at a high intensity than if they attempted to run continuously, thereby increasing the stimulus for training adaptations (Koralsztein & Billat, 2000). Some athletes use very short, supramaximal, anaerobic intervals with long recovery periods to train for muscular power, which contributes to peak running speed. Short but still aerobic intervals with equal recovery (e.g. 15 seconds hard with 15 seconds jog recovery) allow runners to sustain a very high VO_2 without the lactate (La) accumulation that would occur during a constant effort at that intensity (Billat, 2001). Runners completing long aerobic intervals must ensure that the rest period is long enough for phosphocreatine stores to be replenished and La to be cleared but short enough to maintain a high VO_2 (Billat, 2001).

The positive effects of IT in individuals of lower training status are well documented. In one study, a group of untrained subjects performed either continuous cycling at 50% of maximum work output or IT (30 seconds at the maximum work rate with equal recovery at full rest) (Gorostiaga, Walter, Foster, & Hickson, 1991). The continuous-cycling group exhibited greater improvement in muscle oxidative capacity, as measured through an increase in the activity of the oxidative enzyme citrate synthase, and slower La accumulation during continuous cycling. The IT group, however, showed more improvement in VO_{2max}, peak power output, and work rates, demonstrating that high-intensity training is associated with better performance at high intensities (Gorostiaga et al., 1991). In a study by Fox, Bartels, Billings, O'Brien, Bason, and Mathews (1975), a group of untrained males completed either four days per week or two days per week of IT. The group training four days per week undertook short sprints (two sessions), longer intervals (one session), and both short and long intervals (one session). The other group completed one session of short sprints and one session of short and long intervals each week. Both groups increased mean VO_{2max}, and there was no difference in improvements between groups. These findings illustrate that training at a high intensity, rather than the duration or frequency of exercise, is important in improving VO_{2max} (Fox et al., 1975). In a third study, active males trained three days per week for eight weeks in one of four exercise groups: long, slow distance runs; LT runs; short intervals; or long intervals (Helgerud et al., 2007). The IT groups improved VO_{2max} and SV, but the other groups did not.

Trained runners may also show improvement in VO_{2max}- related parameters with IT. In two similar studies, middle- and long-distance runners trained at vVO_{2max} over a period of four weeks (Billat, 2001; T. P. Smith, McNaughton, & Marshall, 1999). The duration of the intervals in these protocols was 50-75% of the time to reach exhaustion at this speed. After the training intervention, the subjects had increased their vVO_{2max}. In the study by Smith et al. (1999), subjects also improved in VO_{2max} and 3-km time trial (TT) speed. These findings show that even trained runners can develop a higher vVO_{2max} over a relatively short time, which may benefit their race performance. Furthermore, such workouts are useful from a coaching perspective, as they are relatively simple to personalize to each athlete (Billat, 2001; T. P. Smith et al., 1999).

However, even with high-intensity (≥ 90% VO_{2max}) training, athletes might not be able to increase VO_{2max} (Billat, 2001; Davies & Knibbs, 1971). For instance, over a year of training, collegiate female runners increased the time to exhaustion (TTE) at VO_{2max} and decreased 5-km race time with no change in VO_{2max} (Berg, Latin, & Hendricks, 1995). Highly trained, elite athletes may reach the maximum trainability of their aerobic capacity. Elite distance runners stratified by performance were tracked over four years of training and racing (Legaz Arrese, Ostáriz, Mallen, & Izquierdo, 2005). While both classes improved their race performance, only runners in the lower tier increased their VO_{2max}. This finding shows that other factors besides VO_{2max} are important in determining running performance. Similarly, Paula Radcliffe, the world record holder in the women's marathon, did not improve her VO_{2max} over fifteen years despite running ever faster races (Jones, 1998). Nevertheless, it may be possible for elite runners to increase their VO_{2max} with such training. Billat, Demarle, Paiva, and Koralsztein (2002) observed that elite marathoners who incorporated running at speeds at or above 10-km race speed during an eight-week period of marathon preparation showed an improvement in VO_{2max}. This result may occur in periodized training in which a block of high-intensity training as part of a taper elicits VO_{2max} increases (Billat et al., 2002). In this case, the observed augmentation of VO_{2max} is likely more related to seasonal fluctuations than from a longer-lasting physiological adaptation.

In contrast, submaximal training may also increase VO_{2max}. A study of untrained subjects compared the effects of IT and continuous training (CT) (Henriksson &

Reitman, 1976). Subjects performed three sessions per week of either IT (five sets of four minutes at 101% VO_{2max}) or CT (steady exercise at 79% of VO_{2max}) for 7-8 weeks. Only the CT group increased VO_{2max}. Moreover, for nine months, well-trained male runners added one 60-minute workout per week at the intensity corresponding with their individual LTs (K. Tanaka et al., 1984). These subjects did improve VO_{2max} as well as 5-km and 10-km race times and maximum velocity. However, the subjects increased their training mileage at the same time as the addition of this LT run, so it is unclear whether this specific submaximal exercise session or the higher volume caused their performance changes. In another study, among master male long-distance runners, performing IT at the maximal lactate steady state (MLSS; a slightly higher intensity than the LT) twice a week for six weeks induced a small increase in VO_{2max} (Billat, Sirvent, Lepretre, & Koralsztein, 2004). Nevertheless, the extent to which highly competitive distance runners can increase VO_{2max} is likely small.

Running economy

Running economy is a second crucial factor in distance-running success; therefore, specific training considerations are necessary to improve RE. As mentioned previously, running economy is the energy cost of running at a given submaximal speed and is typically measured by VO_2 in $ml\,kg^{-1}\,min^{-1}$ (Assumpção et al., 2013; Barnes & Kilding, 2015b; Basset & Howley, 2000; Berg, 2003; Don W. Morgan et al., 1995; Saunders et al., 2004). A person with better RE has a lower VO_2 at a given speed.

This definition of RE has two flaws. First, VO_2 does not scale linearly with body weight; a smaller runner will use proportionally more oxygen than a larger runner, and RE that is not scaled for body weight will artificially inflate the oxygen cost of running for smaller people. Body mass should be raised to a power of -0.67 to -0.75, not -1, to reflect the allometric increase of VO_2 with mass (Barnes & Kilding, 2015a; Berg, 2003). Second, the oxygen cost of running does not accurately reflect the energy cost of running: substrate use affects VO_2 because more oxygen is required to oxidize lipids than carbohydrates. A runner who efficiently oxidizes lipids while running—which is a widely recognized glycogen-sparing adaptation beneficial to marathon runners—would appear to be a less economical runner based solely on VO_2. A more accurate reflection of energy cost would be measured in units of kcal kg^{-1} min^{-1} or kcal km^{-1} min^{-1} (Berg, 2003). These limitations affect the interpretation of most RE-related studies. One cannot compare the RE of a group of runners heterogeneous with respect to body mass if VO_2 is not scaled accurately. In addition, endurance training promotes the oxidation of lipids during exercise, which raises VO_2 (e.g. (Holloszy et al., 1977)). Using VO_2 to determine the utility of a training intervention can obscure metabolic adaptations that actually enhance the efficiency of running by increasing reliance on lipids, an essentially unlimited fuel supply.

Despite these issues, RE is still a valuable predictor of distance running performance. Faster runners have better RE on average than slower runners (Joyner & Coyle, 2008; Don W. Morgan et al., 1995). Basset and Howley (2000) note that endurance running does not typically occur at 100% of VO_{2max}, so submaximal VO_2 better predicts performance than VO_{2max} does. A person with better RE than another has a faster vVO_{2max} (Daniels & Daniels, 1992), which also determines running performance (Jones & Carter, 2000). Moreover, having better RE allows a runner to use a higher $\%VO_{2max}$ for a given distance (Costill, 1972). Running economy is also linked to the LT, as runners with better RE tend to be faster at the speed associated with LT (vLT) and have a lower VO_2 at the LT (Midgley et al., 2007).

Importantly, and in contrast to VO_{2max}, RE can account for performance differences between athletes of a similar VO_{2max} (Assumpção et al., 2013; Burgess & Lambert, 2010; Costill et al., 1973; Daniels & Daniels, 1992; Don W. Morgan et al., 1995). Among elite male distance runners, RE (VO_2) at three submaximal speeds was highly correlated with 10-km race time ($r \geq 0.79$), while VO_{2max} was not significantly related to race time (Conley & Krahenbuhl, 1980). In another example involving two runners with the same VO_{2max}, the athlete with the superior RE also had faster race times (Costill & Winrow, 1970). In two runners with similar two-mile race speeds, one had a high VO_{2max} and low RE, while the other had the opposite relationship between these variables (Daniels, 1974).

Improving RE is associated with better race performance (Saunders et al., 2004); a change in RE of 2.2-2.6% can meaningfully affect performance (Barnes & Kilding, 2015a). Also in contrast to VO_{2max}, RE seems to be more trainable, even in highly trained athletes. Ten elite male distance runners showed an increase in RE over a year of training (Svedenhag & Sjodin, 1985). Furthermore, the aforementioned women's marathon record holder lowered her VO_2 at 16 km/h by 15% over a fifteen-year period while increasing her vVO_{2max} by 3 km/h (Jones, 2006). Similarly, Lance Armstrong, a six-time Tour de France winner, improved his muscular efficiency by 8% in eight years (Coyle, 2005). Jones and Carter (2000) point out that it can, however, take a long time to improve RE substantially, especially in already highly trained athletes.

Many factors influence RE, which relies on the musculoskeletal, neuromuscular, metabolic, and cardiopulmonary systems (Barnes & Kilding, 2015a). A runner using relatively more fat for fuel will have a higher VO_2 than one oxidizing carbohydrates. Substrate selection, as well as muscle damage and energy demands of thermoregulation, may explain the elevated VO_2 seen in trained runners after completing a marathon (Kyröläinen et al., 2000). With endurance training, oxidative enzyme activity increases in muscle, requiring less oxygen to generate enough ATP to fuel running at a given speed. This adaptation contributes to better RE (Saunders et al., 2004) and may explain why long-distance runners and more highly-trained athletes tend to have better RE than others (Barnes & Kilding, 2015b; Burgess & Lambert, 2010; Midgley et al., 2007; Saunders et al., 2004; Svedenhag & Sjödin, 1984). Exercise-induced muscle damage may also impair RE through detrimental effects on the stretch-shortening cycle in muscle and a need to recruit more motor units to compensate for damaged fibers (Burgess & Lambert, 2010).

Many biomechanical factors contribute to having high RE, including being just above average height with small feet and pelvis, having a low percent body fat, having stiff lower-leg musculotendinous junctions, adopting a favorable stride over years of training, and having moderate flexibility (Barnes & Kilding, 2015a; Saunders et al., 2004). Larger horizontal and vertical forces during running are associated with worse RE and slower 3-km time in elite endurance athletes (Støren, Helgerud, & Hoff, 2011). It appears that musculotendinous stiffness (MTS) is vital to having good RE; this property facilitates the storage and use of elastic energy while running, which can lower submaximal VO_2 (Burgess & Lambert, 2010).

Because resistance and plyometric training can increase MTS and cause other running-related benefits, training-intervention studies have frequently focused on how such regimens might affect RE and performance in runners. For example, elite male orienteers did either nine weeks of explosive training (jumps with and without added weight, sprints, and high-speed lifting) or normal training (Paavolainen et al., 1999). The explosive-training group improved RE, speed during a maximal anaerobic running test (vMART), 5-km TT time, and some measures of explosive strength. Speed in the MART was correlated with RE improvement ($r = 0.55$). The authors postulate that vMART, an indicator of muscular power, reflects neuromuscular adaptations that benefit submaximal and race-pace running. Explosive training may act on vMART by making elastic energy storage and use more efficient (Paavolainen et al., 1999). The same group studied the effects of nine weeks of explosive strength training on endurance athletes (Paavolainen et al., 2003). The subjects improved RE along with 5-km TT time and vMART. Improvement in TT performance was related to the changes in RE and vMART, strengthening the evidence that explosive training aids in the development of RE and running ability at faster speeds (Paavolainen et al., 2003). In two studies of highly trained distance runners, plyometric training decreased 3-km TT time and increased MTS (Spurrs et al., 2003) as well as maximal dynamic strength performance (Saunders et al., 2006); RE improved in both cohorts. Plyometric training has repeatedly shown no detrimental effects on body mass or VO_{2max}, making it a potentially useful training method to enhance RE.

Heavy weight training may also augment RE. For example, a cohort of female distance runners performed either endurance training only or heavy strength training three days per week in addition to endurance training for 10 weeks (Johnston et al., 1997). The strength-trained group improved RE, whereas the endurance-only group did not. Moreover, the VO_{2max} and body composition in the intervention group did not change. In a similar study, one group of triathletes underwent heavy weight training along with normal training, while a second group did only normal training (Millet, Jaouen, Borrani, & Candau, 2002). Maximal concentric lower-limb strength and RE increased in the strength-trained athletes only, and no effects on VO_{2max} were observed. In a more recent study, trained male and female runners performed maximal strength training three times per week for eight weeks (Støren et al., 2008). A control group only undertook regular endurance training. In contrast to the control group, in which no performance-related improvements occurred, the strength-trained group increased RE and TTE in a submaximal running test. A strength of this study is that the authors scaled body mass to the power of -0.75, making the RE measurements more valid (Støren et al., 2008).

A combination of plyometric and strength training may also be effective in improving running performance, as a study by Barnes, Hopkins, McGuigan, Northuis, and Kilding (2013) found. For seven to 10 weeks, collegiate cross country runners added two sessions of either plyometrics alone or plyometrics plus heavy resistance training. While the plyometric-trained athletes decreased ground contact time, only the runners who also performed resistance training increased RE and peak speed. This intervention occurred during the cross country season, demonstrating that runners can safely add strength-training programs to a competition schedule. Runners willing to try an unorthodox approach to improving RE might be interested to learn that backward running has recently emerged as a method of enhancing performance. A group of highly trained male runners did backward running on a treadmill for 15 to 19 minutes over 10 weeks

(Ordway, Laubach, Vanderburgh, & Jackson, 2016). Compared to baseline, runners had a higher post-intervention forward-running RE without any change in VO_{2max}. Currently, however, the majority of the literature regarding increasing RE in trained athletes supports the inclusion of strength training, whether through explosive movements or through heavy lifting, to improve this variable.

Lactate threshold

A third vital component of distance running consists of a set of factors related to blood lactate levels. As exercise duration and intensity rise, so does lactate in the blood. Exercise physiologists have delineated lactate thresholds above which exercise performance is limited. When exercise intensity reaches a certain level, aerobic metabolism does not supply sufficient energy, and anaerobic metabolism contributes more significantly to ATP production. At this anaerobic threshold, exhaled carbon dioxide increases, and muscles produce more lactate as glycolysis causes pyruvate to accumulate (Anderson & Rhodes, 1989). Athletes cannot sustain performance in this zone indefinitely because fuel sources for anaerobic metabolism (carbohydrates) are limited, and metabolic waste products can cause muscular fatigue (Anderson & Rhodes, 1989; Basset & Howley, 2000; Timothy D. Noakes, 1988; K. Tanaka, 1990).

Several terms are used to refer to speeds and lactate levels associated with athletic performance (K. Tanaka, 1990). The LT (also called the aerobic or anaerobic threshold, or AT) is the lactate level at which lactate begins to rise above resting levels. The running speed associated with the LT is sometimes called the onset of plasma lactate (OPLA). (The term “OPLA” can denote the level of lactate preceding an increase or the speed at which this elevation occurs.) At this speed, lactate can be removed as quickly as it is produced, and metabolism is still almost entirely aerobic. Above the OPLA, lactate rises exponentially, whereas increases in lactate below the OPLA are approximately linear. For practical purposes, the OPLA and vLT may be considered interchangeable. The maximal steady state (MSS) refers to the speed, heart rate, or VO_2 associated with blood lactate levels of 2.2 mmol/L. This intensity can be sustained for a relatively long time and increases as fitness develops. At the onset of blood lactate (OBLA), the concentration of lactate in the blood is 4 mmol/L. The vOBLA is the speed at which lactate reaches this concentration (K. Tanaka, 1990).

Although lactate itself does not result in fatigue (Lamb & Stephenson, 2006) or affect excitation-contraction coupling in working muscles (Posterino, Dutka, & Lamb, 2001), the onset of lactate accumulation signals the beginning of an exercise intensity that can only be maintained for a relatively short time. As such, the intensity at which anaerobic metabolism begins is associated with distance running performance. Top-level athletes do not begin to accumulate lactate until relatively high intensities, allowing them to exercise for longer at a higher fraction of VO_{2max}. Because of this relationship, the OPLA predicts distance-running performance at least as well as vOBLA or vVO_{2max} (Sjödin, Jacobs, & Svedenhag, 1982; K. Tanaka, 1990).

For instance, in experienced male distance runners, OPLA was correlated with performance in races from 3200m to the marathon ($r \geq 0.91$) (Farrell et al., 1979). The OPLA and VO_2 at the LT, which is typically at 70-75% of VO_{2max}, are highly correlated with marathon speed (K. Tanaka & Matsuura, 1984). While some have found that the vOBLA, which occurs at 85-90% of VO_{2max}, predicts marathon speed, Tanaka and Matsuura (1984) assert that this parameter is more closely linked to speed in five- to 15-

km races. Endurance training, which increases the oxidative capacity of muscle at a given intensity, results in less lactate production and raises the LT. Increasing the LT is associated with better distance-running performance (Holloszy & Coyle, 1984; Holloszy et al., 1977; Ivy, Withers, Van Handel, Elger, & Costill, 1980; Midgley et al., 2007). In highly trained individuals, OPLA may not occur until 75-90% of VO_{2max} (Joyner & Coyle, 2008). A high OPLA is relevant to marathon performance because marathon runners compete at a speed only slightly above OPLA (Farrell et al., 1979). Among elite male runners with similar personal best times for the marathon (~2:12), blood lactate level at a speed of 10 km h^{-1} best predicted marathon time (Legaz Arrese, Munguía Izquierdo, & Serveto Galindo, 2006). Other variables, including VO_{2max} and body composition measures, were not significant predictors of performance. Interestingly, however, in female elites (~2:34 for the marathon), subscapular skinfold value was a better predictor of marathon time than any running performance factor (Legaz Arrese et al., 2006).

Training to improve the LT may result in superior running performance. Returning to the example of Paula Radcliffe, over five years, she decreased blood La levels at given speeds, increased OPLA, and also ran faster races (Jones, 1998). A range of submaximal training protocols has proven effective in increasing LT-associated parameters in runners. A group of male distance runners added an extra 20-minute run per week at vOBLA for 14 weeks (Sjödin et al., 1982). After the study period, the athletes increased vOBLA and also showed evidence of greater skeletal muscle oxidative capacity. In another study, runners completed 20-minute sessions at either the LT or vOBLA six days per week for eight weeks (Yoshida et al., 1990). The athletes who trained at vOBLA improved in 3-km performance as well as vLT, vOBLA, and VO_2 at OBLA, whereas no changes occurred in the LT group. In contrast, training at the LT has been shown to improve performance in some individuals. Male middle-distance runners added a biweekly 60- to 90-minute run at the LT for four months (K. Tanaka et al., 1986). After the intervention, runners increased their vLT, VO_{2max}, and VO_2 at the LT, showing that they could exercise at a higher intensity before the onset of anaerobic metabolism. They also improved their 10-km race times. However, observed improvements may have been due to the 25-35 extra km of training mileage per week and not specifically related to the LT runs.

Further support for the importance of improving the LT comes from a study by Acevedo and Goldfarb (1989). Trained male distance runners added weekly intensity sessions of one IT workout at 90-95% of HR_{max} and two fartlek (speed-play) workouts near 10-km race pace. They completed easy runs on the remaining days of the week and maintained their pre-intervention mileage. After eight weeks, the athletes had lower lactate levels at 85 and 90% of VO_{2max} and faster 10-km race times, which were correlated with observed changes in La ($r = 0.69$ and 0.73, respectively). No changes in VO_{2max} occurred (Acevedo & Goldfarb, 1989). Moreover, master runners who trained at the MSS for six weeks also demonstrated performance increases. These athletes completed biweekly MSS workouts and improved both MSS speed and TTE at MSS (Billat et al., 2004). Interestingly, explosive resistance training might also be useful in enhancing LT-associated measures. In a study by Hamilton, Paton, and Hopkins (2006), distance runners undertook jumps and treadmill hill sprints 10 times over five to seven weeks. A performance-matched control group did their habitual training. The intervention group improved more in vLT, peak speed, 5-km TT time, and predicted 800- and 1500-m time than the controls. These studies show that relatively long workouts near the LT, MSS, or OBLA effectively improve both the LT and performance in trained runners; more intense and even supramaximal training could also prove beneficial, although there is less evidence to support its use.

Summary

Maximal aerobic capacity, RE, and the LT are intimately connected. A higher RE allows an athlete to use a lower fraction of VO_{2max} and to have lower lactate levels at a given speed (Saunders et al., 2004). A runner with a high absolute VO_{2max} has a competitive advantage only if he or she is efficient enough to exercise at a large fraction of that capacity, which also depends on the intensity at which skeletal-muscle lactate production begins to exceed lactate clearance. Fortunately, although VO_{2max} is not easily improved in already trained runners, evidence-based methods to increase RE and the LT abound. Explosive training and heavy weightlifting have shown promise in improving RE even in highly trained athletes. Moreover, the addition of long bouts at or near the OPLA, MSS, or vOBLA can raise the speed at which lactate accumulation limits exercise. Case studies support the relationship between improvement in these parameters and increased distance-running performance, but longer-term studies are necessary to track physiological and performance changes over the course of years and careers. Nevertheless, the majority of the literature suggests that incorporation of the types of interventions outlined above can benefit the competitive distance runner.

Endurance exercise and master athletes

Changes in participation and performance of master athletes

Master athletes are individuals over the age of 35 or 40 years, depending on the sport in which they partake. In recent decades, participation among master athletes in marathons (Lepers & Cattagni, 2012) and other endurance and ultra-endurance events (e.g. Ironman triathlons) (Lepers & Stapley, 2016) has increased. In fact, in such events, participation of athletes over the age of 50 has risen more than in younger age groups (Lepers & Cattagni, 2012; H. Tanaka & Seals, 2008), and masters can make up more than half the field in marathons and ultra-marathons (Lepers & Stapley, 2016).

Notably, performance in the masters category has improved more than in younger runners. For example, between 1980 and 2009 in the New York City Marathon, average finishing times for the top 10 runners in each age group decreased only for females at least age 45 and males at least age 60. During this time, the size of the race expanded, with masters contributing the most to this growth. Masters also increased as a proportion of finishers (Lepers & Cattagni, 2012). In such events as the Western States 100-Mile Endurance Run and Ironman triathlons, elites have gotten older, and older athletes have gotten faster (Lepers & Stapley, 2016).

Several possible reasons exist for this increase in participation in long-distance running events. Middle-aged athletes may have more time and money to devote to training than when they were younger and access to high-quality athletic facilities. Additionally, training strategies encompassing both endurance and muscular strength components, coaching, and better nutritional practices may also aid master athletes (Lepers & Stapley, 2016). Older adults may participate in athletics for fitness and stress relief, to travel, for health benefits, because of social opportunities that sport provides, or simply because they enjoy exercising (Reaburn & Dascombe, 2008). However, masters also must deal with obstacles to training that may not affect younger runners, such as family and work responsibilities, difficulty in finding a coach, and a lack of motivation to train and compete (Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2008). If an older athlete can overcome these psychological and sociological barriers, he or she can pursue high-level competition.

Sex differences in endurance-event participation and performance are also changing. Males typically comprise the majority of finishers in these events; furthermore, the gap in best finishing times is about 12-20% greater than the approximately 10% that physiological differences would predict (Hunter & Stevens, 2013; Reed & Gibbs, 2016). Yet growing numbers of females are entering such races, affecting the male-to-female ratio and sex gaps in performance. In their analysis of the New York City Marathon from 1980 to 2009, Lepers and Cattagni (2012) observed that the number of female finishers rose more than that of male finishers; this pattern held in masters age groups as well. The sex differences in finishing times shrank among the top 10 in all age groups (Lepers & Cattagni, 2012). In a cross-sectional study of a 56-km race, times slowed with age in both sexes, while the sex gap got smaller (M.I. Lambert & Keytel, 2000). In ultra-marathon distances, sex differences in performance might be smaller than in shorter races.

Hunter and Stevens (2013) also observed that the male-to-female ratio of the top 10 age-group finishers at the New York City Marathon fell between 1980 and 2010, with the largest changes occurring in the older age groups. However, as age increased, so did the proportion of male participants and the sex-related difference in pace (Hunter & Stevens, 2013). The authors proposed that differences in participation between males and females, which increase with age, were the primary contributors to the increased speed difference in older runners (Hunter & Stevens, 2013). While the New York City Marathon may not precisely represent all endurance races, similar trends are likely occurring at other events. As younger female runners who have grown up with access to competitive running age into masters, it will be interesting to see how these patterns change.

Changes in endurance performance with age

Performance in endurance events declines with age, but the timing and magnitude of such decrements, as well as sex differences in performance, varies depending on many factors. In an athlete's mid- to late 30s, running performance in events from 10k to the marathon begins to decline by approximately 6-9%/decade, and times increase more rapidly after the late 50s. After age 70, endurance performance falls at an even steeper rate (Brisswalter & Nosaka, 2013; Brisswalter, Wu, Sultana, Bernard, & Abbiss, 2014; Joyner, 1993; Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2003, 2008). In the marathon and half marathon, times are expected to increase 2.6-4.4% per decade between ages 50 and 69 for the top age-group athletes (Brisswalter & Nosaka, 2013). Encouragingly, however, others have found that half and full marathon times don't change meaningfully until after age 50 in both sexes, at least for non-elite racers (Leyk et al., 2007). (This group also found that athletes placing in the top 10 at these distances in races in Germany started to slow after age 35 (Leyk et al., 2007).) In national-caliber masters track and field athletes, performance decreased more sharply in field events than track events and in longer than shorter running races, and females experienced greater decrements than males (Chopra & Tanaka, 2003). Different aspects of performance, such as peak power output or endurance capacity, may decline at different rates and in a sport-specific manner (Brisswalter et al., 2014). Even in highly trained athletes, age-related decreases in performance are inevitable.

The primary cause of worsening endurance performance with age is a decrease in VO_{2max} that begins around age 25 (Reed & Gibbs, 2016). As previously discussed, VO_{2max} is a key predictor of outcomes in long-distance running. Among master athletes of both sexes, VO_{2max} may be the best predictor of distance running performance (Wiswell et al., 2000). As discussed above, maximal aerobic capacity is equal to the product of maximal cardiac output and maximal arteriovenous oxygen difference: $VO_{2max} = Q_{max} * (a - v)O_{2max}$. Maximal cardiac output is the product of maximal heart rate (MHR) and maximal stroke volume (SV_{max}) (Powers & Howley, 2009). Investigators have shown that each component of VO_{2max} decreases with age (Gerstenblith, Lakatta, & Weisfeldt, 1976; Joyner, 1993; Maharam, Bauman, Kalman, Skolnik, & Perle, 1999). It is worth noting, however, that research has consistently shown that older athletes of both sexes have higher VO_{2max} values than sedentary peers because of, for example, their higher blood volume (Stevenson, Davy, Roiling, & Seals, 1994) and other adaptations from endurance training.

Factors contributing to decreased VO_{2max} with age

The fall in Q_{max} contributes most to the decrease in VO_{2max} across all aging populations (Fuchi, Iwaoka, Higuchi, & Kobayashi, 1987; Hawkins & Wiswell, 2003; Maharam et al., 1999; H. Tanaka & Seals, 2008), with a fall in MHR playing a major role (Hawkins & Wiswell, 2003; Joyner, 1993; Lepers & Stapley, 2016; Reaburn & Dascombe, 2008). In trained male cyclists, MHR was strongly and negatively correlated with age ($r = -0.75$) (Balmer, Potter, Bird, & Davison, 2005). Another study focusing on high-level male cyclists found that a lower MHR was a primary cause of decreased

VO_{2max} with age (Capelli, Rittveger, Bruseghini, Calabria, & Tam, 2016). The age-associated reduction in maximum oxygen pulse, which is equal to VO_{2max}/MHR, may account for 80% of the decrease in VO_{2max} with age (Katzel, Sorkin, & Fleg, 2001). Maximum heart rate falls with age even in individuals who were elite athletes at a younger age (Dill, Robinson, & Ross, 1967) and in highly trained, competitive master runners (Hagberg et al., 1985; Pollock, Foster, Knapp, Rod, & Schmidt, 1987).

In a meta-analysis of females of a range of activity levels, all groups had a similar decline in MHR of 7-8 beats per minute (bpm)/decade, and MHR was related to VO_{2max} in all groups, explaining at least 56% of the age-relate variability in VO_{2max} (Fitzgerald, Tanaka, Tran, & Seals, 1997). In healthy, moderately active females and males, the heart rate response to increasing workload decreased with age. At peak workload, older people had a lower MHR but the same Q as younger subjects, demonstrating a higher SV to compensate for the smaller MHR (Rodeheffer et al., 1984). Healthy endurance-trained and sedentary males in a cross-sectional study showed a decrease of approximately 1 bpm/year in MHR (Katzel et al., 2001). Supporting these results, a cross-sectional study of endurance-trained females found that MHR decreased by 0.92 bpm/year (Wiebe, Gledhill, Jamnik, & Ferguson, 1999). However, participants' SV_{max} fell with age. Sex differences in the physiology of aging might account for this discrepancy. Other studies have found smaller decrements in MHR with age, from 0.62 (Pimentel, Gentile, Tanaka, Seals, & Gates, 2003) to 0.66 (Balmer et al., 2005) to 0.73 (Pollock et al., 1997; Trappe, Costill, Vukovich, Jones, & Melham, 1996) bpm/year; the true rate is likely between 0.5 and 1.0 bpm/year, depending on exercise testing modality and subject group.

Reaburn and Dascombe (2008) note that MHR decreases with age in both sexes at similar rates regardless of physical activity (PA) level by approximately one bpm/year after age 10, and Tanaka and Seals (2008) report a similar decline of 0.7 bpm/year. Londeree and Moeschberger (1982) found that accurate prediction of MHR depends on age as well as exercise modality and fitness level. In a group of competitive female master runners ages 35-70, MHR did not differ between age groups, leading the authors to suggest that training can attenuate decreases in MHR (Wells, Boorman, & Riggs, 1992). However, others have noted the MHR falls similarly regardless of activity level (Lepers & Stapley, 2016; Pimentel et al., 2003; H. Tanaka et al., 1997). Therefore, age is an important consideration in determining one's MHR, while the role of fitness is less clear.

Several factors contribute to the age-related decline in MHR. With age, the amount of connective tissue in the heart (e.g. elastic tissue and fat) increases and might alter cardiac signaling, thereby lowering MHR (Gerstenblith et al., 1976). Moreover, older hearts are less responsive to the exercise-induced β-adrenergic stimulation that increases both heart rate and myocardial contractility (Lakatta, 1979; Rodeheffer et al., 1984). This loss of sensitivity may be due to a reduced ability of β-agonists to bind receptors, as receptor density seems to be preserved (Seals, Taylor, Ng, & Esler, 1994). Aging is also associated with a loss of sarcoplasmic calcium ATPase, which takes up calcium from muscle cells and allows relaxation to occur. This decrease in ATPase activity elongates cardiac relaxation time, which limits how fast the heart can beat. However, exercise can slow down the loss of sarcoplasmic calcium ATPase (Maharam et al., 1999).

The other component of Q_{max}, SV_{max}, typically declines with age in both sexes (Ogawa et al., 1992). This decrease can be greater in master athletes than in their sedentary peers (Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2003). Maximal stroke volume may decline with age as arteries become less compliant, which happens in both athletes and sedentary people (Reed & Gibbs, 2016; H. Tanaka & Seals, 2008). Aging arteries show a diminished capacity for vasodilation independent of atherosclerosis, thereby elevating peripheral resistance. An increase in arterial stiffness raises peripheral resistance, increasing the work that the heart must do and limiting its ability to raise Q during exercise. This stiffening is likely due to alterations in vascular connective tissue, namely, a reduction of the function and integrity of elastin and an elevation of the amount of collagen in blood vessels (Gerstenblith et al., 1976).

However, trained older athletes still have higher exercise values of SV (and, thus, Q) than less fit peers (McLaren, Nurhayati, & Boutcher, 1995; McLaren, Nurhayati, & Boutcher, 1997). McLaren and colleagues (1997) also note that older people may have relatively higher SV than younger people to compensate for the age-related decreased sensitivity to β-adrenergic activation that lowers exercise heart rate. Another study tested male distance runners an average of 21.8 years apart. In these subjects, the group that maintained high fitness and continued racing were able to maintain their SV over that time (Trappe et al., 1996). A similar study of top older runners and faster and performance-matched younger runners found that there was no between-group difference in SV either at submaximal or peak exercise (Hagberg et al., 1985). Therefore, training habits might be able to prevent a shrinking SV with age.

Peripheral factors contribute to the fall in $(a - v)O_2$ that occurs with age. This measure depends on oxygen delivery and extraction. Age-related losses of lean body mass (LBM) may reduce the amount of oxygen that skeletal muscle can extract from the blood (Hawkins & Wiswell, 2003; Lepers & Stapley, 2016). With age, sedentary people experience a loss in muscle oxidative capacity (i.e., oxygen extraction) via decreases in capillary size, which limits the amount of oxygen available to muscles; mitochondrial uncoupling; and/or diminishment of oxidative enzyme activity (Reaburn & Dascombe, 2008). In endurance-trained individuals, by contrast, $(a - v)O_2$ more likely decreases because of changes in oxygen delivery, not extraction (Fitzgerald et al., 1997; Gerstenblith et al., 1976; Lepers & Stapley, 2016; H. Tanaka & Seals, 2008). It is also possible that $(a - v)O_2$ does not decline with age (Wiebe et al., 1999), especially in athletes who maintain training regimens with age (Adachi et al., 1991; Fuchi, Iwaoka, Higuchi, & Kobayashi, 1989). While some have claimed that a smaller $(a - v)O_2$ is the major cause of decreased VO_{2max} with aging (Grimby, Nilsson, & Saltin, 1966), the majority of studies do not support this assertion.

Sarcopenia, the loss of muscle mass with age, diminishes muscular strength (Reed & Gibbs, 2016) and may also alter aerobic capacity through effects on $(a - v)O_2$, as discussed above. Sarcopenia begins around age 50 or 60 and causes progressive decreases in strength, with approximately 15% lost between ages 50 and 70 and 30% between ages 70 and 80; 40% of total skeletal muscle is lost by age 80 (Booth, Weeden, & Tseng, 1994). Similarly, in a review, Brisswalter and Nosaka (2013) found that strength falls by 15-35% after age 60, with larger losses after age 65 even in trained athletes.

Muscular strength decreases because of the loss of muscle cross-sectional area (Maharam et al., 1999). Type II muscle fibers are lost preferentially, while type I fibers are preserved (Booth et al., 1994; Brisswalter & Nosaka, 2013; Maharam et al., 1999;

Reaburn & Dascombe, 2008). Because type II fibers are important for power and explosive strength, this shift in fiber type has negative consequences for power-related measures (Brisswalter & Nosaka, 2013). Motor units begin to degenerate and lose function around age 50 (Booth et al., 1994). Even formerly elite distance runners lose LBM and gain body fat with age (Dill et al., 1967). According to Booth and coworkers (1994), sarcopenia has greater effects on overall health than the age-associated decrease in VO_{2max}.

Resistance training, however, can mitigate sarcopenia (Booth et al., 1994; Maharam et al., 1999), and runners who incorporate resistance training might have better running performance than those who don’t (Maharam et al., 1999). In a longitudinal study, Trappe and colleagues (1996) observed that a group of male distance runners who maintained at least some training over time did not lose LBM an average of 21.8 years after initial tests, while both those who were at least age 60 and those who stopped exercising did lose muscle mass. Female and male master runners who were tested at least five years apart did not significantly decrease LBM, showing that endurance training alone might be able to attenuate age-related changes in body composition (Marcell, Hawkins, Tarpenning, Hyslop, & Wiswell, 2003). Strength training is also recommended for the general population to increase LBM (Hawkins & Wiswell, 2003). While resistance training causes hypertrophy of type I and II fibers and can increase the proportion of type II fibers, endurance training helps to maintain type I fiber size, proportion, and function, so a balanced training program is important for preserving muscular health in older athletes (Brisswalter & Nosaka, 2013).

Muscle mass may be related to VO_{2max}, and sarcopenia may contribute to age-related decreases in endurance ability. Interestingly, endurance-trained master athletes might have weaker and smaller muscle fibers than sedentary controls, but this difference is actually adaptive, as it results in a shorter distance for oxygen to diffuse to muscle fibers (Reaburn & Dascombe, 2008). However, sarcopenia overall has negative effects on endurance-sport performance. Middle-aged and older male cyclists showed decreased submaximal power output with age, but this difference disappeared after adjustment for muscle cross-sectional area (Izquierdo et al., 2001). This finding suggests that loss of aerobic exercise capacity is due to shrinkage of muscle volume rather than to changes in muscle function.

Moreover, in a group of male and female master runners, LBM was correlated with VO_{2max} (Wiswell et al., 2001). Both declined with age, implying that muscle mass does play a role in endurance ability. Healthy non-endurance-trained females and males showed a loss of more than 22% of skeletal muscle mass with age between participants aged 30-70, as well as a decrease in VO_{2max}. The authors demonstrated that sarcopenia explained more than half of the age-associated decline in VO_{2max} (Fleg & Lakatta, 1988). Another performance marker, anaerobic capacity, is key for sprints and surges during longer events. In male cyclists, anaerobic power decreases with age, most likely because of sarcopenia and the shift toward type I muscle fibers (Capelli et al., 2016). These results highlight the importance of maintaining muscle mass for master athletes.

The rate of age-related declines in VO_{2max}

That VO_{2max} decreases with age is clear, but determining the rate at which it falls has been contentious. Several age-related confounders have complicated the search for the true rate of decline: body fat tends to increase, PA levels often decrease, the age at initial testing affects this rate, and older people are at a higher risk for diseases that affect their ability to exercise (Buskirk & Hodgson, 1987; Fitzgerald et al., 1997; Hagberg, 1987; Hawkins & Wiswell, 2003; Hodgson & Buskirk, 1977; Joyner, 1993; Katzel et al., 2001; Lepers & Stapley, 2016; Maharam et al., 1999; Reaburn & Dascombe, 2008; Reed & Gibbs, 2016; H. Tanaka & Seals, 2003, 2008; Wilson & Tanaka, 2000).

Whether a study is cross-sectional or longitudinal also affects the observed rate of decline in VO_{2max}, as noted by Dehn and Bruce (1972). Participants in cross-sectional studies are likely to be fitter and healthier than their peers because sick or unfit people are unwilling to undergo exercise testing (Dehn & Bruce, 1972; Hodgson & Buskirk, 1977). However, as Hawkins and Wiswell (2003) point out, subjects in longitudinal studies might die or drop out before follow-up. Longitudinal studies are likely more valid than cross-sectional ones and show a higher rate of decline in VO_{2max} (Hawkins & Wiswell, 2003). Nevertheless, both are subject to selection bias, and controlling for all factors affecting fitness with age is improbable.

A paper by Dill and coworkers (1967) presented case studies of elite male distance runners. These athletes underwent exercise and body-composition testing when they were young and then 18-54 years later. On average, VO_{2max} fell by 1.06 ml kg^{-1} min^{-1} $year^{-1}$. However, the subject who had the lowest rate of decrease by far—only 0.41 ml kg^{-1} min^{-1} $year^{-1}$—was the one who had maintained a high level of training (Dill et al., 1967). A study from 1972 by Dehn and Bruce used both cross-sectional and longitudinal analysis to evaluate the rate of decrease in VO_{2max} in healthy males. They determined that the cross-sectional rate of decline was 0.28 ml kg^{-1} min^{-1} $year^{-1}$, or about 8.5%/decade, while the longitudinal rate was 0.94 ml kg^{-1} min^{-1} $year^{-1}$, a decrease of about 26%/decade.

Moreover, more active subjects always had a higher VO_{2max} than sedentary counterparts, and their aerobic capacity decreased only half as fast (Dehn & Bruce, 1972). A longitudinal study of mostly active females and males found that VO_{2max} fell by approximately 10% per decade (Åstrand, 1960). Importantly, participants had maintained their average body mass, so both relative and absolute VO_{2max} showed the same rate of decrease (Åstrand, Åstrand, Hallbäck, & Kilbom, 1973).

In a longitudinal study of healthy, fairly active females and males (Asmussen, Fruensgaard, & Nørgaard, 1975), the authors reported lower rates of VO_{2max} decrease than Åstrand and colleagues (1973) or Dehn and Bruce (1972). Supporting this finding, in a group of females of varying fitness levels, VO_{2max} declined by approximately 0.32 ml kg^{-1} min^{-1} $year^{-1}$, similar to the cross-sectional rate taken from the same group at follow-up 3.5-9 years later. The decrease in maximal aerobic capacity in these participants did not depend on their level of habitual PA (Plowman, Drinkwater, & Horvath, 1979). The authors of these papers did not provide the percent decrease per year or decade. A cross-sectional study by Fleg and Lakatta corroborating these values tested active non-athletes and found that VO_{2max} decreased each year by 0.25 ml kg^{-1} min^{-1} in females and 0.39 ml kg^{-1} min^{-1} in males. There was no sex difference in the rate of decline as percent of VO_{2max} at age 30 (7.5% and 9.6%/decade for females and males, respectively) (Fleg & Lakatta, 1988). Furthermore, healthy inactive males showed a decrease in VO_{2max} of around 9%/decade in a cross-sectional investigation (Heath, Hagberg, Ehsani, & Holloszy, 1981). Female master athletes have shown a similar fall in VO_{2max} with age. Female national age-group-champion runners lost approximately 8.3%/decade between the ages of 25 and 55, while remaining at fitness levels much higher than sedentary controls (Stevenson, Davy, & Seals, 1994). Both male and female master runners lost aerobic capacity at a rate of approximately 10%/decade in a cross-sectional analysis, with race times slowing similarly between sexes (Wiswell et al., 2001). In a longitudinal study of master runners of both sexes, the authors found a somewhat higher rate of VO_{2max} decrease of approximately 15%/decade, or 1.0 ml kg^{-1} min^{-1} $year^{-1}$ (Marcell et al., 2003). However, in general, it seems that healthy people from a range of fitness levels will experience a decrease in VO_{2max} of approximately 8-10% per decade.

Some studies suggest that endurance training might attenuate this age-related drop in fitness. For example, Rogers and coworkers (1990) conducted a six- to 10.5-year longitudinal study of male distance runners and cyclists and healthy controls. The athletes showed a decrease in VO_{2max} of around 5.5%/decade; the rate observed in the sedentary controls was 12.3%. The authors suggest that the smaller decline in athletes was due to their ability to maintain the number of training sessions per week, and that the decrease would have been smaller if they had also kept up weekly mileage, intensity, and duration (Rogers et al., 1990). Similarly, males participating in an Olympic-distance triathlon showed a mitigation of the age-associated decline in VO_{2max} (Sultana et al., 2012). In this cross-sectional comparison, VO_{2max} decreased by only 6.8%/decade; the authors attribute this finding to the heavy training that all the athletes undertook (Sultana et al., 2012).

A long-term training intervention in active males underscores the role of regular exercise in maintaining endurance capacity (Kasch et al., 1999). This group of 15 mostly non-athletes undertook an endurance training regimen that lasted up to 33 years. They did VO_{2max} tests every few years and kept training logs. Over time, the subjects lowered the intensity of their workouts but compensated by raising duration and frequency. By the twenty-fifth year, VO_{2max} in the participants had decreased by only 6%/decade. Furthermore, the decline was non-linear, with a steady drop until 15 years and then a plateau. Participants were also able to maintain body composition and had lower blood pressure than expected based on their ages (Kasch et al., 1999). A longitudinal study of male runners divided participants at follow-up into those who no longer raced or trained heavily and those who still trained at a similar pace and competed regularly (Pollock et al., 1987). After a mean of 10.1 years, the competitive group did not have a significant decrease in VO_{2max}, while the decline was approximately 8.7% in the less active males. The maintenance of oxygen pulse (VO_{2max}/MHR) along with VO_{2max} implies that the competitive athletes also preserved SV_{max} and/or their capacity for oxygen extraction (Pollock et al., 1987). These results suggest that a vigorous training program undertaken in middle age—and adjusted to compensate for reductions in certain aspects of training load—can attenuate the decline of VO_{2max} with aging.

In a cross-sectional study, male runners ages 30-80 had a rate of decrease in VO_{2max} of 6.9%/decade; again, this relatively low value may be due to their training habits, which were matched across all ages (Fuchi et al., 1989). Participants in this study also held body composition constant, another factor that contributes to the preservation of aerobic capacity (Fuchi et al., 1989). Another cohort of male distance runners showed similar rates of VO_{2max} decline between those who did some training and no training (15%/decade), while athletes who remained competitive and trained vigorously had an only 6%/decade rate of decrease (Trappe et al., 1996). In a comparison of sedentary and endurance-trained males, both groups showed a similar relative rate of decrease in VO_{2max} of around 11%/year, while the athletes had a higher absolute rate (-5.4 vs. -3.9 ml

kg^{-1} min^{-1}) (Pimentel et al., 2003). Importantly, VO_{2max} was related to training volume and 10-km race time (Pimentel et al., 2003). The age-related decrease in training may be responsible for the faster loss of VO_{2max} in athletes; there is not necessarily an intrinsic factor related to being an athlete that causes this discrepancy between PA groups.

Others have demonstrated that VO_{2max} can decline with age more steeply in endurance athletes than in less active people. A group of male athletes and sedentary controls were tested at baseline and then eight or nine years later (Katzel et al., 2001). Cross-sectional data taken at the initial visit predicted a similar rate of decrease of 0.42 and 0.43 ml kg^{-1} min^{-1} $year^{-1}$ for these groups, but at follow-up, athletes had lost 1.46 ml kg^{-1} min^{-1} $year^{-1}$ (29%/decade), whereas the rate among controls was 0.48 ml kg^{-1} min^{-1} $year^{-1}$ (15%/decade). When the athletes were stratified by current exercise levels, those who had maintained heavy training showed a decrease of only 5.8%/decade, while subjects who completely stopped training lost 47%/decade (Katzel et al., 2001). A male distance runner who was tracked by investigators from age 27 to age 64 demonstrated above-expected decreases in speed from 10-km to 90-km races despite remaining healthy (M. I. Lambert et al., 2002). The authors assert that his large declines in performance may have occurred because he lessened his training load over time (M. I. Lambert et al., 2002).

Moreover, male track athletes tested at 10 and 20 years after baseline demonstrated distinct rates of decline depending on their training. Runners who performed high-intensity training lost an average of 11.5%/decade from their VO_{2max}, and those who did only low-intensity exercise lost 26%/decade (Pollock et al., 1997). Therefore, changes in training with age can have a major impact on how fast fitness decreases. Athletes who are in peak physical form at initial testing but reduce their training as they age may show rates of decrease in VO_{2max} much greater than the expected 10%. This trend is also seen in other studies of former high-level athletes, like that of Dill and colleagues (1967), and in other sports besides running, e.g. rowers and kayakers (Ładyga, Faff, & Burkhard-Jagodzińska, 2008).

In contrast, the interaction between age and training in females may differ from males. Healthy sedentary females and endurance athletes showed that while athletes had a higher absolute amount of decrease in VO_{2max}, both groups had a similar rate of decline of 9-10%/decade (H. Tanaka et al., 1997). The authors note, as will be discussed below, that a "baseline effect" might explain these findings: people with a high VO_{2max} at initial testing have more to lose than sedentary, low-VO_{2max} individuals (H. Tanaka et al., 1997). Among top age-group female master distance runners and sedentary peers, the athletes lost absolute VO_{2max} more than twice as fast but at the same relative rate of 15-18%/decade (Eskurza, Donato, Moreau, Seals, & Tanaka, 2002). While the full-group results imply that training might not be able to prevent a decline in VO_{2max} in females, the authors note that in the athletes in this study, the decrease in VO_{2max} was closely related to the observed age-related decline in training volume ($r = 0.63$). Therefore, if the athletes had maintained their training with age, they might have slowed their loss of fitness (Eskurza et al., 2002).

In contrast to some research in males, a study by Plowman and coworkers (1979) observed that active females did not show a faster decrease in VO_{2max} than sedentary peers. The rate from this longitudinal investigation was unexpectedly not larger than predicted based on cross-sectional data. However, the authors note that less fit subjects may have dropped out, and most participants neither decreased PA nor increased body mass (BM) over the course of the study (Plowman et al., 1979). These considerations may have biased the sample group at follow-up toward females with higher cardiorespiratory fitness. Importantly, this study, like others in which healthy subjects have maintained exercise levels and body mass over time, shows that there is some unavoidable decline in VO_{2max} with age.

Given such conflicting results regarding the rate of decline in VO_{2max} with age, it is not surprising that reviews and meta-analyses have also arrived at different conclusions regarding this value. Hodgson and Buskirk (1977) propose that exercise training can at least mitigate, if not prevent, some age-related decrease in VO_{2max}. They also hold that sedentary people experience a steeper decline in VO_{2max} than active people do. In a later review, these authors discuss confounders in determining the rate of decrease in VO_{2max} (Buskirk & Hodgson, 1987). Notably, longitudinal studies have provided a much larger range of possible rates because they are dependent on PA status and changes in training levels. In males, it seems that sedentary people have a fast rate of decline in VO_{2max} at a younger age than athletes, but then experience a plateau. In contrast, the rate in active people drops more slowly until after age 60, when PA tends to diminish and fitness decreases rapidly: the baseline effect.

Due to the relative dearth of studies on females, it is difficult to assess whether sex differences exist in the rate of decrease of fitness with age. However, the authors claim that the true rate of VO_{2max} decrease in all people must be around 0.4 ml kg^{-1} min^{-1} $year^{-1}$, because a higher rate would leave sedentary people with an unrealistically low fitness level by age 50 or 60 (Buskirk & Hodgson, 1987). Further complicating this matter is the tendency of people to gain fat mass and lose LBM as they age. In a review of training, VO_{2max}, and aging, Hagberg and coworkers (1987) note that endurance training can mitigate declines in absolute VO_{2max}, which depends on the inverse of body mass, by preventing weight gain.

Moreover, based on studies in which older male runners were matched with younger runners for training and performance at similar ages, VO_{2max} in highly active older males seems to decrease by only 5%/decade, half as much as the 10%/decade that is the consensus value for sedentary males. This argument is logical, as the authors extrapolate backward from males aged 60-70 who had VO_{2max} values of 59-61 ml kg^{-1} min^{-1}. If their VO_{2max} had decreased by 10%/decade, they would have had VO_{2max} of more than 85 ml kg^{-1} min^{-1} at age 25; based on their performance at that age, that was not the case (Hagberg, 1987).

Joyner (1993) agrees that male athletes may have a smaller drop in VO_{2max} of only 6-9% as they age. He qualifies this assertion by adding that if athletes stop training (presumably at a fairly young age), they will lose 9-10% of their VO_{2max} per decade, similar to sedentary people. Moreover, Maharam and coworkers (1999) hold that VO_{2max} decreases by 10%/decade in sedentary people but only 5%/decade in highly trained masters. They attribute this discrepancy to numerous factors interacting synergistically: engaging in high-intensity and –volume training; remaining normotensive; expending a large amount of energy; maintaining a healthy BM; having a high cardiac reserve; and being genetically lucky (Maharam et al., 1999). While master athletes might be able to meet these requirements, it is perhaps not entirely realistic to expect most older competitors to fulfill all of them.

A meta-analysis by Wilson and Tanaka (2000) more specifically examines the role of training factors in the age-related decrease in VO_{2max}. Male subjects were classified based on habitual activity levels. The authors observed no difference in the rate of decline of VO_{2max} between fitness groups. However, among endurance athletes, VO_{2max} was strongly related to training speed ($r = 0.91$) and weekly mileage ($r = 0.73$). Endurance-trained males also decreased their speed and mileage with age. Therefore, the authors suggest that a reduction in training likely has a large effect on the decline of VO_{2max} with age in endurance-trained males (Wilson & Tanaka, 2000).

Aging females might be subject to the same baseline effect that causes male athletes who reduce their training to experience a steep drop in VO_{2max}. A meta-analysis of sedentary, active, and endurance-trained females found that athletes had the largest absolute decline in VO_{2max} with age, approximately 6.2 ml kg^{-1} min^{-1} $decade^{-1}$, while sedentary people had the smallest, 3.5 ml kg^{-1} min^{-1} $decade^{-1}$(Fitzgerald et al., 1997). This finding is in contrast with that of Wilson and Tanaka (2000), in which the absolute rate of decline did not depend on PA level. The authors here attribute this difference to changes in training that the athletes made with age. However, as a percent of peak VO_{2max}, all groups lost around 10-11% per decade (Fitzgerald et al., 1997). It is important to note that this analysis does not show that females cannot maintain VO_{2max} with training as males can: this was a cross-sectional report, and the authors did not examine age-related training alterations.

A review by Hawkins and Wiswell (2003) describes reasons for the discrepant findings on the rate of VO_{2max} decrease with age. Cross-sectional research has seemed to show that athletes have a rate of loss around half as great as in active and sedentary peers:

5% vs. 10%/decade. However, the studies suggesting this difference had small sample sizes and were subject to selection bias: older people willing to complete maximal exercise tests are more fit than the general population. Longitudinal studies also tend to support a rate of decrease in VO_{2max} of approximately 10%/decade but also show that athletes can have a higher rate than in less active people. The authors explain that the aging process can make it increasingly difficult for athletes to maintain the training programs they used when they were younger (Hawkins & Wiswell, 2003). Keeping up intense exercise can help slow down a loss of fitness. When training decreases, the decline in VO_{2max} is steeper than in sedentary adults because it represents training effects plus normal aging effects. In addition, the age of testing at baseline and follow-up is important, as older masters tend to show a faster decrease in VO_{2max} than younger athletes. The authors also address sex differences in fitness changes with age. Due to age-related changes in sex hormones, it is possible that females cannot use training to slow VO_{2max} decreases as males can (Hawkins & Wiswell, 2003).

Tanaka and Seals (2003, 2008) corroborate these assertions in two reviews on aging and fitness. There seems to be a similar rate of absolute VO_{2max} decrease between sedentary and endurance-trained males, while in females, the rate in athletes may be higher. However, the authors state that both males and females have the same relative rate of decline in VO_{2max} (as percent of peak) regardless of PA status (H. Tanaka & Seals, 2003, 2008). Decreases in training stimulus as older people reduce their exercise levels are most likely responsible for observed rates of $VO2_{2max}$ decline that are faster in endurance athletes than in others. A diminished training load would reduce the oxidative capacity of skeletal muscle as well as SV_{max}. Moreover, the baseline effect helps to explain why endurance athletes, who have a high VO_{2max} at a young age, have an above-expected rate of loss of VO_{2max}. When expressed as a percent of initial VO_{2max}, endurance-trained and sedentary people of both sexes exhibit similar rates of decrease in fitness (H. Tanaka & Seals, 2003).

Reaburn and Dascombe's 2008 review supports these concepts as well as the flaws in study design (selection bias, alterations in training, age of testing, and cross-sectional vs. longitudinal studies) that Hawkins and Wiswell note in their 2003 paper. Regardless of these issues, a value of approximately 10%/decade has arisen as a probable true rate of decline in VO_{2max} with age, not accounting for changes in PA or BM. More research is needed to clarify sex differences and evaluate the extent to which cessation of training elevates the rate of loss of fitness in former high-level athletes.

Additional predictors of performance in master distance runners: lactate threshold and running economy

While VO_{2max} can predict performance in master runners (Wiswell et al., 2000), other parameters might change with age and be related to running performance in this group. With age, VO_{2max} decreases relatively more than overall performance does, suggesting that LT and running economy (RE) fall less than VO_{2max} does (H. Tanaka & Seals, 2003). Some studies have been done to evaluate parameters associated with the lactate threshold (LT) in master athletes. The LT affects distance running ability in elites of all ages and both sexes (Joyner, 1993). It tends to fall with age but is maintained or even increased when measured as a percent of VO_{2max} because maximal aerobic capacity decreases more rapidly than the LT does (Joyner, 1993; Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2003, 2008). As discussed above, LT parameters are valid predictors of distance running performance in younger athletes and can improve with training. It is worthwhile to consider the role of these parameters in master runners as well.

A study by Allen and colleagues (1985) compared performance factors in three groups of male distance runners: top age-group masters, young runners who were matched to the masters by 10-km race time, and faster young runners. The masters and matched young runners had the same VO_2 and speed at LT (defined here as 2.5 mM of blood lactate). However, because masters had a lower VO_{2max}, they reached LT at a higher percent of VO_{2max}. Interestingly, the fast young runners and the masters ran at the same percent of VO_{2max} at LT despite the younger males being faster. At 10-km race speed, the masters and fast young athletes did not differ in their percent of VO_{2max}, and both were at higher levels than the slower young runners. The masters could also run about the same speed as the matched younger runners despite having a 9% lower VO_{2max}. The authors propose that the master runners could work at a higher percent of VO_{2max} at their LT and race pace than the matched young runners because the older athletes—who would have been faster than these younger athletes at the same age—had maintained capillarization and functionality of their muscle oxidative enzymes with age. Other factors besides VO_{2max} must also be important for performance in master runners (Allen et al., 1985).

Another cross-sectional study supports the idea that master runners maintain relative LT with age. Cohorts of young, middle-aged, and older male distance runners were matched for age-group-rankings, body composition, and weekly mileage (Iwaoka, Fuchi, Higuchi, & Kobayashi, 1988). Such matching is a major strength of this investigation. The authors measured VO_{2max} and onset of blood lactate (OBLA), the VO_2

at which lactate increases quickly above baseline. They observed that the older runners had a lower absolute OBLA, but there were no differences when expressed as percent of VO_{2max}. The older athletes had a lower VO_{2max} and slower race times than the younger males. Oxygen consumption at OBLA and VO_{2max} were correlated with 5-km race time (r = -0.59 – -0.803) in all groups, and VO_{2max} and VO_2 at OBLA were also associated (r = 0.603 – 0.816) (Iwaoka et al., 1988). Therefore, VO_2 at OBLA can be used to predict performance in male master runners. In runners with the same relative performance (in contrast to Allen et al. (1985), who matched by absolute performance), LT can occur at the same percent of VO_{2max} across a runner's career.

To determine which physiological factors contribute to distance running performance in older runners, Tanaka and coworkers (K. Tanaka, Takeshima, Kato, Niihata, & Ueda, 1990) tested older competitive male runners to determine their VO_{2max} and several LT-related parameters. Lactate threshold was defined as the intensity at which lactate began to increase non-linearly. A weakness of this study is that the authors used cycle ergometry despite having only runners as subjects. Running economy was also not tested here. The authors found that the best predictors of race speed in 5-km, 10-km, and marathon races were age and the VO_2 at LT. Because the VO_2 at LT can improve with training more than VO_{2max} can, this study implies that a training intervention targeting this outcome can result in faster distance races (K. Tanaka et al., 1990).

The lactate threshold is also important in female master runners. In female runners of varying ages in a 1995 study (Evans, Davy, Stevenson, & Seals), 10-km race speed was positively associated with the speed at LT (where La rose above baseline levels), VO_2 at LT, and VO_{2max} (r = 0.89, 0.84, and 0.89, respectively). Like the study by Iwaoka and coworkers (1988), these runners were matched by age-adjusted 10-km race time. Among these female athletes, VO_{2max} explained 74% of the variability in 10-km race performance in the oldest age group (ages 49-56), and speed at LT explained 60% in the younger two cohorts (ages 23-47). The authors postulate that these factors are the most important in the decrease in running performance with age in females. The relative importance of each changes with age, as VO_{2max} matters more than LT in older runners (Evans, Davy, Stevenson, Reiling, & Seals, 1995).

In contrast, a cross-sectional evaluation of male and female master runners did not find consistent relationships between LT parameters and running performance (Wiswell et al., 2000). The authors conducted VO_{2max} tests and defined the LT as the point where the plot of lactate against time changed slope; they also determined VO_2 at 2.5 and 4.0 mM La. A regression model to predict performance found that the most important factors in females were weekly mileage and VO_{2max}; VO_2 at LT was a significant predictor only for the 5k and 10k, not for the marathon. In males, the best predictors were age, weekly mileage, and VO_{2max}. The authors did observe that LT as a percent of VO_{2max} increased with age. However, VO_{2max} remained a better predictor of running performance in both sexes (Wiswell et al., 2000). Another cross-sectional study by Wiswell and colleagues (2001) found conflicting results about the LT in older runners. Lactate threshold as percent of VO_{2max} did not change with age in females, while it increased in males (Wiswell et al., 2001). In both studies, the authors did not match participants for performance, which may explain their findings in light of those from the aforementioned studies that did support LT parameters as meaningful to performance in master runners.

A later cross-sectional study supported the finding of no change in LT with age.

The authors defined LT as the speed where lactate increases by 1 mM twice in a row (Quinn et al., 2011). Among competitive distance runners of both sexes and a wide range of ages, the speed at which LT occurred decreased with age. However, there was no difference in LT as percent of VO_{2max} with age, and VO_{2max} was only lower in the oldest group, in which athletes were at least age 60. These results demonstrate that factors related to distance running performance show different patterns of diminishment with age (Quinn et al., 2011).

To clarify the relationships between LT parameters and performance, Marcell and coworkers (2003) conducted a longitudinal study of master runners. Participants of both sexes completed exercise testing about 5-6 years apart; the LT was measured as the point where lactate increased above steady-state levels. There were no sex differences in VO_2 at LT as a percent of VO_{2max} or in changes to this variable with age: As a percent of VO_{2max}, LT increased. Notably, LT was not related to 10-km race time in either sex. The authors credibly assert that changes in LT parameters occur because of reductions in VO_{2max} (Marcell et al., 2003).

The lactate threshold is related to RE: Athletes with an LT as a higher percent of VO_{2max} also have high RE. A 2008 study (Burtscher, Förster, & Burtscher) shows that this relationship holds in older runners as well as younger athletes. They measured VO_2 at the LT, which depends on both VO_{2max} and the percent of VO_{2max} at which LT occurs. The authors tested participants in a masters mountain running championship and calculated VO_2 at LT, where respiratory exchange ratio remained at or above 1.0. Race time increased and VO_2 at LT decreased, with both changes not evident until age 49, which is later than in other distance runners. The authors claim that mountain running must depend heavily on VO_2 at LT and thus on RE (Burtscher et al., 2008).

Less research has been done on RE in master athletes. The literature to this point suggests that RE might be preserved with age. In their 1985 study, Allen and colleagues compared RE in the older and matched younger runners at a fixed submaximal speed of 188 m/min (7.0 mph). There was no difference in VO_2 or percent of VO_{2max} between groups at this speed (Allen et al., 1985). Similarly, there may be no relationship between RE and age in females. Among competitive female runners, age was not correlated to RE, which was measured as VO_2 at an individual's 10-km race pace and at a fixed speed of 10 km/h (6.2 mph) (Evans, Davy, Stevenson, Reiling, et al., 1995; Evans, Davy, Stevenson, & Seals, 1995). Running economy at race pace did not occur at a different percent of VO_{2max} between age groups, leading the authors to propose that RE is maintained with age in trained runners and does not play a role in performance declines with age (Evans, Davy, Stevenson, & Seals, 1995).

The study by Quinn and coworkers (2011) suggests that RE is maintained across a wide range of ages and in both sexes in subelite runners. At four submaximal speeds, there was no difference in RE, assessed as VO_2, between groups. Maximal aerobic capacity and the percent of VO_{2max} used were key predictors of RE at each speed (Quinn et al., 2011). Running economy may not be preserved with age in other endurance athletes. In male triathletes preparing for an Olympic-distance race, master athletes had a higher VO_2 at a fixed submaximal speed (5.6 mph) than younger athletes did (Sultana et al., 2012). The older group also used a higher percent of VO_{2max} in this effort. However, these athletes were not matched for performance; the older group had a lower VO_{2max} and speed at VO_{2max}, so it is logical that they would need to use more of their maximal capacity at the same speed as the younger triathletes. Therefore, it may not be valid to compare VO_2 between these groups and come to any conclusions about age differences in RE.

An investigation into the biomechanics of running in older and younger people suggests a mechanism by which RE may decline in master athletes. Participants in this study ran on a force platform at different speeds, and the authors measured their vertical oscillation, vertical stiffness, and internal and external work (Cavagna, Legramandi, & Peyré-Tartaruga, 2008). The older people had a greater step rate and less storage of elastic energy and did less internal but more external work. The older people had to use more energy to do the same mechanical work as the younger runners because of their impaired ability to store elastic energy, potentially related to the loss of muscular strength with age (Cavagna et al., 2008). Three factors limit the generalizability of this study: More than half the participants were sedentary, the mean age of the older group was 73.6, and no older females were tested. Highly trained athletes likely have different running biomechanics than do sedentary individuals. Additionally, the older subjects were considerably older than the “older” group in other studies (typically around 55-65 years of age). The lack of females in the older group also fails to provide insights into RE in this population.

As with VO_{2max}, training habits likely contribute to the maintenance of RE with age. When Trappe and colleagues (1996) studied male distance runners over more than 21 years, they evaluated RE as VO_2 at 12 km/h (7.5 mph). Among participants who kept up any level of training, RE did not change, while those who had stopped training had a higher VO_2 at this speed. In general, results from studies on RE in master runners suggest that RE is maintained with age in endurance-training runners both sexes and is not related to performance decrements with age (Brisswalter & Nosaka, 2013; Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2008).

Adaptations to exercise training in older adults

The literature shows that sedentary older adults can benefit from exercise training, and such adaptations can occur even in individuals older than age 60. As in younger people, a training program must impost a physiological overload for training adaptations to occur (Spina, 1999). The training intensity needed to increase VO_{2max} might be lower than in younger people, e.g. 40% of VO_{2max} rather than 60-70%, depending on initial fitness levels. To reap the other benefits of endurance training, like better insulin sensitivity and body composition, a higher exercise intensity is required (Hagberg, 1987). Older sedentary people of both sexes can increase VO_{2max} to a similar relative extent as younger people, i.e. 20-30% (Hagberg, 1987; Hodgson & Buskirk, 1977; Spina, 1999). Additionally, training can help maintain left ventricular systolic function with age. However, Spina (1999) proposes some sex differences in the responses to training in older people. While older females seem to be able to improve their VO_{2max} through higher $(a - v)O_{2max}$ only, males also can increase their Q_{max}. Moreover, females may not be able to increase LV filling after a training intervention. Spina (1999) believes that this discrepancy might be due to diminished estrogen levels in post-menopausal females.

In one study, healthy males and females with a mean age of 63 years underwent a 12-month training intervention in which they gradually increased the intensity of exercise (Seals, Hagberg, Hurley, Ehsani, & Holloszy, 1984). For the first six months, they walked moderately three times per week; over the next six months, they progressed to exercising by walking on an inclined treadmill, running, or using a bicycle and moved from 75 to 80% of heart rate reserve (HRR). They received supervision during this second period. After this intervention, their absolute VO_{2max} (ml min^{-1}) had increased by 25%, and their relative VO_{2max} (ml kg^{-1} min^{-1}) had risen by 30%, with more improvement coming after the second six-month period. A control group that did not change PA levels did not improve their VO_{2max}. The increase in aerobic power in the exercise group came via an elevation in $(a – v)O_{2max}$, likely due to increased mitochondrial enzyme activity. The exercising adults also lowered their percent body fat and had a lower heart rate at a given submaximal workload. The responses of these older adults to a training intervention were similar to results seen in younger subjects, showing that aging bodies can still adapt to endurance training (Seals et al., 1984).

Another exercise trial in adults over age 60 controlled for interaction with investigators by adding a yoga control group to an endurance-exercise group and non-exercising controls (Blumenthal et al., 1989). The group that undertook aerobic exercise performed cycling at 70% of HRR in addition to some walking, jogging, and arm-cycling, while the yoga group did an hour of yoga. Both interventions lasted for 16 weeks. Maximal aerobic capacity increased only in the aerobic exercise group, as did the anaerobic threshold, defined as the intensity at which ventilatory equivalents increased nonlinearly. Demonstrating the importance of the yoga group, self-reported quality of life increased in the exercise and yoga participants, with no change seen in the non-exercising controls (Blumenthal et al., 1989). These results show that older adults of both sexes can improve their fitness with endurance training.

In a 1989 study, Hagberg and colleagues explored whether resistance training could improve VO_{2max} in older adults by mitigating the effects of sarcopenia. These participants were also older than in previous studies and were between the ages of 70 and 79. Subjects either underwent progressive endurance- or resistance-training programs for 26 weeks or did no exercise. Only the endurance group experienced a significant increase in VO_{2max}, while the strength-training participants were the only ones who improved their muscular strength. There were two main findings from this investigation: Resistance training can increase strength in older adults, but to a lesser extent than in younger people; and endurance training can improve cardiorespiratory fitness to a similar relative magnitude as in younger people. Because the resistance-training group did not increase muscle mass, the authors note that their program might not have been adequately intense (Hagberg et al., 1989).

A controlled trial in older and younger adults tested whether initial fitness, training parameters, and/or age affected the response to an exercise training intervention (Kohrt et al., 1991). Healthy, active older males and females were assigned to exercise or non-exercise groups, and sedentary young people also did the training intervention. For 9-12 months, the exercisers did a progressive endurance-training program. Among all participants in the training group, VO_{2max} increased by around 20% after adjusting for decreased BM, while VO_{2max} did not change in the control group. Furthermore, neither age, baseline cardiorespiratory fitness, nor training duration, intensity, or frequency were correlated with changes in VO_{2max} (Kohrt et al., 1991). These results show that sedentary adults over age 60 can increase their aerobic fitness with training as well as adults in their 20s and 30s can.

Older individuals might be able to improve their submaximal endurance capacity more than their VO_{2max} through implementing a training program. A group of males with an average age of 67 years participated in a nine-week training program that involved walking or jogging at 70% of VO_{2max} four times per week (Poulin, Paterson, Govindasamy, & Cunningham, 1992). Their VO_{2max} increased by 10.6% from baseline. The authors also determined time to exhaustion (TTE) in a treadmill test designed to elicit a VO_2 between the ventilatory threshold (a level near the LT) and VO_{2max} as measured at pre-testing. In these subjects, TTE during this test was 180% at post-testing, conducted at the same speed as initial testing. The authors report that compared to younger males, these participants had similar endurance as determined by the relative intensity of their submaximal exercise (Poulin et al., 1992). Therefore, in previously sedentary males, even a relatively short training program can increase VO_{2max} but have an even more substantial effect on submaximal exercise capacity.

In contrast to studies that have been done with the aim of improving performance in younger runners and raising basic fitness levels in inactive people, little research has been conducted to investigate the responses to a training intervention in master athletes. However, two groups have explored how strength training might affect RE in master runners. A 2010 study implemented either endurance training only (E) or endurance plus strength training (ES) in experienced recreational marathon runners (Ferrauti, Bergermann, & Fernandez-Fernandez, 2010). Participants were of both sexes and had a mean age of 40 years. The intervention lasted for the first eight weeks of their 12-week training cycle, and mileage was based on each individual's prior training. The endurance component consisted of habitual training plus one 15-km session per week at 90-95% of goal marathon speed. The ES group also did two lifting sessions each week focusing on leg and core muscles. In a weakness of the study, the ES group spent more time training than the E subjects. After the eight-week program, ES was the only group to increase muscle strength; both groups improved their VO_{2max} and some LT parameters. Neither group exhibited changes in RE, which was measured as VO_2 at 2.4 and 2.8 m/s (5.4 and 6.3 mph). The authors had predicted that strength training could improve RE by stabilizing core muscles and making running muscles more efficient, but that did not occur in these runners. The ES participants did not increase their BM, so incorporating strength training into marathon-training regimens likely will not promote disadvantageous weight gain among recreational runners, even if it does not necessarily improve performance (Ferrauti et al., 2010).

A study by Piacentini and coworkers (2013) also examined the effects of concurrent ES training in master runners. Participants in this project had a mean age of 44 and were all in a running club and training for the same marathon. They were randomized to one of three groups: maximal strength training (MST), resistance training (R), or controls. All athletes undertook their normal endurance training program, which included 50 km of running per week and incorporated both high-quality and easy running. Twice a week for the first six weeks of the 12-week marathon training plan, the MST group did full-body lifting sessions with high weight and low repetitions, while the R group performed sessions with lower weight and more repetitions. Similarly to the study by Ferrauti and colleagues (2010), the control group did no extra training. Running economy was evaluated at goal marathon pace and at slightly slower and faster speeds. After the intervention, the MST group had improved RE at marathon pace, with no other changes in RE observed among any participants. The MST athletes decreased VO_2 at this speed by 6%, which is similar to RE improvements seen in younger athletes. Interestingly, the R group demonstrated increased leg musculotendinous stiffness (which, as previously discussed, might improve RE), while control subjects improved in some measures of explosive power. Overall, the results of this study suggest that ES training in masters can improve running performance (Piacentini et al., 2013). However, more research is needed to determine what types of resistance training are most effective in older long-distance runners.

Summary

Maximal aerobic capacity is a good predictor of distance running performance in master athletes of both sexes. All people experience a loss of VO_{2max} with age; VO_{2max} drops approximately 10% per decade after age 25. However, the rate at which VO_{2max} decreases depends on age and changes in training status. The main contributing factor to the age-related decline in VO_{2max} is a fall in Q_{max}, mainly due to the inevitable drop in MHR with age. Maximal stroke volume, the other component of Q_{max}, may also fall somewhat, but $(a - v)O_{2max}$, which is also a part of VO_{2max}, likely does not change meaningfully with age in training athletes. Endurance training can slow the loss of VO_{2max}; however, the cessation of training will accelerate this decrease. The decline of VO_{2max} with age helps to explain the decrements in running performance that occur as athletes get older. Alterations in the LT may help to preserve distance running ability, as the LT increases as a percent of VO_{2max}. There is little data on RE in competitive older runners, but it likely does not change significantly in this population. Furthermore, older sedentary people can increase their aerobic fitness through endurance training, while master athletes may be able to increase strength through concurrent endurance and strength training. There is a lack of data on physiological and performance changes in female master runners; most studies to date have examined males. Moreover, RE has traditionally been measured as VO_2, while more recent reports have argued that allometric and energy-cost models are more valid. Additionally, the effects of endurance and strength training in already highly trained older people need to be more fully described. The aging population and the desire of runners to compete throughout their lifespans will necessitate a more thorough understanding of the physiology of running in older adults.

Conclusions

Many physiological factors interact to regulate the speed and endurance of a long-distance runner. Maximal aerobic capacity is a key determinant of running performance. It is equal to the product of maximal arteriovenous oxygen difference and maximal cardiac output. Among athletes homogeneous for VO_{2max}, RE better predicts performance. Substrate utilization, muscle fiber types, environmental conditions, and biomechanical factors affect RE. However, traditional measurements of RE may not accurately reflect an athlete's economy. The use of allometric scaling of body mass and energy cost models may be more appropriate in explaining performance differences between runners. Parameters associated with the LT also control the speed that a runner can maintain over a certain distance.

In trained athletes, it may be difficult to increase VO_{2max} over time, with the exception of fluctuations related to periodized training programs. However, the LT and RE can improve with training. Plyometric exercises and heavy resistance training can result in better RE, while speedwork can benefit both the LT and RE. Athletes training for a marathon may incorporate these types of training as part of their specific pre-race buildups. Less is known about whether training can improve these measures in master runners.

The fields in running races are aging, and older athletes are getting faster. Maximal aerobic capacity decreases unavoidably with age, but endurance training may be able to slow this rate. Furthermore, RE seems to be preserved, even as other physiological determinants of performance decline. There may be sex differences in the aging process of endurance athletes, but a lack of research on females precludes making firm assertions on this matter.

The following studies aim to address these gaps in the literature. In the first study, we hypothesized that experienced young marathon runners would improve their RE over the course of marathon training and that a higher VO_{2max} would be associated with faster marathon performance. In the second study, we predicted that age and VO_{2max} would be reliably and negatively correlated, whereas age would not be significantly associated with measures of RE; in addition, we hypothesized that we would observe sex differences in the relationships between age and variables related to running performance. Finally, in the third study, we hypothesized that VO_{2max} would be significantly correlated with long-distance race performance and that a group of master runners heterogeneous with respect to performance would have equally diverse training practices.

CHAPTER 3: Effects of marathon training on maximal aerobic capacity and running economy in experienced marathon runners

Abstract:

Maximal aerobic capacity (VO_{2max}) and running economy (RE) are markers of running performance. A valid evaluation of RE may occur through allometric scaling of body mass (alloVO_2; ml $kg^{-0.66}$ min^{-1}), energy cost (EC; kcal kg^{-1} km^{-1}), or percent of VO_{2max} (%VO_{2max}). Little is known about physiological changes that occur in competitive runners over a marathon training cycle. The VDOT score, incorporating VO_{2max} and RE, enables comparison of race performances under different temperature conditions. The study's purpose was to determine whether VO_{2max} and measures of RE change with marathon training; to evaluate the relationship between these variables and VDOT. Eight runners (age 34±2 years; marathon <3:00 males, <3:30 females; five females) completed treadmill marathon-intensity-effort (MIE) and VO_{2max} tests at 10 and 1-2 weeks pre-marathon. Body composition (%BF) was determined using hydrostatic weighing. Paired t-tests were used to compare pre- and post-training values. The alpha level for significance was set at 0.05. Body fat decreased from 18.7±1.5% to 16.7±1.6%, VO_{2max} increased from 51.6±2.4 to 63.9±1.1 ml kg^{-1} min^{-1}, and %VO_{2max} during the MIE decreased from 82.1±2.0 to 72.3±3.2% ($p < 0.05$ for all). VDOT was significantly associated with alloVO_2 ($r = -0.779$, $p = 0.039$) but not with VO_{2max} ($r = 0.071$, $p = 0.867$). Experienced competitive runners may increase VO_{2max} and decrease %BF after a marathon-specific training cycle. The decrease in %VO_{2max} in a MIE is likely due to a

higher VO_{2max}, as other measures of RE did not change significantly. In this cohort, $alloVO_2$ was negatively correlated with race performance.

Introduction

Maximal aerobic capacity (VO_{2max}) and running economy (RE) are two key predictors of distance-running performance. A high VO_{2max} allows the efficient delivery of a large volume of oxygen to peripheral tissues, facilitating the provision of energy to working muscles (Barnes & Kilding, 2015b). Maximal aerobic capacity depends on adequate bronchodilation, the diffusing capacity of the lungs, cardiac output, the ability of the blood to carry oxygen, and skeletal-muscle oxygen uptake (Basset & Howley, 2000; Joyner & Coyle, 2008). Stroke volume, a component of cardiac output, increases with endurance training and is a major contributor to VO_{2max} (Arbab-Zadeh et al., 2014; Wilmore et al., 2001). Aerobic training also improves augmented muscular oxygen extraction (Holloszy & Booth, 1976). A relationship between VO_{2max} and distance running performance has repeatedly been shown in runners of both sexes (Costill, 1967; Costill et al., 1973; Foster, 1983; Mello et al., 1988). Running economy (RE) is the cost of running at a given submaximal speed (Basset & Howley, 2000; Berg, 2003; Saunders et al., 2004). Numerous factors, including biomechanical parameters, cardiopulmonary function, and muscle fiber distribution affect RE (Saunders et al., 2004). Running economy can explain differences in performance between individuals of similar VO_{2max} (Conley & Krahenbuhl, 1980; Costill et al., 1973; Daniels, 1974; Daniels & Daniels, 1992; Don W. Morgan et al., 1995). Improvements in RE are associated with better running performance (Saunders et al., 2004).

Many of the human body's adaptations to endurance training have been described extensively. Mitochondrial density and oxidative enzymes in skeletal muscle rise due to an increase in mitochondrial biogenesis (Holloszy et al., 1977). Thus, skeletal muscle can rely more heavily on the body's vast lipid stores for energy during exercise. Cardiac remodeling facilitates pumping a larger volume of blood with decreased myocardial oxygen demand (Holloszy et al., 1977; Prior & La Gerche, 2012). Such remodeling may contribute to a higher cardiac output, augmenting blood flow during exercise and improving VO_{2max} (Holloszy et al., 1977). Additionally, training improves RE (Saunders et al., 2004). Not only does enhanced RE allow athletes to run longer at a given speed or faster at a given rate of energy expenditure, it can also predict marathon performance among athletes with similar VO_{2max} (Coyle, 2007).

Despite the expansive research on exercise performance, the current body of literature on endurance training adaptations lacks longitudinal studies on competitive marathon runners. Experimental training regimens undertaken by non-elite athletes tend to require only 15-120 minutes of aerobic exercise per session—a typical duration is 40 minutes—and do not necessarily represent the type of training done by high-level athletes in preparation for a marathon race (Cornelissen & Fagard, 2005; Holloszy & Coyle, 1984). In addition, athletes may train for and complete numerous marathons and show an overall trend of improvement. Therefore, until the occurrence of injury or age-related declines in aerobic capacity, physiological adaptations from successive marathon-specific training cycles must not be maximal. Finally, RE has traditionally been evaluated as the submaximal rate of oxygen consumption (VO_2), in ml kg (body mass) $^{-1}$ min^{-1}. Because oxygen requirements do not increase linearly with body mass, allometric scaling of body mass and calculation of the energy cost of running have been proposed as more valid measures of RE (Barnes & Kilding, 2015a; Berg, 2003). Analysis of the percent of VO_{2max} ($\%VO_{2max}$) at which an athlete can compete is also useful. The ability to run using a large $\%VO_{2max}$ at a given distance may be more important to race outcomes than only the value of an athlete's VO_{2max} (Costill et al., 1973). Trained runners are predicted to run a marathon at between 80 and 85% of VO_{2max} (Basset & Howley, 2000).

In highly trained distance runners, VO_{2max} is relatively stable but may increase due to training periodization (Billat et al., 2002) or interval training (Billat, 2001; T. P. Smith et al., 1999). However, even with high-intensity ($\geq$ 90% VO_{2max}) training, athletes may demonstrate no change in VO_{2max} despite improved race performance (Berg et al., 1995; Billat, 2001; Davies & Knibbs, 1971). Running economy, in contrast, can improve in competitive athletes through the incorporation of heavy lifting and explosive and/or plyometric exercises (Barnes et al., 2013; Johnston et al., 1997; Millet et al., 2002; Paavolainen et al., 2003; Paavolainen et al., 1999; Spurrs et al., 2003; Støren et al., 2008). This type of training may allow runners to be more economical through its positive effects on musculotendinous stiffness (Paavolainen et al., 1999).

Given the popularity of marathon running, it is important to identify physiological and performance-related changes that occur over the course of a marathon training cycle. Athletes experience adaptations following marathon training that enable them to finish the demanding race and, potentially, to run a faster time than in previous marathon races. The identification of the running-performance markers that change with marathon training will allow coaches and athletes to develop more targeted training strategies to address specific areas of weakness.

Environmental conditions during a marathon race may affect how fast participants are able to run. Hot weather in particular is known to negatively impact performance (Cheuvront & Haymes, 2001; El Helou et al., 2012; Vihma, 2010). Relating predictive markers to the time it takes to complete a race may not be meaningful if the race occurred in warm conditions. Therefore, a participant's temperature-adjusted VDOT score may be a more useful indicator of performance. The VDOT is a score that allows for the comparison of running performances at different distances (Daniels, 2014). It incorporates the $\%VO_{2max}$ and the oxygen cost required for a given race duration. Daniels and Gilbert (1979) developed regression equations relating velocity to VO_2 and race duration to $\%VO_{2max}$. By accounting for RE, the VDOT score represents the interaction between a person's economy and his or her maximal capacity (Daniels, 2014). Therefore, it may be more useful than a VO_{2max} value, attained under laboratory conditions, for comparing field performances.

Therefore, the primary purpose of the present study was to determine whether important measures of running performance change in highly trained, sub-elite runners following a specific marathon-training program. Additionally, we aimed to evaluate the relationship between VO_{2max}, MIE VO_2, alloVO_2, EC, and $\%VO_{2max}$, measured in controlled laboratory settings, and actual marathon performance (VDOT score) adjusted for race-day temperature. We hypothesized that RE would improve and that VO_{2max} would be positively correlated with converted VDOT.

Methods

Subjects

Participants were recruited from the Twin Cities metropolitan area via an online running newsletter and emails to local running teams. To be eligible for the study, potential subjects were required to have run at least one marathon in the past two years with a time of ≤ 180 minutes (males) or ≤ 210 minutes (females) or have met these criteria more than two years ago and be enrolled at the discretion of the primary investigator. Participants were also required to be between the ages of 18 and 40, to have run at least 30 miles per week on average for the preceding three months, and not to have run a marathon within two months before enrollment. Potential subjects were screened for eligibility via email prior to scheduling study visits. This study was reviewed and approved by the University of Minnesota Institutional Review Board, and all subjects provided written consent prior to enrollment in the study.

Thirteen subjects met these criteria and were enrolled; however, four dropped out due to running injuries. One additional subject was excluded from analysis, as this runner did not follow a discernible training plan with the exception of a weekly long run. Therefore, the total number of participants included in analysis of body composition, running performance variables, and training data was eight.

Participants were highly trained and sub-elite; for reference, time standards for entry into this study were more stringent than Boston Qualifying times.

Experimental Approach to the Problem

A prospective, uncontrolled cohort study was conducted to examine changes in running performance after a marathon training cycle. High-caliber athletes are not likely to be willing to cede control of their training plan to investigators; therefore, participants in this study were allowed to adhere to training programs of their choice. Moreover, allowing athletes to select their own training has greater ecological validity than an experimental training intervention. These programs were developed by the athletes themselves or by their coaches. To ensure that structured plans were followed, we asked the subjects to plan their workouts at least one week in advance. The athletes entered all planned and actual workouts in an online spreadsheet visible to the primary investigator. In the online training log, participants entered the description (e.g. easy run, interval workout, threshold run, etc.), mileage, and duration of daily running workouts as well as strength workouts. Subjects recorded the intensity of each workout on a 1-10 Borg scale.

Participants came to the laboratory for testing on two occasions. The first study visit took place approximately 10 weeks before each person's goal marathon, and the second visit occurred 1-2 weeks before the marathon. This timeline was chosen because marathon training plans for highly trained runners are approximately 12 weeks in duration. Moreover, the marathon-training programs that competitive runners typically follow contain similar elements: base training, with moderate mileage and fewer high-intensity workouts, in the early weeks, and lower mileage with more high-intensity workouts closer to the marathon. Regardless of the specific plan that each runner followed, subjects would be partaking in similar types of workouts at 10 and 1-2 weeks pre-marathon.

Maximal aerobic capacity and RE are known contributors to distance running performance. We measured RE in a treadmill test in which subjects maintained a heart rate of 88% of their age-predicted maximum heart rate (MHR). This value was chosen because trained runners are predicted to complete a marathon at 80-85% VO_{2max} (Basset & Howley, 2000). Eighty percent of VO_{2max} corresponds to a heart rate of 88% of the

MHR (Londeree, Thomas, Ziogas, Smith, & Zhang, 1995; Swain, Abernathy, Smith, Lee, & Bunn, 1994).

Procedures

Testing Sessions

Subjects reported to the Clinical Exercise Physiology Laboratory at the University of Minnesota for both of their visits. We attempted to schedule each person’s first and second visits at a similar time of day. Testing procedures occurred in the order described below and was the same at both study visits. Participants were asked not to eat, consume caffeine or alcohol, or use tobacco within three hours of their study visits. We also requested that they not engage in strenuous exercise, defined as long runs, quality workouts, or strength training, within 24 hours of their visits.

Anthropometric and Body Composition Measurements

Height, body mass, and body composition were evaluated at both testing sessions. Height was measured to the nearest 0.25 inch using a stadiometer (ACCUSTAT™ Stadiometer, Genentech, San Francisco, CA), and weight was measured to the nearest 0.1 pound on an electronic scale (Etekcity, Anaheim, CA). Body mass index (BMI) was calculated as mass in kg per height (in m) squared. Body composition was assessed with Flotaweigh hydrostatic weighing software (EXERTECH, Dresbach, MN). Six to eight measurements of body composition were taken for each person; the highest and lowest body fat percentages were dropped, and percent body fat (%BF) was calculated as the mean of the remaining values.

Running Economy Testing

All treadmill tests were conducted on a Woodway Pro XL treadmill (Woodway, Waukesha, WI). Running economy was evaluated in a submaximal treadmill test designed to mimic a marathon-intensity effort (MIE). Respiratory gases were measured throughout the MIE bout (Ultima CPX and BreezeSuite software, MGC Diagnostics, St. Paul, MN). Competitive runners complete a marathon race at approximately 80% of VO_{2max} (Basset & Howley, 2000), which corresponds to 88% of MHR (Londeree et al., 1995; Swain et al., 1994). Each subject was allowed to warm up for several minutes at a 1% incline and speed of their choice. Investigators adjusted the treadmill speed so that the runner reached their target heart rate, which was 88% of their age-predicted MHR. To calculate predicted MHR, the following equation was used:

MHR = 208 – (0.7 * age) (H. Tanaka, Monahan, & Seals, 2001).

Participants ran for five minutes in this target heart rate zone while investigators adjusted the treadmill speed as necessary. Rating of perceived exertion was measured at the beginning and end of this five-minute period.

Maximal Aerobic Capacity Testing

Participants performed an incremental treadmill test to exhaustion to determine their VO_{2max}. This test occurred approximately 10 minutes after the end of the RE test. The speed for this test was based on subjects' self-reported estimated current 5-km race pace (W. A. Braun & Paulson, 2012). Subjects began by walking for one minute at 1.39 $m\ s^{-1}$ (3.1 mph) on a level treadmill. Treadmill grade was then increased to 1%, and speed increased to 75% of each subject's 5-km race speed for three minutes. All subsequent stages lasted one minute. Over five stages, speed was increased to reach 5-km race speed. In the following stages, grade was raised by 1.5% each minute. Rating of perceived exertion (RPE) on a 6-20 Borg scale (Borg & Noble, 1974) was recorded at the end of each stage. Subjects ran to volitional exhaustion. An Ultima CPX cart and BreezeSuite software (MGC Diagnostics, St. Paul, MN) were used for collection and analysis of respiratory gas data throughout the maximal exercise test. Participants also wore a heart rate monitor (Polar, Bethpage, NY) throughout treadmill testing.

Training data

Training data were collected from participants' online training logs. These logs were Google Drive spreadsheets and were set up for 12 or 13 weeks of training, depending on the day of the week on which the goal race occurred. The participants were requested to fill in planned workouts prior to the beginning of each week. Each day, athletes entered their actual workouts and denoted distance in miles, time in minutes, RPE on a 1-10 scale, and a brief workout description. The training logs also included spaces for cross-training in which the participants were instructed to fill in time they spent doing alternative exercises or ancillary training (e.g. cycling or strength training). To determine the number of quality sessions that each subject undertook, the primary investigator read through workout descriptions for key words such as track workout, intervals, threshold run, tempo run, race, etc. Races were included as quality workouts; the pre- and post-training test sessions required for the present study were not. For analysis, distances were converted to km, and mean and peak values for distance, time, quality sessions, and strength sessions were calculated.

Statistical Analyses

Maximal aerobic capacity was determined by mid-five-of-seven analysis by the breath-by-breath BreezeSuite software. VDOT values came from a calculator on the following website: http://runsmartproject.com/calculator/. The VDOT calculator takes into account the time it takes for an individual to complete a race and relates this number to a %VO_{2max} value, while the runner's velocity corresponds to a given VO_2. This information is then used to predict VO_{2max} (Daniels & Gilbert, 1979). The website also calculates predicted race times and VDOT scores based on race-day temperatures. We collected temperature data for approximately 1-2 hours after the starting time of each race from www.wunderground.com and used this information to determine converted VDOT scores for each subject.

Running economy was evaluated using several different methods. Submaximal oxygen consumption was measured in ml kg^{-1} min^{-1} (VO_2) and was also calculated with allometric scaling of body mass to the -0.66 power, i.e. ml $kg^{-0.66}$ min^{-1} (alloVO_2). The energy cost (EC) of running, in kcal kg^{-1} km^{-1}, in the MIE was also calculated. Average respiratory exchange ratio (RER) over the five-minute running test was used to determine a caloric equivalent value in kcal l O_2^{-1} (Péronnet & Massicotte, 1991). This value was multiplied by VO_2 and divided by each participant's average speed in m/min to find EC. Finally, the percent of VO_{2max} (%VO_{2max}) that the MIE required was calculated as mean VO_2 divided by VO_{2max} and multiplied by 100%.

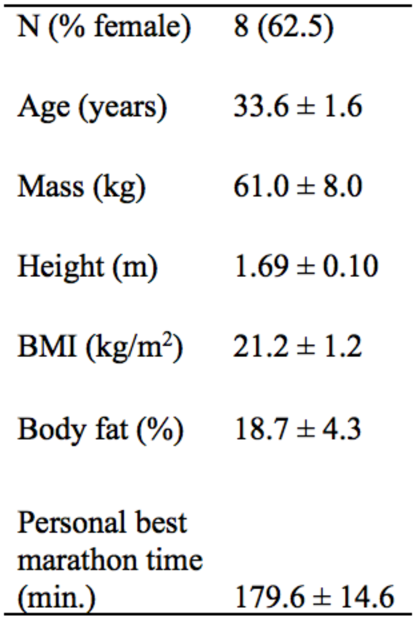
We used Statistical Package for the Social Sciences (SPSS; IBM, Armonk, NY) for all statistical analyses. Paired t-tests were used to compare pre- and post-training values of %BF, VO_{2max}, and submaximal VO_2, alloVO_2, RER, speed, RPE, EC, and %VO_{2max}. The alpha level for statistical significance was set at $p < 0.05$.

To determine whether there are relationships between temperature-converted VDOT score and VO_{2max}, MIE VO_2, alloVO_2, EC, and %VO_{2max}, Pearson's correlation coefficient *r* was calculated. The alpha level for statistical significance was set at $p < 0.05$.

Results

Subject demographics at baseline are reported in Table 1. Following approximately eight weeks of marathon training in our participants, we observed a significant decrease in %BF, from 18.7 ± 1.5% to 16.7 ± 1.6% ($p = 0.020$). Maximal aerobic capacity increased significantly, from 51.56 ± 2.43 ml kg^{-1} min^{-1} to 63.87 ± 1.06 ml kg^{-1} min^{-1} ($p = 0.005$). The percent of VO_{2max} required to complete the five-minute MIE bout decreased significantly, from 82.11 ± 2.0% to 72.32 ± 3.21% ($p = 0.029$). The MIE VO_2, RPE, speed, RER, EC, and alloVO_2 did not change significantly. These variables are depicted in Figure 1 (respectively, %BF, VO_{2max}, MIE VO_2, MIE RPE, MIE speed, MIE RER, MIE alloVO_2, MIE EC, and MIE %VO_{2max}).

Table 1. Descriptive characteristics of the participants.



N (% female)	8 (62.5)
Age (years)	33.6 ± 1.6
Mass (kg)	61.0 ± 8.0
Height (m)	1.69 ± 0.10
BMI (kg/m^2)	21.2 ± 1.2
Body fat (%)	18.7 ± 4.3
Personal best marathon time (min.)	179.6 ± 14.6

BMI: body mass index. Data are reported as mean ± SD unless otherwise indicated.

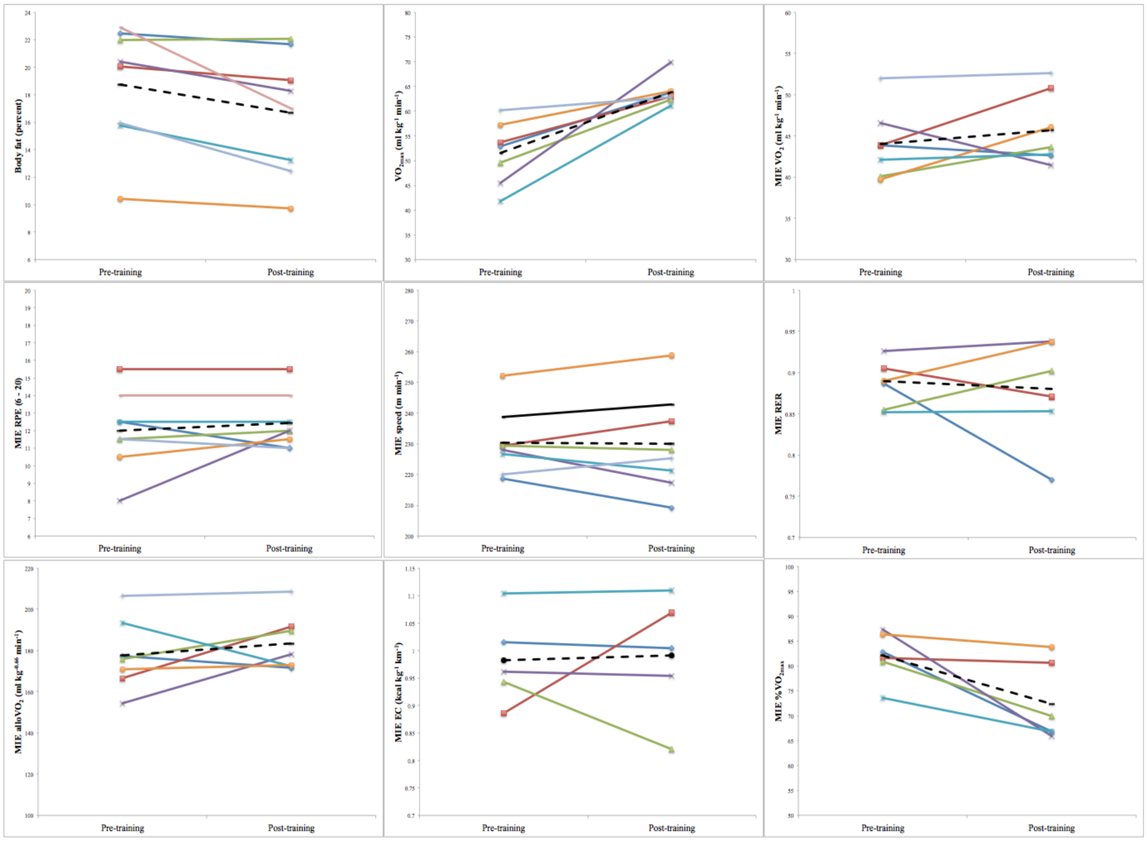


Figure 1. Changes in body composition and performance variables following a marathon training cycle.

VO_{2max}: maximal aerobic capacity; MIE: marathon-intensity effort; VO_2: oxygen consumption; RPE: rating of perceived exertion; RER: respiratory exchange ratio; alloVO_2: allometrically scaled VO_2; EC: energy cost; pre-training: ~10 weeks before goal marathon; post training: 7-14 days before goal marathon. Each subject is represented as a single line. The dotted line in each graph represents the mean change in each parameter.

One participant who completed the study dropped out of their goal race; therefore, only seven subjects were included in analysis of race performance, i.e. the correlation of VO_{2max} with temperature-converted VDOT. Maximal aerobic capacity was not significantly associated with converted VDOT ($r = -0.326$, $p = 0.475$), MIE VO_2 ($r = -0.336$, $p = 0.462$), MIE EC ($r = -0.386$, $p = 0.393$), or MIE %VO_{2max} ($r = 0.195$, $p =$

0.676) (Figure 2). However, MIE alloVO$_2$ had a significant negative relationship with converted VDOT (r = -0.779, p = 0.039).

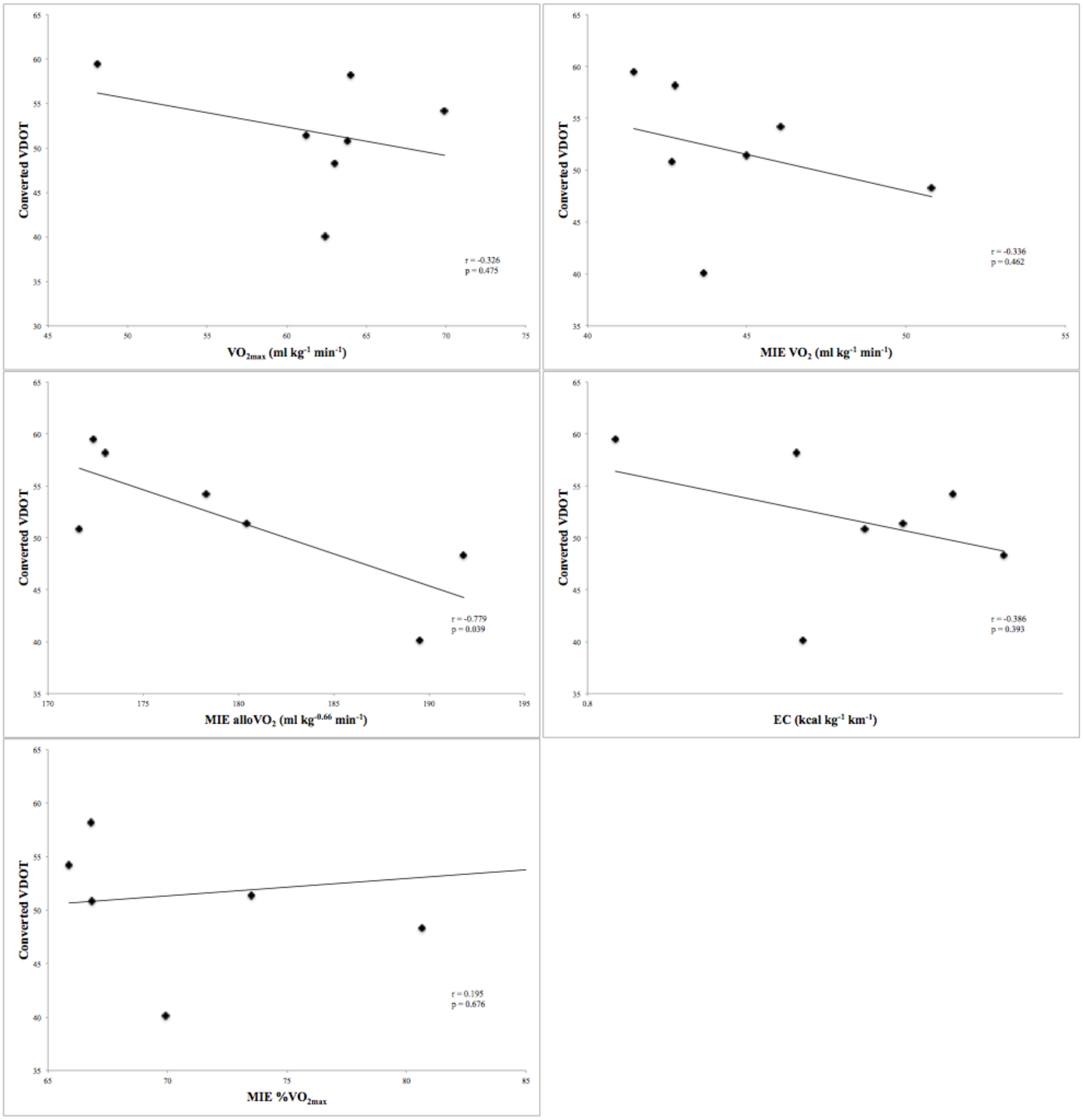


Figure 2. Correlations between converted VDOT score and running performance variables.

VO$_{2max}$: maximal aerobic capacity; MIE: marathon-intensity effort; VO$_2$: oxygen consumption; alloVO$_2$: allometrically scaled VO$_2$; EC: energy cost.

All subjects completed the online daily training logs for a minimum of 12 full weeks. One participant did not keep track of RPE. Their RPE data was not included in the analysis. The athletes ran an average of 85.6 ± 13.6 km week^{-1} and spent 409.9 ± 66.6 minutes running each week. The average weekly RPE over the training period was 4.8 ± 1.3, and an average of 1.1 ± 0.6 quality sessions and 0.04 ± 0.08 strength sessions were completed each week. Table 2 summarizes the training data of the participants.

Table 2. Data from participants' training logs.

Weekly distance (km)		Weekly time (min.)		Weekly RPE (1-10)		Weekly quality sessions (no.)		Weekly strength sessions (no.)	
Average	Peak	Average	Peak	Average	Peak	Average	Peak	Average	Peak
85.6 ± 13.6	113.6 ± 17.3	409.9 ± 66.6	546.8 ± 88.6	4.8 ± 1.3	5.7 ± 1.4	1.1 ± 0.6	2.0 ± 0.9	0.04 ± 0.08	0.38 ± 0.74

RPE: rating of perceived exertion. Data are reported as mean ± SD. N = 8 for distance, time, quality sessions, and strength; n = 7 for RPE.

Discussion

In this prospective study, we have demonstrated that highly trained, sub-elite marathon runners may show statistically significant changes in physiological and performance markers of distance-running ability in response to a marathon training cycle of approximately 10 weeks. This cohort of primarily highly trained athletes improved significantly in VO_{2max}, a traditional marker of running performance. They also decreased the percent of VO_{2max} at which they completed a MIE at a fixed target heart rate, demonstrating an improvement of RE. However, the runners did not experience significant changes in VO_2, the typical measure of RE, during this run. They also did not show changes in other parameters in the MIE. Furthermore, VO_{2max} was not significantly associated with race performance as evaluated by VDOT score.

Notably, in the present study, mean VO_{2max} among the athletes rose by nearly 24% between pre- and post-training testing, and all participants showed an increase in this parameter. For reference, elite marathoners improved their VO_{2peak} by approximately 5% after eight weeks of marathon-specific training (Billat et al., 2002). As seen in Figure 1, there was some level of variability in the VO_{2msx} response to training. Based on findings by Bouchard and colleagues (1999), this result is not unexpected, as there is a high degree of interindividual differences in the VO_{2max} response to exercise training.

Interestingly, the athlete whose VO_{2max} increased by the largest magnitude also performed well in their goal marathon. This person had a personal best marathon time of 2:44, but their best time in the past two years was 3:38. In the race for which the athlete trained for during this study, they ran a time of 2:58. One other participant improved on their best marathon time, lowering it by approximately 10 minutes, from 2:57 to 2:47. This athlete increased their VO_{2max} from 57.2 to 64 ml kg $^{-1}$ min^{-1}. However, no other athletes ran a personal best time in their goal races for this study in spite of demonstrating higher VO_{2max} values at post-testing compared to pre-testing.

These athletes significantly improved their body composition after marathon training. The subject group began with a relatively low %BF of 18.7% and ended their marathon training at 16.7%. In females and males, respectively, these values were 20.3% and 17.9%, and 16.1% and 14.7%. A survey of female American distance runners reported that elites had a mean %BF of 14.3%, while “good” runners had approximately 16.8% BF (Russell R. Pate & Neill, 2007). Meanwhile, a study of national- and international-class female distance runners found that these athletes had 16.9% BF (Wilmore, Brown, & Davis, 1977). In contrast, male distance runners tend to have %BF of around 6-12% (Wilmore et al., 1977). The %BF that we observed in our cohorts of both sexes would predict their performances to fall somewhat beneath that of top-level athletes.

There is little data regarding alterations in body composition during marathon training in competitive athletes. In novice marathoners of both sexes, males tended to lose BF, while there was no change in females (Janssen, Graef, & Saris, 1989). It appears that both male and female competitive marathon runners may favorably alter their body composition with marathon-specific training.

During the MIE, study participants required a smaller fraction of VO_{2max} to run at a fixed heart rate in the post-training bout than in the pre-training test. This finding is likely due to the overall increase in VO_{2max} that occurred in the group. Treadmill speed and RPE did not change significantly during this run from pre- to post-training, showing that similar effort levels were required to elicit the target heart rate during both testing sessions. Oxygen consumption measured as VO_2 or alloVO_2, with body mass scaled to the -0.66 power, also failed to change significantly with marathon training. Therefore, the elevation in VO_{2max} that occurred with training can explain the decrease in %VO_{2max} during the MIE.

In practical terms, the athletes had a deeper well from which to draw during post-testing, but there was no change in how fast they needed to run or the degree to which they exerted themselves to reach the estimated marathon-level heart rate target. Alternatively, the lack of change in VO_2 may be explained by the fact that endurance training promotes an elevation in the ability to oxidize lipids during exercise (Holloszy et al., 1977). Using lipids for fuel requires more oxygen than does the oxidation of carbohydrates (Holloszy et al., 1977). Thus, the athletes may have experienced endurance-training metabolic adaptations that were not captured by VO_2 or alloVO_2. Additionally, while participants' first and second visits took place at similar times of day, we did not control for dietary intake prior to the RE test. Because substrate selection affects VO_2 and RER (Jeukendrup & Wallis, 2005), differences in food intake may have obscured true training effects on RE. Furthermore, the improvement in %VO_{2max} did not translate into faster running times compared to previous marathons. This change may simply demonstrate that the athletes had higher aerobic fitness than they did at the beginning of their marathon training cycles. A longer-term study to track the VO_{2max} of these runners across years of training is needed to clarify whether the observed increase in VO_{2max} is lasting or related to periodization (Billat et al., 2002). The failure of EC to change significantly suggests that this subject cohort may not have experienced metabolic changes that affected their RE.

We did not observe a significant change in most measures of RE following a marathon training cycle. This finding may be related to the aforementioned fact that most subjects in the present study did not improve on their two-year-best race times. When RE does improve, it may be due to metabolic adaptations related to endurance training. Elevations in muscular oxidative enzyme activity with training result in lower VO_2 with submaximal exercise at a fixed intensity (Saunders et al., 2004), explaining why trained distance runners are more economical than others (Barnes & Kilding, 2015b; Midgley et al., 2007; Svedenhag & Sjödin, 1984). Musculotendinous stiffness also contributes to RE by enabling runners to store and use elastic energy during exercise, thereby lowering submaximal VO_2 (Burgess & Lambert, 2010).

Resistance and plyometric training can enhance RE even in well-trained endurance athletes (Barnes et al., 2013; Johnston et al., 1997; Millet et al., 2002; Paavolainen et al., 2003; Paavolainen et al., 1999; Spurrs et al., 2003; Støren et al., 2008). Such explosive and/or power-based training likely increases RE by augmenting MTS (Paavolainen et al., 1999). In the present study, none of the athletes undertook consistent resistance training, which may explain why most measures of RE, on average, did not change.

We did not find a significant correlation between VO_{2max} or most measures of RE and temperature-converted VDOT. Notably, $alloVO_2$ was significantly and negatively related to converted VDOT score, implying that allometric scaling of submaximal VO_2 may improve its usefulness as a performance-predictive tool. The lack of other statistically significant associations is somewhat unexpected because VDOT, VO_{2max}, and RE are expected to reflect aerobic fitness (Daniels, 2014). However, race-day conditions for one marathon, affecting two athletes, may have posed thermoregulatory challenges. The mid-race temperature of the 2017 Boston Marathon was 23.3° C (73.9° F). The corresponding wet-bulb globe temperature (WBGT) was 15.9 °C (60.6° F). The American College of Sports Medicine reports that the risk of heat-related exertional illness increases with a WBGT between 18.4-22.2° C (Armstrong, 2007). Suping and colleagues (1992) found that air temperature was significantly and positively correlated to marathon times, with larger effects on faster athletes. Participants in the present study were relatively fast runners. Thus, the athletes in the 2017 Boston Marathon may have experienced heat-related decrements in performance that affected the relationship between VO_{2max} and VDOT more than adjustment for temperature could account for. One participant who ran the Boston Marathon took more than four hours to do so despite having a personal best time of 2:57, illustrating the detrimental role that warm environmental conditions can play in marathon racing. With our small sample size, this particularly poor performance could have affected the statistical significance of our findings. There may still be practically significant correlations between VDOT and markers of running performance in addition to the statistically significant association with alloVO_2.

The participants in this group ran an average of 85.6 km (53.2) mi per week, with a peak of 113.6 km (70.6 mi). A 2001 study by Billat and colleagues followed elite marathon runners over the 12 weeks before the 2000 Portuguese and French Olympic trials. The investigators found that males ran approximately 168-206 km (104.4-128 mi.) per week, while females ran about 150-166 km (93.2-103.1 mi.) per week (Billat et al., 2001). This group performed approximately two quality sessions per week (Billat et al., 2001). In contrast, a cohort of male marathon entrants aged 20-28 ran an average of 79.2 km (49.2 mi) each week (Ogles & Masters, 2000). This group of more recreational runners was closer in ability to the subjects in the present study, with a mean personal best time of 196 minutes. While highly elite athletes do incorporate more running volume in their training programs than other competitive runners do, we are not equipped in the present study to conclude that additional mileage would have led to faster marathon times in our participants.

A major limitation of this study was its small sample size, which was exacerbated by equipment failure. One subject did not complete a pre-training VO_{2max} test. Furthermore, MIE RER data were not obtained for two subjects in pre-training tests, and

VO_2 data were not collected for one subject in the post-training MIE. Therefore, comparison of VO_{2max} was only made in seven subjects; VO_2 in seven; alloVO_2 in seven; RER in six; %VO_{2max} in six; and EC in five. All eight participants completed body composition testing and had data for MIE RPE and speed.

Practical Applications

High-level athletes training for a marathon race typically include a relatively high volume of running as well as quality workouts. Maximal aerobic capacity can increase in this population, which is already well trained. The percent of VO_{2max} utilized during a marathon-effort run may still change favorably following a period of marathon-specific training, potentially contributing to improved performance during the goal marathon. Using allometric scaling of body mass to express RE as submaximal VO_2 can predict race-day performance in experienced runners. Additionally, experienced runners can decrease their %BF over the course of a marathon-training program.

CHAPTER 4: The relationships between age and running performance in fit master runners

Abstract:

Maximal aerobic capacity (VO_{2max}) tends to decline with age, even in trained long-distance runners. However, it is possible that running economy (RE), another predictor of performance, may be preserved. Furthermore, previous research has measured RE as the submaximal rate of oxygen consumption in ml O_2 kg body mass $^{-1}$ min $^{-1}$ (VO_2), whereas it is more valid to express RE using allometric scaling of body mass (alloVO_2) or as the energy cost of running (EC), in kcal kg body mass $^{-1}$ min $^{-1}$. The percent of VO_{2max} (%VO_{2max}) at which a submaximal run occurs is also related to performance. PURPOSE: To evaluate VO_{2max}, alloVO_2, EC, and %VO_{2max} in runners in master runners and determine whether age is associated with these performance-related measures. METHODS: Runners aged 40-71 years completed two running tests. Study visits took place within four weeks of a goal race of 10-26.2 miles. Subjects ran for five minutes at 88% of their predicted age-based maximum heart rate, which approximates a marathon-intensity effort (MIE). Athletes then performed a VO_{2max} test. For the MIE, AlloVO_2 was calculated using body mass$^{0.66}$. Energy cost was determined using caloric equivalents based on mean respiratory exchange ratio, which takes substrate utilization into account. Pearson's correlations were used to determine relationships between age and running performance variables. RESULTS: Runners (n = 31, 13 females; mean age 54.9 ± 8.4 years; body mass index 22.6 ± 2.7 kg m^{-2}) had a mean VO_{2max} of 52.5 ± 7.9 ml O_2 kg^{-1} min^{-1}. Age was significantly correlated with VO_{2max} ($r = -0.580$, $p = 0.001$) and alloVO_2 (r = -0.454, p = 0.034). Age was also related to EC in females (r = 0.649, p = 0.042) and MIE VO_2 in males (r = -0.600, p = 0.039). CONCLUSIONS: In this population, age was negatively associated with VO_{2max} and alloVO_2. Females showed a positive relationship between age and EC, while males had a negative correlation between age and MIE VO_2. Aerobic capacity declines with age, but there may be sex differences in age-related alterations in submaximal running parameters.

Introduction

In the past several decades, the participation of master athletes—defined as individuals over the age of 35 or 40, depending on the sport—in endurance and ultra-endurance events has risen (Lepers & Cattagni, 2012; Lepers & Stapley, 2016). Athletes over the age of 50 have increased participation in these events more than younger athletes (Lepers & Cattagni, 2012; H. Tanaka & Seals, 2008), and masters may comprise a majority of the field in marathons and ultra-marathons (Lepers & Stapley, 2016). Furthermore, as the increase in numbers of female masters endurance athletes outpaces that of males, the sex gap in performance is shrinking (M.I. Lambert & Keytel, 2000; Lepers & Cattagni, 2012). Overall, the performance of master athletes has improved more than in younger runners over the past several decades; the ages of elites has increased, and older runners have gotten faster (Lepers & Cattagni, 2012; Lepers & Stapley, 2016).

Performance in endurance sports decreases unavoidably with age. In events from 10 km to the marathon, running performance declines by approximately 6-9% per decade beginning in an athlete’s mid- to late 30s, with greater decrements observed after the late

50s and after age 70 (Brisswalter & Nosaka, 2013; Brisswalter et al., 2014; Joyner, 1993; Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2003, 2008). The main cause of slowing in older distance runners is a decline in maximal aerobic capacity (VO_{2max}) (Reed & Gibbs, 2016), a key predictor of performance in long-distance running. In female and male masters athletes, VO_{2max} may be the best running-performance predictor (Wiswell et al., 2000).

Another major predictor of distance-running performance is running economy (RE). Running economy quantifies the oxygen or energy cost of running at a given submaximal speed; it is typically measured as the rate of oxygen consumption (VO_2) in ml kg body weight^{-1} min^{-1} (Berg, 2003). Among athletes with similar VO_{2max} values, RE can account for performance differences (Costill et al., 1973; Daniels & Daniels, 1992; Don W. Morgan et al., 1995). Moreover, faster runners typically have better RE than slower runners (Joyner & Coyle, 2008; Don W. Morgan et al., 1995). In contrast to VO_{2max}, RE may be preserved with age. At a given absolute speed (Allen et al., 1985) or relative intensity level, e.g. 10-km race pace (Evans, Davy, Stevenson, & Seals, 1995), RE—as assessed through VO_2—has been found to have no relationship with age in runners of both sexes.

Despite the predominance in running-performance literature of submaximal VO_2 as the major measure of RE, this traditional method of evaluating RE may not be valid. The oxygen cost of running does not increase linearly with body weight, as a smaller person uses relatively more oxygen than a larger person. To account for the allometric increase in VO_2 with mass, body mass should be scaled to a power of –0.66 to -0.75 (alloVO_2) (Barnes & Kilding, 2015a; Berg, 2003; Bergh, Sjödin, Forsberg, & Svedenhag, 1991). Furthermore, oxygen cost does not serve as an accurate proxy for energy cost. More oxygen is required to oxidize lipids than carbohydrates, raising VO_2. Yet a runner whose body is adapted to oxidize its lipid stores, rather than carbohydrates, is arguably more efficient than one who might exhibit a lower VO_2. Therefore, energy cost (EC) should instead be measured in units including kcal (Berg, 2003). In addition, the percent of VO_{2max} ($\%VO_{2max}$) at which an athlete can complete a given effort is also important for race performance and is related to RE (Costill, 1972).

The extent and timing of declines in distance-running performance may differ between the sexes, although the dearth of studies including female master athletes precludes making firm assertions on this matter. While VO_{2max} decreases similarly in sedentary and endurance-trained males, female athletes may exhibit a steeper decline than sedentary counterparts (H. Tanaka & Seals, 2003, 2008). Additionally, evidence suggests that age-related performance decrements differ by age, with athletes experiencing relative stability between the mid-30s and age 50, and larger changes thereafter (Brisswalter & Nosaka, 2013; Brisswalter et al., 2014; Joyner, 1993; Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2003, 2008).

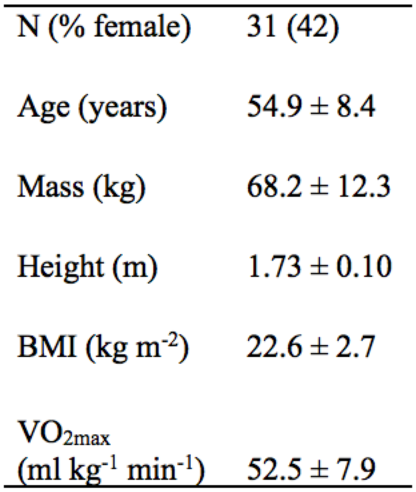
Several issues concerning performance in master athletes remain uncertain. More data are needed on this population, including female masters, to determine whether the effect of aging on performance is consistent across the sexes. It is also unclear whether RE changes with age, especially when evaluated using a more useful measure than simply VO_2. Therefore, the major aim of this study was to determine whether age is related to VO_{2max}, submaximal VO_2, alloVO_2, EC, or $\%VO_{2max}$ in runners training for long-distance races. Additionally, we sought to determine whether these relationships differ between females and males. We predicted that age would be negatively correlated with VO_{2max} but not significantly related to measures of RE, and that we would observe sex differences in relationships between age and running performance variables.

Methods

Subjects

This study was reviewed and approved by the University of Minnesota Institutional Review Board, and all subjects provided written consent prior to enrollment in the study. Participants were recruited from the Twin Cities metropolitan area via an online running newsletter and emails to local running teams. To be eligible for the study, potential subjects were required to be in training for a long-distance race, defined here as between 10 miles and a marathon in distance. Potential subjects were screened for eligibility via email prior to scheduling study visits. Thirty-one participants (13 females and 18 males) enrolled in the study. Descriptive characteristics of the subjects can be found in Table 3.

Table 3. Descriptive characteristics of the subjects.



N (% female)	31 (42)
Age (years)	54.9 ± 8.4
Mass (kg)	68.2 ± 12.3
Height (m)	1.73 ± 0.10
BMI (kg m^{-2})	22.6 ± 2.7
VO_{2max} (ml kg^{-1} min^{-1})	52.5 ± 7.9

Values are reported as mean ± SD unless otherwise indicated. BMI: body mass index; VO_{2max}: maximal aerobic capacity.

Experimental Approach to the Problem

We recruited master runners, aged 40 and older, who planned to participate in a long-distance race of at least 10 miles but no longer than a marathon. Study visits took place within four weeks of each master athlete's goal race. At the visits, all runners completed a treadmill marathon-intensity effort (MIE) and VO_{2max} test.

Maximal aerobic capacity and RE are known contributors to distance running performance. We measured RE in a treadmill test in which subjects maintained a heart rate of 88% of their age-predicted maximum heart rate (MHR). This value was chosen because trained runners are predicted to complete a marathon at 80-85% VO_{2max} (Basset & Howley, 2000). Eighty percent of VO_{2max} corresponds to a heart rate of 88% of the MHR (Londeree et al., 1995; Swain et al., 1994).

Procedures

Testing Sessions

Participants reported to the Clinical Exercise Physiology Laboratory at the University of Minnesota for study visits. Testing procedures occurred in the order described below. Participants were asked not to eat, consume caffeine or alcohol, or use tobacco within three hours of their study visits. We also requested that they not engage in strenuous exercise, defined as long runs, quality workouts, or strength training, within 24 hours of their visits.

Anthropometric Measurements

Height was measured to the nearest 0.25 inch using a stadiometer (ACCUSTAT™ Stadiometer, Genentech, San Francisco, CA), and weight was measured to the nearest 0.1 pound on an electronic scale (Etekcity, Anaheim, CA). Body mass index (BMI) was calculated as mass in kg per height (in m) squared.

Running Economy Testing

All treadmill tests were conducted on a Woodway Pro XL treadmill (Woodway, Waukesha, WI). Running economy was evaluated in a submaximal treadmill test designed to mimic a marathon-intensity effort (MIE). Respiratory gases were measured throughout the MIE bout (Ultima CPX and BreezeSuite software, MGC Diagnostics, St. Paul, MN). Competitive runners complete a marathon race at approximately 80% of VO_{2max} (Basset & Howley, 2000), which corresponds to 88% of MHR (Londeree et al., 1995; Swain et al., 1994). Each subject was allowed to warm up for several minutes at a 1% incline and speed of their choice. Investigators adjusted the treadmill speed so that the runner reached their target heart rate, which was 88% of their age-predicted MHR. To calculate predicted MHR, the following equation was used:

$MHR = 208 – (0.7 * age)$ (H. Tanaka et al., 2001).

Participants ran for five minutes in this target heart rate zone while investigators adjusted the treadmill speed as necessary. Rating of perceived exertion was measured at the beginning and end of this five-minute period. During the MIE, we monitored participants' RER to ensure that it stayed below 1.0. A RER of 1.0 or lower is required to calculate a caloric equivalent value and measure EC (Péronnet & Massicotte, 1991). If athletes exhibited RER consistently at or above 1.0, we ended the MIE run early so as not to cause undue fatigue.

Maximal Aerobic Capacity Testing

Participants performed an incremental treadmill test to exhaustion to determine their VO_{2max}. This test occurred approximately 10 minutes after the end of the RE test. The speed for this test was based on subjects' self-reported estimated current 5-km race pace (W. A. Braun & Paulson, 2012). Subjects began by walking for one minute at 1.39 $m\ s^{-1}$ (3.1 mph) on a level treadmill. Treadmill grade was then increased to 1%, and speed increased to 75% of each subject's 5-km race speed for three minutes. All subsequent stages lasted one minute. Over five stages, speed was increased to reach 5-km race speed. In the following stages, speed remained constant and grade was raised by 2.5% each minute. Rating of perceived exertion (RPE) on a 6-20 Borg scale (Borg & Noble, 1974) was recorded at the end of each stage. Subjects ran to volitional exhaustion. An Ultima CPX cart and BreezeSuite software (MGC Diagnostics, St. Paul, MN) were used for collection and analysis of respiratory gas data throughout both the maximal and submaximal exercise tests. Participants also wore a heart rate monitor (Polar, Bethpage, NY) throughout treadmill testing. Maximal aerobic capacity was determined using BreezeSuite breath-by-breath software.

Statistical Analyses

The present study had a cross-sectional design. Maximal aerobic capacity was determined with mid five-of-seven averaging recorded by the BreezeSuite software. Running economy was evaluated using several different methods. Submaximal oxygen consumption was measured in ml kg^{-1} min^{-1} (VO_2) and was also calculated with allometric scaling of body mass to the -0.66 power, i.e. ml $kg^{-0.66}$ min^{-1} ($alloVO_2$). The energy cost (EC) of running, in kcal kg^{-1} km^{-1}, in the MIE was also calculated (Fletcher, Esau, & MacIntosh, 2009). Average respiratory exchange ratio (RER) over the five-minute running test was used to determine a caloric equivalent value in kcal l O_2^{-1} (Péronnet & Massicotte, 1991). This value was multiplied by VO_2 and divided by each participant's average speed in m/min to find EC. Finally, the percent of VO_{2max} ($\%VO_{2max}$) that the MIE required was calculated as mean VO_2 divided by VO_{2max} and multiplied by 100%.

We used Statistical Package for the Social Sciences (SPSS; IBM, Armonk, NY), version 23, for all statistical analyses. Correlation was used to evaluate the relationships between age and VO_{2max}, submaximal VO_2, $alloVO_2$, EC, and $\%VO_{2max}$. The Shapiro-Wilk test was used to check that each variable was normally distributed. The alpha level for significance for tests was set at $p < 0.05$.

In addition to evaluating these relationships in the group as a whole, we explored whether sex differences exist in the age-related changes to maximal and submaximal running-performance variables. To explore this issue, we performed correlation tests on males and females separately.

Results

Thirty-one participants, including 13 females and 18 males, were enrolled in the study. All runners completed the VO_{2max} test. MIE data are unavailable for five participants who had RER values greater than 1.0 (one female and four males), nor for four other runners due to technical issues (two females and two males). Therefore, submaximal VO_2, alloVO_2, and EC were determined for 22 participants (ten females and 12 males).

In the group as a whole, age was significantly and negatively related to VO_{2max} (r = -0.580, p = 0.001). AlloVO_2 also declined significantly with age (r = -0.454, p = 0.034). There were no other statistically significant relationships between age and running parameters when considering all runners. Figure 3 depicts the relationships between age and VO_{2max}, submaximal VO_2, alloVO_2, EC, and %VO_{2max} among all subjects.

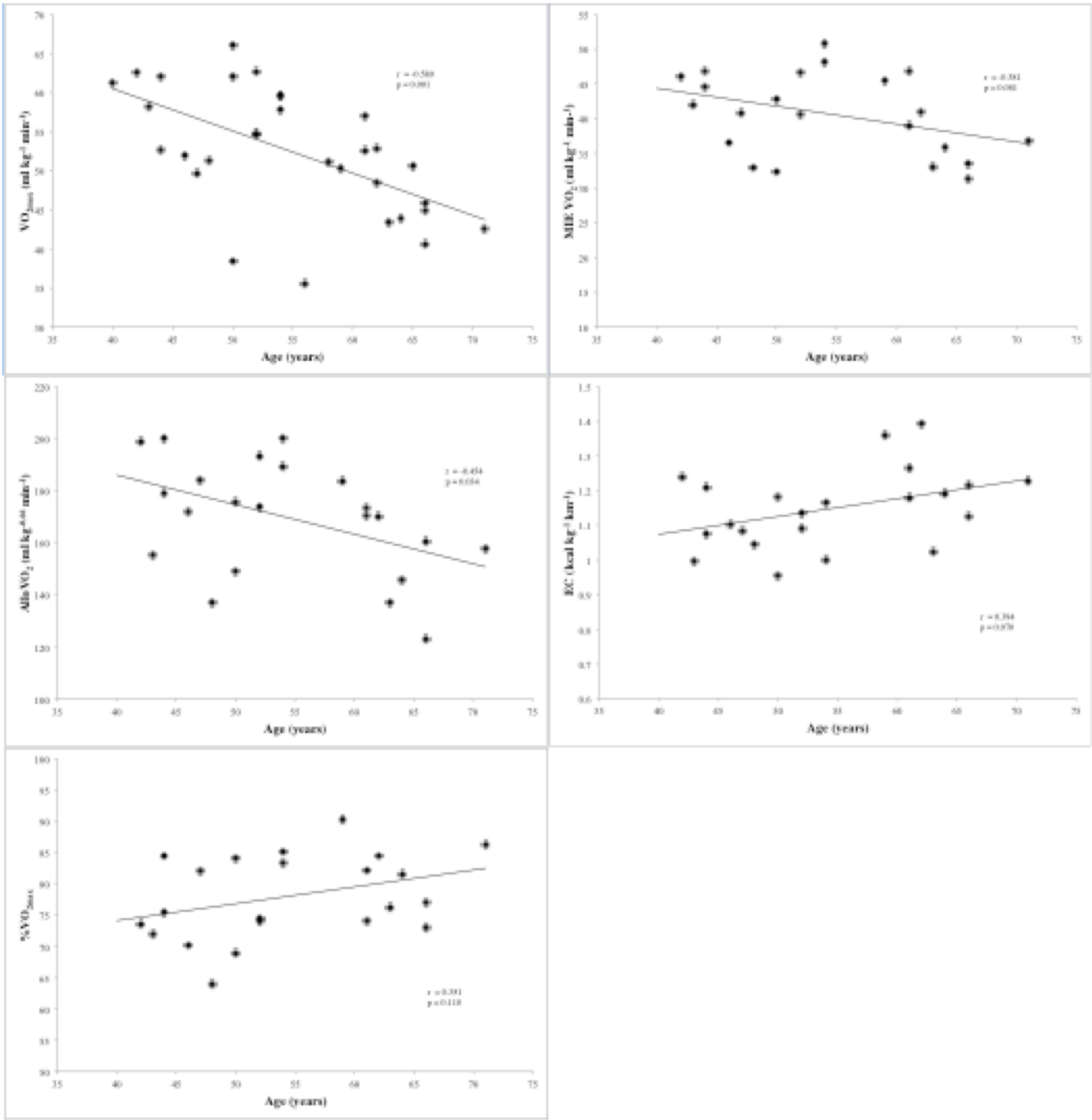


Figure 3. Relationships between age and running performance variables in all participants.
VO_{2max}: maximal aerobic capacity; MIE: marathon-intensity effort; VO_2: oxygen consumption; alloVO_2: allometrically scaled VO_2; EC: energy cost.

In the analyses of each sex separately, age was positively related to EC in females only (r = 0.649, p = 0.042). Meanwhile, males exhibited a significant negative relationship between age and VO_{2max} (r = -0.720, p = 0.001), MIE VO_2 (r = -0.600, p = 0.039), and MIE alloVO_2 (r = -0.730, p = 0.007), while females did not. Figures 4 and 5 show the relationships between age and running performance variables in females and males, respectively.

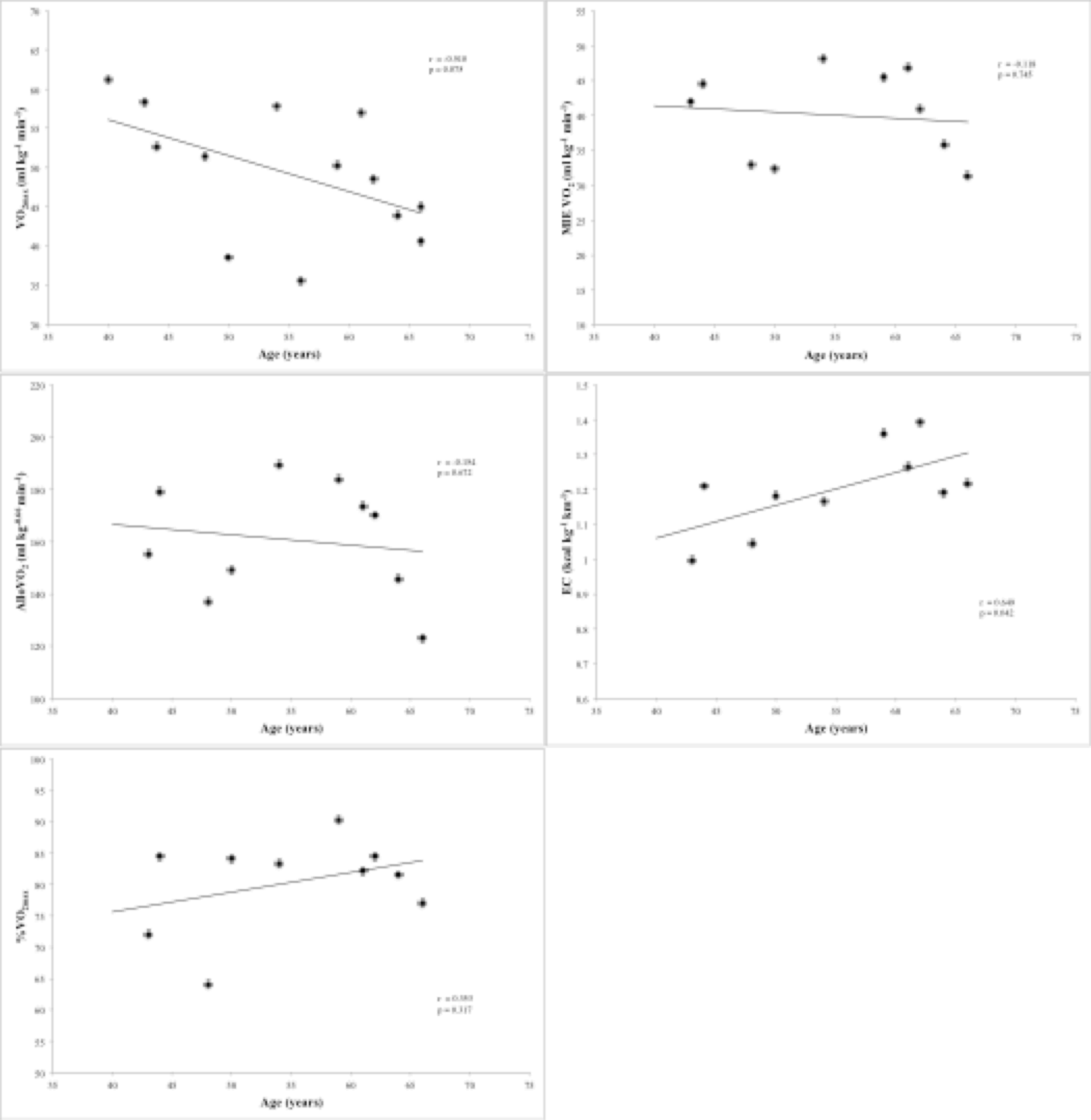


Figure 4. Relationships between age and running performance variables in female master runners.
VO_{2max}: maximal aerobic capacity; MIE: marathon-intensity effort; VO_2: oxygen consumption; alloVO_2: allometrically scaled VO_2; EC: energy cost.

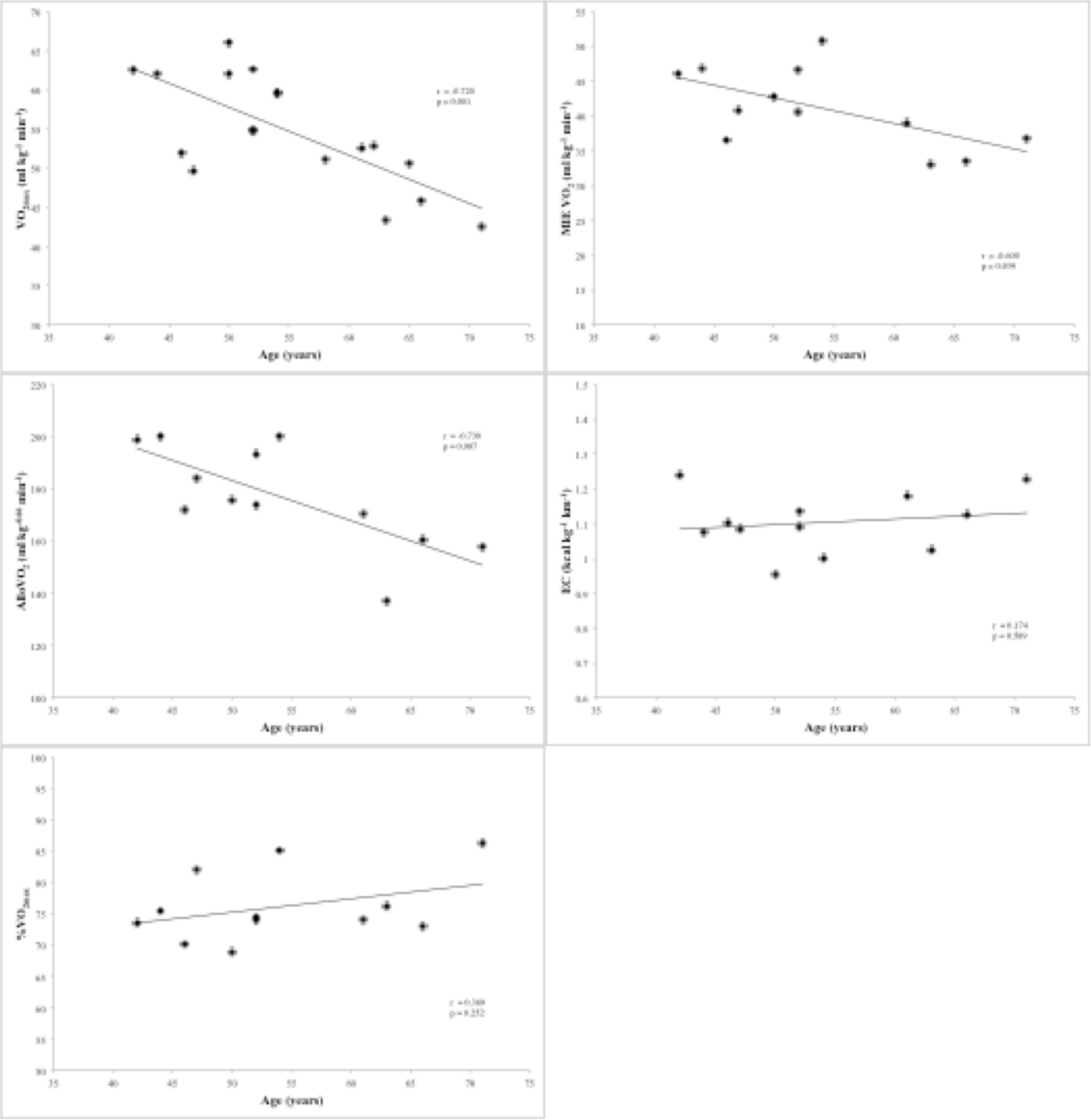


Figure 5. Relationships between age and running performance variables in male master runners.
VO_{2max}: maximal aerobic capacity; MIE: marathon-intensity effort; VO_2: oxygen consumption; alloVO_2: allometrically scaled VO_2; EC: energy cost.

Discussion

In this cross-sectional study, we found that maximal aerobic capacity and allometrically scaled VO_2 during a marathon-run simulation were significantly and negatively associated with age in distance-trained runners of both sexes, while age was not significantly related to other measures of RE. The change in VO_{2max} is unsurprising based on consistent findings in previous studies on older athletes, while our observation of alterations in RE with age contrasts with the results of other studies. We also found that female and male master runners may differ in the age-related changes in running performance that they experience.

As expected based on a wide body of literature on the effects of aging on exercise, VO_{2max} decreased with age (Figure 3). Other studies have consistently found that VO_{2max} is lower in older than younger people (Buskirk & Hodgson, 1987; Fitzgerald et al., 1997; Hagberg, 1987; Hawkins & Wiswell, 2003; Hodgson & Buskirk, 1977; Joyner, 1993; Katzel et al., 2001; Lepers & Stapley, 2016; Maharam et al., 1999; Reaburn & Dascombe, 2008; Reed & Gibbs, 2016; H. Tanaka & Seals, 2003, 2008; Wilson & Tanaka, 2000). As others have noted, cross-sectional studies of masters athletes do not necessarily represent VO_{2max} trends in the general population due to selection bias: older people who enroll in studies that require maximal exercise testing tend to be healthy and fit (Hawkins & Wiswell, 2003; Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2003, 2008). Therefore, our finding of an average decrease in VO_{2max} of -0.580 ml kg^{-1} min^{-1} $year^{-1}$ in both sexes between the ages of 40 and 71 might be lower than the true value in the population of this age range.

The increase in EC with age in female runners implies that athletes do become less economical as they get older. This result is in contrast with those of previous studies that have found a preservation of VO_2 at submaximal speeds (Allen et al., 1985; Evans, Davy, Stevenson, & Seals, 1995; Quinn et al., 2011). However, compared to using VO_2 as a measure of RE, EC presents an advantage. While VO_2 depends on substrate oxidation (Péronnet & Massicotte, 1991), EC represents an absolute value of energy required, regardless of whether it comes from lipids or carbohydrates. Our study extends the findings of Fletcher, Esau, and MacIntosh (2009). This group tested trained male runners at three submaximal speeds and evaluated both VO_2 and EC in kcal kg^{-1} km^{-1}. The oxygen cost of running was not significantly different at each speed, but EC increased with speed (Fletcher et al., 2009). Similarly, we saw no significant change in VO_2 (ml kg^{-1} min^{-1}) with age, whereas EC was positively associated with age. This result supports the use of EC as a more sensitive means of evaluating RE in trained runners.

A recent study may explain why the EC of submaximal running increases with age in female masters (figure 2). Running economy depends on metabolic, cardiopulmonary, neuromuscular, and biomechanical factors (Barnes & Kilding, 2015a). A key biomechanical attribute associated with high RE is musculotendinous stiffness in the lower legs (Barnes & Kilding, 2015a; Saunders et al., 2004). Such stiffness enables efficient storage and use of elastic energy, which can reduce submaximal VO_2 by lowering horizontal and vertical oscillations unnecessary for the motion of running (Burgess & Lambert, 2010). Among elite endurance athletes, larger horizontal and vertical forces are related to reduced RE and slower 3-km running time (Støren et al., 2011). Cavagna and colleagues (2008) compared the storage of elastic energy and work done in older and younger people running at different speeds. The older group (mean age 73.6 years) did more external work and did not store as much elastic energy as the younger group (mean age 20.8). Thus, compared to the younger participants, the older subjects required more energy to do the same amount of mechanical work. The application of these findings to the present study is limited by the inclusion of sedentary participants and the lack of females in the older group, as well as the greater age of older participants (Cavagna et al., 2008). However, if these results hold for better-trained, younger, and female runners, then the reduction in mechanical efficiency with age may account for the higher energetic cost of running with age.

Our finding of a significant relationship between MIE alloVO_2 and age, but not MIE VO_2 and age, across the whole group supports the use of allometric scaling of body mass in the use of VO_2 to quantify RE. Because VO_2 does not increase linearly with body mass, scaling body mass to the -2/3 or -0.75 power allows comparison of RE among runners with different body mass (Barnes & Kilding, 2015a; Bergh et al., 1991). We chose to scale body mass to the -0.66 power in the present study to facilitate such comparison. This result also contradicts findings of past studies in which RE, evaluated as submaximal VO_2, has not been significantly related to age (Allen et al., 1985; Evans, Davy, Stevenson, & Seals, 1995; Quinn et al., 2011). Interestingly, however, we observed a significant negative relationship between MIE VO_2 and age in male master runners, but not in their female counterparts. Males alone also showed a significant negative association between age and VO_{2max}, while this relationship was not significant in females. These patterns would mean that males lose maximal aerobic capacity with age but become more economical at lower exercise intensities. Perhaps hormone-related differences in aging, as discussed below (Hawkins & Wiswell, 2003), can account for the apparently distinct effects of aging on running performance variables between the sexes.

We observed three sex differences in the effects of age on running-performance variables (Figures 4 and 5): namely, that EC during a MIE run increased with age in females, and VO_{2max} and MIE VO_2 decreased with age in males. Others have found conflicting results regarding sex differences and athletic performance. In a cross-sectional examination of national-level masters track athletes, females had larger performance decreases than males (Chopra & Tanaka, 2003). In contrast, Fleg and Latakka (1988) observed no sex difference in the rate of VO_{2max} decline with age. Our findings regarding MIE VO_2 would suggest that RE is less tightly coupled to age in females than in males. However, it is possible that age-related alterations in sex hormone levels interact with general aging processes to cause discrepant changes in athletic performance between the sexes (Hawkins & Wiswell, 2003). The lack of research on endurance-trained female masters athletes inhibits making firm conclusions regarding sex differences in running performance with age.

We must consider the possibility that MHR does not change according to the predictions of Tanaka and colleagues (2001), which would undermine our attempt to standardize effort level by heart rate. If MHR decreases more with age than predicted by the equation we used, then older participants would have been using a greater percent of their MHR than younger subjects.

It is also possible that the percent of maximal capacity, and hence percent of MHR, at which runners complete a marathon changes with age. Based on the findings of Basset and Howley (2000), trained open-age runners use approximately 80% of VO_{2max} during a marathon. Masters athletes may be able to use a smaller fractional capacity, in which case they would have exerted themselves above marathon intensity in the MIE.

Finally, the relationship between $\%VO_{2max}$ and percent of MHR may not be maintained as athletes get older. The target MIE heart rate for all subjects was 88% of the age-predicted MHR, corresponding to 80% of VO_{2max} (Londeree et al., 1995; Swain et al., 1994). In older runners, 80% of VO_{2max} may equate to a smaller percent of MHR as age increases. If this were the case, then we should have targeted lower heart rates during the MIE to reach 80% of VO_{2max}.

Our study has several limitations. Not all participants were tested at exactly the same point in their training relative to their goal races. We tested subjects within four weeks of their races; training periodization might have affected the VO_{2max} values that we measured (Billat et al., 2002). Nevertheless, we attempted to control for training status by requiring that subjects refrain from high-intensity workouts in the 24 hours prior to their testing session. Among female athletes, we did not control for menopausal status. However, menopause is a part of the aging process and therefore does not need to be adjusted for when considering the effects of age on running performance. Finally, although we requested that participants refrain from food intake within three hours of testing, we did not require standardized meal consumption prior to each study visit. The composition of meals eaten before testing might have altered observed RER values (Péronnet & Massicotte, 1991) which would affect the measurement of VO_2 and calculation of EC.

In conclusion, we have found that maximal aerobic capacity declines with age in master athletes who are in peak physical condition for a long-distance race. In female masters, more energy is required to run at a submaximal effort level as age increases. The increase in EC represents a loss of RE, as aging runners require more calories to support a given intensity level. Because long-distance races are completed at submaximal intensities, this change in EC may be detrimental to race performance. Meanwhile, male master runners show a decrease in submaximal VO_2 and alloVO_2, suggesting an improvement in RE with age. Importantly, our inclusion of female runners contributes to the relatively small body of literature on female endurance athletes.

CHAPTER 5: Predictors of long-distance race performance in master runners

Abstract:

Maximal aerobic capacity (VO_{2max}) and parameters related to training are associated with long-distance running performance in master athletes. Running economy (RE) predicts performance in younger runners, but its relationship to racing ability in older athletes is unclear. Allometrically scaled RE (alloVO_2; ml $kg^{-0.66}$ min^{-1}), energy cost (EC; kcal kg^{-1} km^{-1}), and percent of VO_{2max} (%VO_{2max}) required in a submaximal bout represent RE more accurately than VO_2. The VDOT score, estimating VO_{2max} and RE, can be used to compare races of different distances. PURPOSE: To determine predictors of temperature-converted VDOT in master runners training for a long-distance race (10-26.2 mi). METHODS: Twenty-three master runners (age 57±9 years; eight females) performed treadmill marathon-intensity-effort (MIE) and VO_{2max} tests within four weeks of their goal race. The MIE occurred at 88% of predicted maximum heart rate, which corresponds to estimated marathon intensity. Participants completed online training-history surveys. Stepwise multiple linear regression was used to find key predictors of VDOT. The alpha level for significance was 0.05. RESULTS: Converted VDOT was significantly associated with 3-year peak weekly training distance (3YP) ($r = 0.454$, $p = 0.039$), VO_{2max} ($r = 0.845$, $p = 0.000$), alloVO_2 ($r = 0.623$, $p = 0.005$), and EC ($r = -0.528$, $p = 0.018$). The best-fitting model included VO_{2max} and 3YP ($r = 0.898$). CONCLUSION: Physiological and training factors are related to race performance in master runners. The best predictors of VDOT are VO_{2max} and 3YP. Training to enhance these variables may improve distance-running performance in masters.

Introduction

Maximal aerobic capacity (VO_{2max}) is a notable predictor of performance in distance-running events (Basset & Howley, 2000). Differences in VO_{2max} can account for race times from one mile to the marathon (Foster, 1983). Among master runners, defined as runners aged 40 and older, VO_{2max} is an important predictor of distance running performance (Wiswell et al., 2000). As endurance athletes age beyond their mid-twenties, their VO_{2max} decreases (Reed & Gibbs, 2016). Race times in long-distance events, i.e. 10 km to the marathon, increase by approximately 6-9% with each decade of age beyond the mid- to late thirties; performance decrements tend to become steeper after the late 50s and again after age 70 (Brisswalter & Nosaka, 2013; Brisswalter et al., 2014; Joyner, 1993; Reaburn & Dascombe, 2008; H. Tanaka & Seals, 2003, 2008).

Several studies have shown that training factors may play a role in maintaining VO_{2max} with age, or slowing its decline. Dill and colleagues (1967) tracked young elite male distance runners over time and found the lowest rate of decline in VO_{2max} in the athlete who had kept up a high level of training throughout the study period. In non-elite populations, study participants with higher activity levels consistently demonstrate higher VO_{2max} and a slower rate of decrease than their sedentary counterparts (e.g.(Dehn & Bruce, 1972)). The frequency, volume, and intensity of training required to mitigate age-related declines in VO_{2max} remain unclear.

Running economy (RE) quantifies the efficiency of running at a submaximal speed and is typically reported in VO_2 (ml kg^{-1} $min^{=1}$) (Saunders et al., 2004). Among long-distance runners with similar VO_{2max}, RE may account for differences in race performance (Saunders et al., 2004). As with VO_{2max}, training may be important in maintaining RE as age increases (Trappe et al., 1996). However, in trained master runners, age does not appear to have negative effects on RE, measured as VO_2 (Evans, Davy, Stevenson, & Seals, 1995; Quinn et al., 2011).

Notably, the traditional units of RE may be flawed, as oxygen consumption does not increase linearly with body mass: a lighter athlete will use more oxygen per kg of body mass than a heavier person at the same relative intensity. Therefore, some have proposed that RE should be evaluated as ml O_2 kg $^{-0.66}$ min^{-1} or ml O_2 kg $^{-0.75}$ min^{-1}, using allometric scaling to account for size-based differences in VO_2 (alloVO_2; here, scaling body mass to the -0.66 power) (Barnes & Kilding, 2015a; Berg, 2003).

Additionally, a more accurate reflection of the energy cost of submaximal running would incorporate a measurement of calories (kcal) burned. With endurance training, lipid oxidation during exercise increases (Holloszy et al., 1977), which raises submaximal VO_2 and would make an endurance-adapted individual seem less efficient based on VO_2 alone (Berg, 2003). The energy cost of submaximal running (EC) can be calculated using the respiratory exchange ratio (RER) at a submaximal speed (Péronnet & Massicotte, 1991).

A third alternative to VO_2 is the percent of VO_{2max} (%VO_{2max}) that a submaximal effort elicits. A competitive runner will use approximately 75-85% of VO_{2max} in a marathon and 90-100% of VO_{2max} in a 10-km race (Basset & Howley, 2000; Costill et al., 1973). Running economy determines the percent of VO_{2max} at which a person can run for a certain time or distance, thus setting his or her top speed for those parameters (Barnes & Kilding, 2015a; Basset & Howley, 2000; Costill et al., 1973). A more economical runner will use a lower percent of VO_{2max} at the same relative intensity than a less efficient person will.

Comparing runners' performances at different distances requires more than calculation of pace, as athletes naturally run faster at shorter distances. The VDOT score allows for such comparison. The formula estimated VO_{2max} based on an athlete's race time, and it accounts for RE by incorporating the estimated percent of VO_{2max} that a person requires for a given race distance (Daniels, 2014). The VDOT score may also be adjusted for temperature, as hot conditions can cause distance runners' pace to slow (Cheuvront & Haymes, 2001; El Helou et al., 2012). Therefore, VDOT can be a useful tool to evaluate races of varying distances held in different environmental conditions.

In spite of the recent increases in participation and performance of master runners (Lepers & Cattagni, 2012; Lepers & Stapley, 2016), little is known about the training habits of older runners in preparation for long-distance races or whether training factors are related to race outcomes. The relationship between RE and performance also remains uncertain, especially using more appropriate measures of RE, i.e. alloVO_2, EC, and $\%VO_{2max}$. Therefore, the purposes of this study were to determine the most important predictors of long-distance race performance (10 miles to the marathon) in master runners and to characterize training patterns of master runners in their buildup to a long-distance race. We hypothesized that VO_{2max} would be significantly correlated with VDOT score and that we would observe a wide range of training volumes and workout frequencies among this group of master runners.

Methods

Subjects

Participants were recruited from the Twin Cities metropolitan area via an online running newsletter and emails to local running teams. To be eligible for the study, potential subjects were required to be in training for a road race between 10 miles and a marathon in distance. They were at least 40 years old and were thus classified as master athletes. Potential subjects were screened for eligibility via email prior to scheduling study visits. The University of Minnesota Institutional Review Board approved this study, and all participants provided written informed consent before enrollment. Twenty-three participants (eight females and 15 males) enrolled in the study.

Experimental Approach to the Problem

We recruited master runners who planned to participate in a long-distance race of at least 10 miles but no longer than a marathon. Study visits took place within four weeks of each person's goal race. At the visits, runners completed a treadmill marathon-intensity effort (MIE) and VO_{2max} test.

Maximal aerobic capacity and RE are known contributors to distance running performance. We measured RE in a treadmill test in which subjects maintained a heart rate of 88% of their age-predicted maximum heart rate (MHR). This value was chosen because trained runners are predicted to complete a marathon at 80-85% VO_{2max} (Basset & Howley, 2000). Eighty percent of VO_{2max} corresponds to a heart rate of 88% of the MHR (Londeree et al., 1995; Swain et al., 1994).

Procedures

Testing Sessions

Participants reported to the Clinical Exercise Physiology Laboratory at the University of Minnesota for study visits. Testing procedures occurred in the order as described below. Participants were asked not to eat, consume caffeine or alcohol, or use tobacco within three hours of their study visits. We also requested that they not engage in strenuous exercise, defined as long runs, quality workouts, or strength training, within 24 hours of their visits.

Anthropometric Measurements

Height was measured to the nearest 0.25 inch using a stadiometer (ACCUSTAT™ Stadiometer, Genentech, San Francisco, CA), and weight was measured to the nearest 0.1 pound on an electronic scale (Etekcity, Anaheim, CA). Body mass index (BMI) was calculated as mass in kg per height (in m^2).

Running Economy Testing

All treadmill tests were conducted on a Woodway Pro XL treadmill (Woodway, Waukesha, WI). Running economy was evaluated in a submaximal treadmill test designed to mimic a MIE. Competitive runners complete a marathon race at approximately 80% of VO_{2max} (Basset & Howley, 2000), which corresponds to 88% of MHR (Londeree et al., 1995; Swain et al., 1994). Each subject was allowed to warm up for several minutes at a 1% incline and speed of their choice. Investigators adjusted the treadmill speed so that the runner reached their target heart rate, which was 88% of their age-predicted MHR. To calculate predicted MHR, the following equation was used:

$MHR = 208 - (0.7 * age)$ (H. Tanaka et al., 2001).

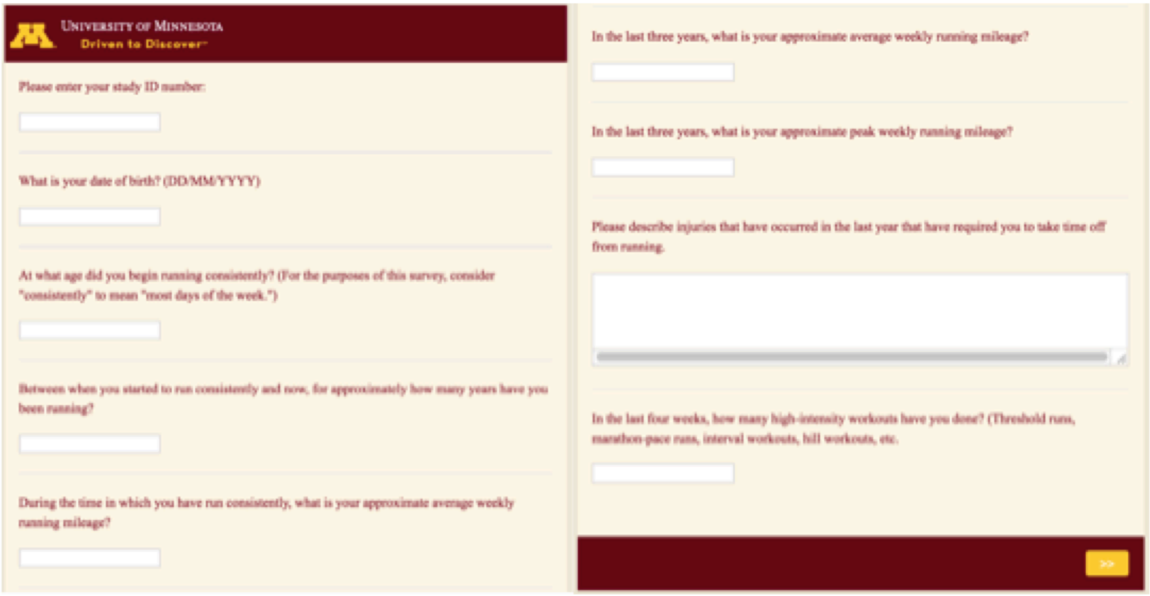
Participants ran for five minutes in this target heart rate zone while investigators adjusted the treadmill speed as necessary. Rating of perceived exertion was measured at the beginning and end of this five-minute period.

Maximal Aerobic Capacity Testing

Participants performed an incremental treadmill test to exhaustion to determine their VO_{2max}. This test occurred approximately 10 minutes after the end of the RE test. The speed for this test was based on subjects' self-reported estimated current 5-km race pace (W. A. Braun & Paulson, 2012). Subjects began by walking for one minute at 1.39 m s^{-1} (3.1 mph) on a level treadmill. Treadmill grade was then increased to 1%, and speed increased to 75% of each subject's 5-km race speed for three minutes. All subsequent stages lasted one minute. Over five stages, speed was increased to reach 5-km race speed. In the following stages, grade was raised by 2.5% each minute. Rating of perceived exertion (RPE) on a 6-20 Borg scale (Borg & Noble, 1974) was recorded at the end of each stage. Subjects ran to volitional exhaustion. An Ultima CPX cart and BreezeSuite software (MGC Diagnostics, St. Paul, MN) were used for collection and analysis of respiratory gas data throughout both the maximal and submaximal exercise tests. Participants also wore a heart rate monitor (Polar, Bethpage, NY) throughout treadmill testing. Maximal aerobic capacity was determined as the highest VO_2 value as recorded by the BreezeSuite breath-by-breath software.

Survey Questions

Study participants completed a brief online survey within 1-2 weeks prior to their study visit. Figure 6 shows the survey questions. Runners were asked about their training history and about recent injuries. Participants reported training volume in miles, which we later converted to km. For the purpose of this study, we considered only three-year average weekly training distance (3YA), three-year peak weekly training distance (3YP), and the number of intensity sessions completed in the four weeks prior to the study visit (4WI). Intensity sessions were described as interval workouts, fartlek workouts, tempo or threshold runs, hill workouts, etc.



Please enter your study ID number:

What is your date of birth? (DD/MM/YYYY)

At what age did you begin running consistently? (For the purposes of this survey, consider "consistently" to mean "most days of the week.")

Between when you started to run consistently and now, for approximately how many years have you been running?

During the time in which you have run consistently, what is your approximate average weekly running mileage?

In the last three years, what is your approximate average weekly running mileage?

In the last three years, what is your approximate peak weekly running mileage?

Please describe injuries that have occurred in the last year that have required you to take time off from running.

In the last four weeks, how many high-intensity workouts have you done? (Threshold runs, marathon-pace runs, interval workouts, hill workouts, etc.

Figure 6. Survey questions administered to master athletes.

Statistical Analysis

This study employed a cross-sectional design. Statistical Package for the Social Sciences (SPSS) was used for all statistical analyses. Stepwise multiple linear regression was used to determine the relationships between converted VDOT score and running performance variables. This method corrects for multiple testing. Independent variables included 3YA, 3YP, 4WI, VO_{2max}, $alloVO_2$, EC, and $\%VO_{2max}$. The criterion to keep a variable in the final model was an F-statistic ≤ 50, while the criterion to remove a variable from the model was an F-statistic ≥ 100. The VDOT calculator is available online at http://runsmartproject.com/calculator/. The formulas on which it is based take into account the time it takes for an individual to complete a race. This duration is related to a %VO_{2max} value, while the runner's velocity corresponds to a given VO_2. This information is then used to predict VO_{2max} (Daniels & Gilbert, 1979). The website also calculates predicted race times and VDOT scores based on race-day temperatures. We collected temperature data for each race from www.wunderground.com and used this information to calculate converted VDOT scores for each subject. To evaluate training parameters, means, standard deviations, and ranges were calculated for 3YA, 3YP, and 4WI.

Results

Of the 23 participants enrolled in the study, we collected VO_{2max} data from all runners and MIE data from 19 athletes. Demographic characteristics of the subjects are presented in Table 4. Survey data were obtained from all participants. Table 5 shows the self-reported training characteristics of the athletes. There was a wide range of reported mileage and intensity sessions.

Table 4. Descriptive characteristics of the participants.

N (% female)	23 (35)
Age (years)	57 ± 9
Mass (kg)	68.7 ± 11.2
Height (m)	1.75 ± 0.09
BMI (kg/m^2)	22.4 ± 2.7
VO_{2max} (ml/kg/min)	52.5 ± 8.1

Values are mean ± SD unless otherwise indicated. BMI: body mass index; VO_{2max}: maximal aerobic capacity.

Table 5. Self-reported training characteristics of the participants.

Training parameter (N)	Mean ± SD (range)
3YA (km) (23)	47.2 ± 23.0 (6.4, 120.7)
3YP (km) (23)	84.3 ± 35.4 (37.0, 185.1)
4WI (no.) (22)	7.2 ± 3.5 (2, 15)

3YA: three-year average weekly training distance; 3YP: three-year peak weekly training distance; 4WI: number of intensity sessions completed in the four weeks prior to the study visit.

We used stepwise multiple linear regression to evaluate relationships between converted VDOT and 3YA, 3YP, 4WI, VO_{2max}, alloVO_2, EC, and %VO_{2max}. Of these variables, converted VDOT had a significant relationship with 3YP ($r = 0.454$, $p = 0.039$), VO_{2max} ($r = 0.845$, $p = 0.000$), alloVO_2 ($r = 0.623$, $p = 0.005$), and EC ($r = -0.528$, p = 0.018). The best-fitting model for VDOT included VO_{2max} and 3YP, after correcting for multiple testing. The r-statistic for the model including VO_{2max} alone was 0.845, and the r-statistic for the second model, which also included 3YP, was 0.898. The unstandardized beta weights for the first and second model, respectively, were 0.980 (VO_{2max}) and 0.915 (VO_{2max}) and 0.081 (3YP). The standardized beta weights were 0.845 (VO_{2max}) and 0.788 (VO_{2max}) and 0.311 (3YP) for the first and second model, respectively. Figure 7 displays the relationships between converted VDOT and VO_{2max} (A) and 3YP (B).

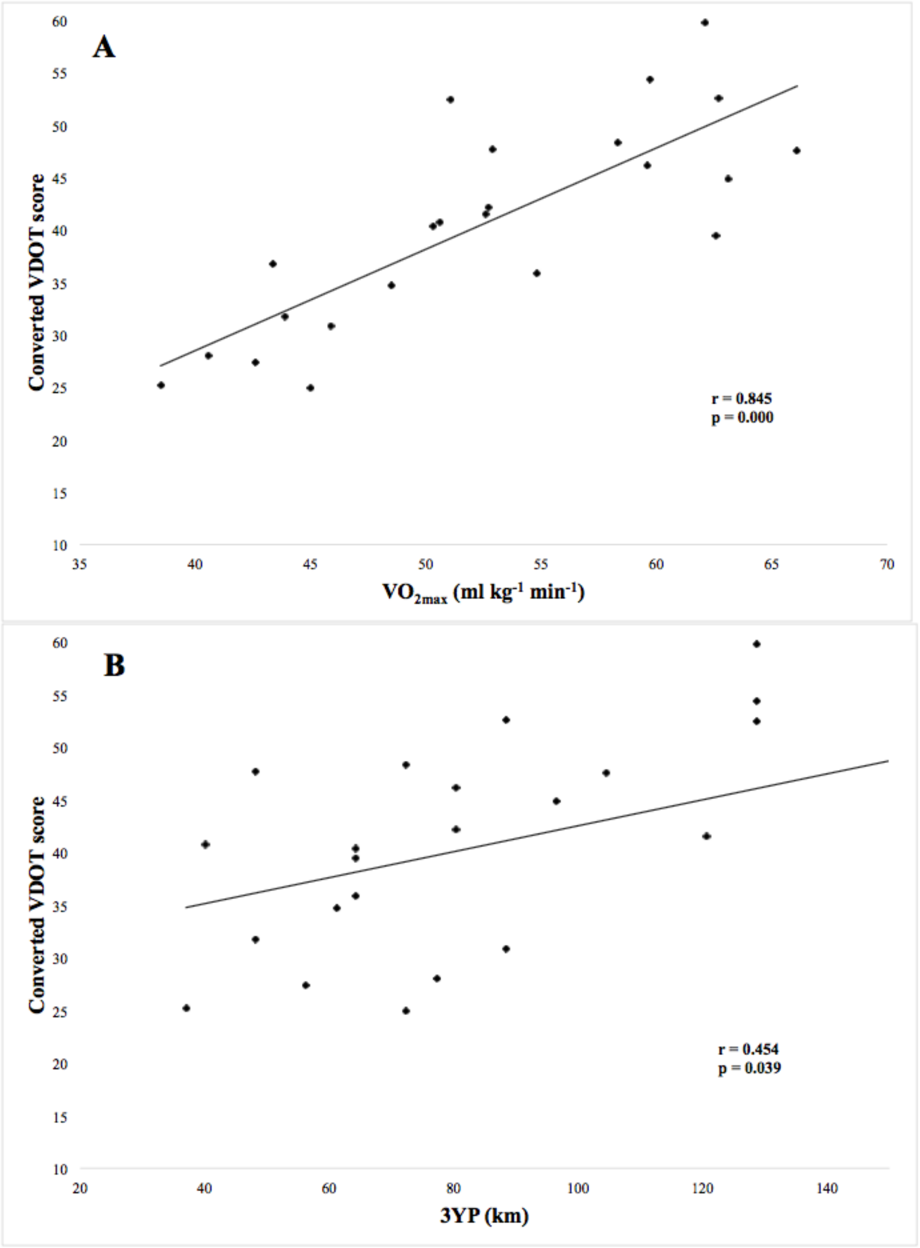


Figure 7. Relationships between converted VDOT score and VO_{2max} (A) and 3YP (B). VO_{2max}: Maximal aerobic capacity. 3YP: reported peak weekly training distance over the past three years.

Discussion

In this cross-sectional study of master runners, we have shown that maximal aerobic capacity and the peak weekly distance run in the three years leading up to a goal long-distance race are highly correlated with actual performance in that race, as quantified through a VDOT score. We have also found that master athletes complete a wide range of weekly training distances and high-intensity workouts during preparation for races.

The VDOT score, similar to a predicted VO_{2max} value, was developed by Jack Daniels to facilitate comparison of race performances at different distances (Daniels, 2014). A race of a given distance is predicted to require a certain fraction of one's maximal capacity; a runner can use his or her time in a race of one distance to predict a time in a race of a different distance (Daniels, 2014). Notably, VDOT scores account for both RE and VO_{2max}: a person may have a high measured VO_{2max} but, due to having a low RE, perform more poorly than expected on the basis of VO_{2max} alone (Daniels, 2014). Thus, VDOT scores can serve as a basis of comparison between athletes who have run varying race lengths. The strength of VDOT comparisons decreases as the discrepancy between race lengths grows (e.g. it may not be useful to compare a mile performance with a marathon time) (Daniels, 2014), but we believe that races from 10 miles to a marathon in length are similar enough in a non-elite population to merit the use of VDOT scores.

Stepwise multiple linear regression showed that both physiological and training factors may influence race performance. Maximal aerobic capacity represents the body's ability to take in and use oxygen (Basset & Howley, 2000). In a group of people of different VO_{2max} values, maximal capacity explains much of the discrepancy in running performance (Timothy D. Noakes, 1988). In the present study, participants had a wide range of VO_{2max} (38.5 – 66.1 ml kg^{-1} min^{-1}). Therefore, it is logical that VO_{2max} was closely correlated with VDOT (r = 0.845, p = 0.000), a marker of race performance. Previous studies have found that VO_{2max} can predict performance in master athletes. In a group of male and female master runners, VO_{2max} was the best predictor of race times in 5-km, 10-km, and marathon distances completed in the past year (Wiswell et al., 2000). Among female distance runners aged 49-56, VO_{2max} explained nearly three-quarters of the differences in race times between runners (Evans, Davy, Stevenson, Reiling, et al., 1995). Our study corroborates these findings. Moreover, we have also shown that the relationship between VO_{2max} and race performance holds for master runners who are in peak shape for a long-distance race.

In addition to VO_{2max}, we found that two measures of running economy are significantly correlated with the performance of master runners in a long-distance race. $AlloVO_2$ was positively related to VDOT score (r = 0.623, p = 0.005), while EC showed a negative association with VDOT (r = -0.528, p = 0.018). The positive correlation between $alloVO_2$ and VDOT is somewhat surprising. Faster runners are typically more economical than slower runners (Joyner & Coyle, 2008; Don W. Morgan et al., 1995) and would be expected to require less oxygen to run at a given intensity (e.g. half-marathon race pace) than slower runners do. However, we have shown that the faster runners in the present study—those with higher VDOT scores—also tended to have higher VO_{2max} values than the runners with slower performances. We did not find a significant association between VDOT and $\%VO_{2max}$ elicited from the MIE. Assuming that actual races elicited a similar effort as the MIE in the laboratory, all runners may have been using a similar fraction of their VO_{2max} during their races, and those with higher maximal capacities would consume more oxygen simply due to their greater VO_{2max}.

The negative relationship between EC and VDOT score may be linked to the importance of efficiency during long-distance races. Energy cost is calculated using the respiratory exchange ratio during a submaximal running bout. The mean RER over this time period corresponds with a caloric equivalent value, in kcal l O_2^{-1} (Péronnet & Massicotte, 1991). When the caloric equivalent is multiplied by the average VO_2, in ml kg^{-1} min^{-1}, and divided by the speed in km min^{-1}, the resulting energy cost has units of kcal kg^{-1} min^{-1}, a measure proposed by Berg (2003) and Barnes and Kilding (2015a) to capture RE. Such a value reflects the actual demands of running better than VO_2 does because EC accounts for substrate utilization.

In long-distance races, energy supply is a limiting factor. Running gradually depletes glycogen stores in skeletal muscle, and runners must slow when energy supplied to muscle becomes insufficient to support their current pace (Coyle, 2007). Athletes with good RE have high activity of oxidative enzymes in their muscles, enhancing their ability to oxidize lipids, sparing carbohydrate stores (i.e. glycogen), and requiring less oxygen to produce ATP to fuel the maintenance of their pace (Saunders et al., 2004). A runner who can use less energy than another person can theoretically run faster and/or longer than the less economical athlete. This explanation supports our observation of a significant negative association between energy cost and VDOT score. Participants who required more energy for a given body mass and speed also had slower race times than athletes who were more energetically efficient. Furthermore, EC may increase with age. A study by Cavagna and coworkers (2008) found that older runners had to do more external work than younger runners did at a given speed. The older subjects had a diminished ability to store elastic energy, possibly due to an age-related decrease in muscular strength

(Cavagna et al., 2008). We did not include age as a predictor of VDOT in the present study, but age-associated changed in EC may contribute to the general slowing of long-distance race times that occurs in master runners (Brisswalter & Nosaka, 2013).

The reported top weekly training distance over the past three years was significantly and positively associated with VDOT score, whereas average weekly training distance and quality workouts in the past four years were not. Other investigators have found that training parameters can predict race performance in master runners. Among a cohort of master runners, weekly training distance was a key predictor of 5-km, 10-km, and marathon performance in both sexes (Wiswell et al., 2000). Training habits, such as weekly distance and average pace, have also been found to correlate significantly with VO_{2max} (Eskurza et al., 2002; Pimentel et al., 2003; Pollock et al., 1997; H. Tanaka et al., 1997). Runners who better maintain the frequency, volume, and intensity of training as they age may also exhibit smaller declines in VO_{2max} than their counterparts who reduce their training (Pollock et al., 1997; Trappe et al., 1996). Training practices that contribute to the maintenance of VO_{2max} may also help to mitigate declines in race performance.

In the present study, we did not find a significant relationship between VDOT and average training distance over the past three years, only with VDOT and peak weekly distance. This observation may be due to the wide range of weekly volumes that our participants reported (from 6.4 to 120.7 km week^{-1}), which is in keeping with other studies of training in master runners (e.g. (Wiswell et al., 2001)). However, we also saw great variation in reported 3YP: from 37.0 to 185.1 km week^{-1}. This result suggests that incorporating high training volumes may contribute to faster race times; conversely, faster runners may also be able to complete higher weekly distances than slower runners simply because it takes them less time to do so.

A limitation of this study is that the intensity that we chose to mimic a marathon effort, 80% of VO_{2max} (Basset & Howley, 2000), may have been greater than the actual proportion of VO_{2max} that our participants were able to use in their goal races. As Coyle (2007) notes, slower racers may use only 50-60% of their maximal capacity. Most of the study subjects who ran a marathon did so in three hours or greater, meaningfully longer than the 2:30 that Coyle (2007) cites for fast runners. Therefore, a more appropriate percent of VO_{2max} to target in the MIE bout may have been closer to 70% of VO_{2max} than 80%. However, of our 23 athletes, nine ran 10-mile or half marathon races. With the shorter distance and time, they would be expected to be able to use a higher percent of their VO_{2max} than they would in a marathon. The discrepancies between $\%VO_{2max}$ elicited during the MIE could have cancelled each other out when considering the marathon runners (for whom the intensity may have been too high) and shorter-distance racers (for whom the intensity may have been too low) together. In addition, one participant misunderstood the survey question regarding intensity sessions and entered an improbable number. This point was excluded from analysis.

In conclusion, the present cross-sectional study has shown that VO_{2max} and self-reported 3YP are the most important predictors of VDOT score in master runners who are training for a long-distance race. Two measures of RE, namely alloVO_2 and EC, also show significant relationships with VDOT score. Master athletes with higher maximal aerobic capacities and recent peak training distances, but who use less energy to run at a marathon-simulation effort, may expect faster race times than runners who are less efficient, have completed lower peak running volume, and have lower VO_{2max} values. Our study is novel in that we have evaluated RE, VO_{2max}, and training habits shortly before the goal races of our participants, thus gaining the ability to draw stronger relationships between these variables and actual race performance. Master runners and coaches may be able to apply our findings to their training parameters, working to increase or maintain VO_{2max} and to reach a high training volume leading up to a goal long-distance race.

CHAPTER 6: Conclusion

Physiological adaptations to endurance training may occur in experienced long-distance runners. Among competitive runners who completed a marathon-specific training cycle, VO_{2max} increased between the beginning and end of the training period, while the fraction of VO_{2max} required to perform a MIE bout decreased. Such adaptations may contribute to the phenomenon of runners being able to improve their performance over successive marathons despite already being highly trained. The findings of this study suggest that runners' bodies do not necessarily reach limits of adaptation even with repeated marathon training cycles.

Moreover, while the negative relationship between age and VO_{2max} in master distance runners is well established, RE during a MIE run may also change with age in this population. When measured as alloVO_2, RE improved with age. However, in considering males and females separately, we have found that there may be sex differences in age-related alterations in running performance. The energy cost of running significantly increased with age in females, while MIE VO_2, without allometric scaling, declined in males as age increased. Hormonal processes may bear on these discrepancies.

Among master runners, training parameters and physiological factors are significantly related to long-distance race performance. Maximal aerobic capacity shows the strongest association with VDOT score, but alloVO_2, EC, and 3YP are also correlated with VDOT. Master athletes who can maintain or improve their VO_{2max}, and who reach higher peak running volumes, may be expected to perform better in distance races than those who run less or have lower maximal aerobic power. Furthermore, allometric scaling and energy-cost models of RE are important predictors of running performance in this population.

These studies have contributed useful insights to the scientific literature on long-distance running. Chapter one showed that sub-elite runners with prior marathon experience can enhance their VO_{2max} over a block of training focused on preparing to complete another marathon. Thus, VO_{2max} is trainable even in athletes with competitive marathon times who have already benefited from adaptations to endurance training. Chapter two demonstrated that the negative association between age and VO_{2max} holds in master runners who are near their peak long-distance fitness. This study adds to the literature an investigation of relationships between age and measures of RE that have not been previously explored in this population, namely alloVO_2, EC, and %VO_{2max}. Finally, chapter three uses running-performance data collected from these master runners to establish the factors that are correlated with actual race performance in this group. Both training and physiology play a role in race outcomes among master athletes. Master athletes and their coaches may be able to apply techniques focused on improving VO_{2max} and RE, and on increasing mileage, to yield faster long-distance race times.

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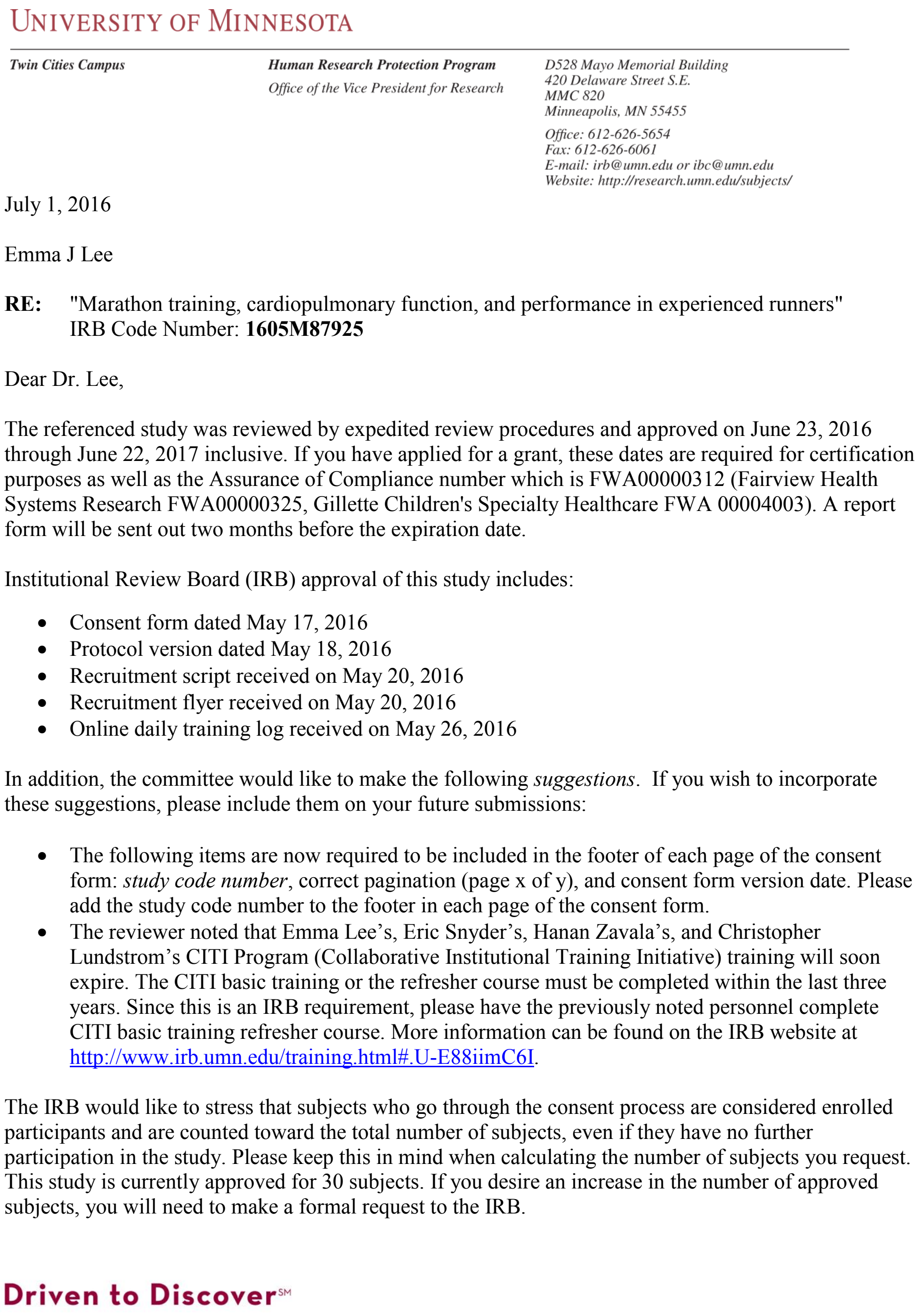
CHAPTER 8: Appendices

8.1 IRB approval letters



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July 1, 2016

Emma J Lee

RE: "Marathon training, cardiopulmonary function, and performance in experienced runners"
IRB Code Number: **1605M87925**

Dear Dr. Lee,

The referenced study was reviewed by expedited review procedures and approved on June 23, 2016 through June 22, 2017 inclusive. If you have applied for a grant, these dates are required for certification purposes as well as the Assurance of Compliance number which is FWA00000312 (Fairview Health Systems Research FWA00000325, Gillette Children's Specialty Healthcare FWA 00004003). A report form will be sent out two months before the expiration date.

Institutional Review Board (IRB) approval of this study includes:

- Consent form dated May 17, 2016
- Protocol version dated May 18, 2016
- Recruitment script received on May 20, 2016
- Recruitment flyer received on May 20, 2016
- Online daily training log received on May 26, 2016

In addition, the committee would like to make the following *suggestions*. If you wish to incorporate these suggestions, please include them on your future submissions:

- The following items are now required to be included in the footer of each page of the consent form: *study code number*, correct pagination (page x of y), and consent form version date. Please add the study code number to the footer in each page of the consent form.
- The reviewer noted that Emma Lee’s, Eric Snyder’s, Hanan Zavala’s, and Christopher Lundstrom’s CITI Program (Collaborative Institutional Training Initiative) training will soon expire. The CITI basic training or the refresher course must be completed within the last three years. Since this is an IRB requirement, please have the previously noted personnel complete CITI basic training refresher course. More information can be found on the IRB website at http://www.irb.umn.edu/training.html#.U-E88iimC6I.

The IRB would like to stress that subjects who go through the consent process are considered enrolled participants and are counted toward the total number of subjects, even if they have no further participation in the study. Please keep this in mind when calculating the number of subjects you request. This study is currently approved for 30 subjects. If you desire an increase in the number of approved subjects, you will need to make a formal request to the IRB.

Driven to Discover℠

The code number above is assigned to your research. That number and the title of your study must be used in all communication with the IRB office.

As the Principal Investigator of this project, you are required by federal regulations to inform the IRB of any proposed changes in your research that will affect human subjects. Changes should not be initiated until written IRB approval is received. Unanticipated problems and adverse events should be reported to the IRB as they occur. Research projects are subject to continuing review and renewal. Notify the IRB when you intend to close this study by submitting the Study Inactivation Request form. If you have any questions, call the IRB office at 612-626-5654.

On behalf of the IRB, I wish you success with your research.

Sincerely,

Melissa Nowicki, CCRP
Research Compliance Supervisor
MN/do

CC: Christopher Lundstrom, Elizabeth Peitzman, Eric Snyder, Hanan Zavala

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APPROVAL OF CONTINUING REVIEW

June 6, 2018

Eric Snyder

snyd0180@umn.edu

Dear Eric Snyder:

On 6/6/2018, the IRB reviewed the following submission:

Type of Review:	Continuing Review
Title of Study:	Marathon training, cardiopulmonary function, and performance in experienced runners
Title of Submission:	Continuing Review for Study Marathon training, cardiopulmonary function, and performance in experienced runners
Investigator:	Eric Snyder
IRB ID:	1605M87925
Submission ID:	CR00001399
Sponsored Funding:	None
Grant ID/Con Number:	
Internal UMN Funding:	None
Fund Management Outside University:	None
IND, IDE, or HDE:	None
Documents Reviewed with this Submission:	Continuing Review submission

The IRB determined that the criteria for approval continue to be met and that this study continues to involve greater than minimal risk.

The IRB approved the study from 6/6/2018 to **5/20/2019** inclusive. You will be sent a reminder from ETHOS to submit a Continuing Review submission for this study. You must submit your Continuing Review no later than 30 days prior to the last day of approval in order for your study to be reviewed and approved for another Continuing

Review period. If Continuing Review approval is not granted before 5/20/2019 approval of this protocol expires immediately after that date.

You must also submit a Modification in ETHOS for review and approval prior to making any changes to this study.

Previously approved consent forms or recruitment materials are located in the Documents tab in the ETHOS study workspace.

In conducting this study, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the HRPP Toolkit Library on the IRB website.

For grant certification purposes, you will need the approval and last day of approval dates listed above and the Assurance of Compliance number which is FWA00000312 (Fairview Health Systems Research FWA00000325, Gillette Children's Specialty Healthcare FWA00004003).

Sincerely,

Clinton Dietrich, MA, CIP
IRB Analyst

We value feedback from the research community and would like to hear about your experience. The link below will take you to a brief survey that will take a minute or two to complete. The questions are basic, but your responses will help us better understand what we are doing well and areas that may require improvement. Thank you in advance for completing the survey.

Even if you have provided feedback in the past, we want and welcome your evaluation.

https://umn.qualtrics.com/SE/?SID=SV_5BiYrqPNMJRQSBn

8.2 Consent form

Marathon training, cardiopulmonary function, and performance in experienced runners

CONSENT FORM

You are invited to participate in a research study of physiological changes that occur during a marathon training cycle in experienced and inexperienced runners. You were selected as a possible participant because you have completed at least one recent marathon or are a novice runner, plan to train for an upcoming marathon, and fulfill study inclusion criteria; or because you are a masters runner training for a long-distance race. We ask that you read this form and ask any questions you may have before agreeing to be in the study.

This study is being conducted by Emma Lee, M.S., in the School of Kinesiology at the University of Minnesota. It is funded by indirect cost recovery from Dr. Eric Snyder's R01 grant.

Study Purpose

The purpose of the study is to evaluate changes in cardiopulmonary function that take place over the course of marathon training and to determine whether these changes are related to marathon running performance. Additionally, we aim to explore how aging might affect running performance. To do so, we will assess selected cardiopulmonary measures, i.e. diffusing capacity of the lung, cardiac output, stroke volume, and markers potentially associated with running performance, at rest and during exercise.

Study Procedures

If you agree to participate in this study, we would ask you to do the following:
Experienced and novice marathon runners:

- Come to the Clinical Exercise Physiology Laboratory at the University of Minnesota for two visits, one 10 weeks and one 10-14 days before your goal marathon. Each visit will take 90 minutes to two hours.
- At each visit, complete body composition assessment via hydrostatic (underwater) weighing, a submaximal run, and a treadmill VO_{2max} test.
- During the submaximal run, we will noninvasively measure your cardiopulmonary function. You will be asked to breathe into a special mouthpiece at rest and after you have reached 88% of your predicted maximum heart rate.
- We will ask you to fill out a daily online training log that study personnel will provide to you. In this log, you will report the mileage, intensity, and duration of

each of your workouts. If you use a heart rate monitor, we will also ask you to record your resting (morning) heart rate, your average heart rate for each workout, and your maximum heart rate for each workout.

Masters runners:

- Come in for one study visit within four weeks of your goal event. The visit will take approximately one hour.
- Complete body composition assessment, a submaximal run, and a treadmill VO_{2max} test.
- Provide information about your training history (when you started running, habitual mileage, best times, etc.)

Risks of Study Participation

The study has the following risks:

- During the VO_{2max} test, there is a risk of cardiac arrest; however, in healthy subjects, this risk is essentially zero. All research staff members are trained in CPR and in the use of the automatic external defibrillator present in the laboratory.
- You will be asked to breathe in inert gases for assessment of cardiopulmonary function. These gases are harmless at the very low concentrations used.
- You may become dizzy or faint during the VO_{2max} test and/or evaluation of cardiopulmonary function. Study personnel will physically support you as needed and will provide a place for you to sit down if necessary.
- Your name, date of birth, email address, and postal address will be collected. We will use your name and postal address to mail your compensation check after you have completed the study. We will correspond with you via your email address. Your date of birth will be used to determine your age. All of your data will be stored on password-protected, secure University of Minnesota servers. You will be given a unique study number that we will use in place of your name or any other identifying information on paper documents. Any paper documents containing potential identifiers will be shredded following completion of the study.

Benefits of Study Participation

There are no direct benefits resulting from your participation in this study.

Study Costs/Compensation

Participants will not receive monetary compensation for completing the study. We do not expect you to incur participation-related costs besides parking fees.

Research-Related Injury

In the event that this research activity results in an injury, treatment will be available, including first aid, emergency treatment and follow-up care as needed. Care for such injuries will be billed in the ordinary manner to you or your insurance company. If you think that you have suffered a research related injury, let the study physicians know right away.

Confidentiality

The records of this study will be kept private. In any publications or presentations, we will not include any information that will make it possible to identify you as a subject. Your record for the study may, however, be reviewed by departments at the University with appropriate regulatory oversight. Study information will not be recorded in your medical record. To these extents, confidentiality is not absolute. Study data will be encrypted according to current University policy for protection of confidentiality.

Voluntary Nature of the Study

Participation in this study is voluntary. Your decision whether or not to participate in this study will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting those relationships.

Contacts and Questions

The researchers conducting this study are Emma Lee, M.S., and her advisor, Dr. Eric Snyder, Ph.D. You may ask any questions you have now, or if you have questions later, **you are encouraged to** contact them at:

Emma Lee: leex4357@umn.edu
Eric Snyder: 612-626-5408; snyd0180@umn.edu

If you have any questions or concerns regarding the study and would like to talk to someone other than the researcher(s), you are encouraged to contact the Fairview Research Helpline at telephone number 612-672-7692 or toll free at 866-508-6961. You may also contact this office in writing or in person at *Fairview Research Administration, 2344 Energy Park Drive, St. Paul, MN 55108.*

You will be given a copy of this form to keep for your records.

Statement of Consent

I have read the above information. I have asked questions and have received answers. I consent to participate in the study.

Signature of Subject__________________________________

Date_________________

Signature of Person Obtaining
Consent____

Date_________________

8.3 Recruitment emails

Marathon study (open runners) recruitment email

Emma Lee, a graduate student in the School of Kinesiology at the University of Minnesota, is looking for experienced and novice marathon runners for a research study.

This study will evaluate changes in cardiopulmonary function that occur over the course of a marathon training cycle. To be included in this study, you must be training to run a marathon in at least 12 weeks and must be planning to follow a set training program (of your own choice) to prepare for the marathon. You must be between the ages of 18 and 40 and not take beta-agonist medication. Additional inclusion criteria are as follows:

Experienced runners: You must run at least 30 miles per week habitually. Additionally, you must have completed at least one marathon in the past two years with a time of < 3:30 (females) or < 3:00 (males).

Novice runners: You must not have trained for or completed a prior marathon.

Participants will come to the Clinical Exercise Physiology Laboratory (CEPL) at the University of Minnesota for two visits. The first visit will occur approximately 10 weeks prior to your goal marathon, and the second will take place 10-14 days before the marathon. At both visits, you will complete a submaximal run, a VO_{2max} test, and a body composition test. Measures of cardiopulmonary function, including lung diffusing capacity and cardiac output, will be collected noninvasively at rest and during the submaximal run. Additionally, you will fill out a basic online training log (mileage, intensity, and duration) provided to you by the research staff. You will receive the results of your VO_{2max} and body composition testing.

If you are interested in taking part in this study or have questions about the study, please contact Emma Lee at leex4357@umn.edu.

Masters study recruitment email

Emma Lee, a student in the School of Kinesiology at the University of Minnesota, is looking for masters runners to participate in a research study.

This study will explore how aging might affect potential markers of running performance. To be included in this study, you must be training to run a race of 10 miles to a marathon in distance. You must be at least 40 years old and have been running for at least five years.

Participants will complete one study visit at the Clinical Exercise Physiology Laboratory at the University of Minnesota. The visit will occur within four weeks of your goal event and will last approximately one hour to 90 minutes. We will ask you to complete a submaximal run and a VO_{2max} test on a treadmill. We will also ask you some questions about your training history. We will share the results of your VO_{2max} test with you.

If you are interested in taking part in this study or have questions about the study, please contact Emma Lee at leex4357@umn.edu.

8.4 Pre-test instructions

Instructions for open runners

Hi (name),

Thank you for your interest in the study. Your first visit is scheduled for **date, time** at the Clinical Exercise Physiology Laboratory. The lab is located in Cooke Hall, 1900 University Ave. SE, Minneapolis, MN 55455; you can enter Cooke Hall through doors across from the old entrance to the recreation center. These doors are near a skyway connecting Cooke to the recreation center, *not* by the new entrance to the recreation center. There is a parking ramp on University Ave. just east of the recreation center, but it will be cheaper to park in the daily lot on 5th St. SE (near Ridder and Mariucci Arenas). When you arrive in Cooke, please wait in the lobby, and I will meet you to bring you down to the lab.

Your visit will likely last about sixty to seventy-five minutes. (The second visit will be shorter.) We will measure your body composition using underwater weighing. Then, you will run on a treadmill at approximately marathon effort. You will probably run for 10 minutes or fewer. After you have completed these tests, you will have a brief recovery period, and then you will do a VO2max test. We will make sure that you understand how to use your online training log; if you have any questions about it, let me know.

Please bring the following items to your visit:
- Swimsuit or spandex (and an extra sports bra, if female) for underwater weighing
- Towel
- Dry running clothes and running shoes
- Your calendar to schedule your next visit, which will be 7-14 days before your goal marathon-- a training plan will also be helpful for scheduling this visit

We will do underwater weighing first, so feel free to come ready with your swimsuit or spandex on.

Please do not eat, consume caffeine or alcohol, or use tobacco for at least three hours before your visit. Do not do any strenuous exercise within 24 hours of your visit. (It's ok to do an easy run, but don't do a long run, hard workout, or strength training.)

If you have any questions, please email me; on the day of your visit, you can also reach me by phone: 651-331-0013.

Take care,
Emma

Instructions for master runners

Hi

Your visit is scheduled for **date, time** at the Clinical Exercise Physiology Laboratory. The lab is located in Cooke Hall, 1900 University Ave. SE, Minneapolis, MN 55455; you can enter Cooke Hall through doors across from the old entrance to the recreation center. These doors are near a skyway connecting Cooke to the recreation center, *not* by the new entrance to the recreation center. There is a parking ramp on University Ave. just east of the recreation center, but it will probably be cheaper to park in the daily lot on 5th St. SE (near Ridder and Mariucci Arenas) or at a meter. When you arrive in Cooke, please wait in the lobby, and I will meet you to bring you down to the lab.

Your visit will last about an hour or less. We will start with the consent process. Then, you will complete a treadmill run with five minutes at a target heart rate. (This heart rate is 88% of your predicted age-based maximum heart rate.) After a brief recovery, you will do a VO2max test on the treadmill.

Please come dressed to run. Please do not eat, consume caffeine or alcohol, or use tobacco for at least three hours before your visit. Do not do any strenuous exercise within 24 hours of your visit. (It's ok to do an easy run, but don't do a long run, hard workout, or strength training.)

If you have any questions, please email me; on the day of your visit, you can also reach me by phone: 651-331-0013.

Take care,
Emma