Original Article

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

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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. This study's purpose was to determine whether VO_{2max} and measures of RE change with marathon training, and 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. **Keywords:** VO_{2max}; Performance; Sub-elite.

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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 augments 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, Thomason, & Roberts, 1973; Foster, 1983; Mello, Murphy, & Vogel, 1988). Running economy (RE) is the cost of running at a given submaximal speed (Basset & Howley, 2000; Berg, 2003; Saunders, Pyne, Telford, & Hawley, 2004). Numerous factors, including biomechanical parameters, cardiopulmonary function, and muscle fibre 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; 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, Rennie, Hickson, Conlee, & Hagberg, 1977). Thus, skeletal muscle can rely more heavily on the body's vast lipid stores for energy during exercise. Cardiac remodelling facilitates pumping a larger volume of blood with decreased myocardial oxygen demand (Holloszy et al., 1977; Prior & La Gerche, 2012). Such remodelling 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 may 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, Demarle, Paiva, & Koralsztein, 2002) or interval training (Billat, 2001; Smith, McNaughton, & Marshall, 1999). However, even with high-intensity (≥ 90% VO_{2max}) training, athletes may demonstrate no change in VO_{2max} despite improved race performance (Berg, Latin, & Hendricks, 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, Hopkins, McGuigan, Northuis, & Kilding, 2013; Johnston, Quinn, Kertzer, & Vroman, 1997; Millet, Jaouen, Borrani, & Candau, 2002; Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 2003; Paavolainen, Häkkinen, Hämäläinen, Nummela, & Rusko, 1999; Spurrs, Murphy, & Watsford, 2003; Støren, Helgerud, Støa, & Hoff, 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 have negative impacts on 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 race time alone. 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. By accounting for RE, the VDOT score represents the interaction between a person's economy and his or her maximal capacity (Daniels, 2014). The VDOT score may thus 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.

MATERIAL AND METHODS

Participants

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 enrolment. 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 participants provided written consent prior to enrolment in the study.

Thirteen participants met these criteria and were enrolled; however, four dropped out due to running injuries. One additional participant 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 (five females; mean age 33.6 ± 1.6 years).

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

Procedures

A prospective, uncontrolled cohort study was conducted to examine changes in running performance after a marathon training cycle. High-calibre 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 participants 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).

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.

Measures

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) (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 (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.

Analysis

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%.

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.

We used Statistical Package for the Social Sciences (SPSS; IBM, Armonk, NY), version 23, 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 $p < 0.05$.

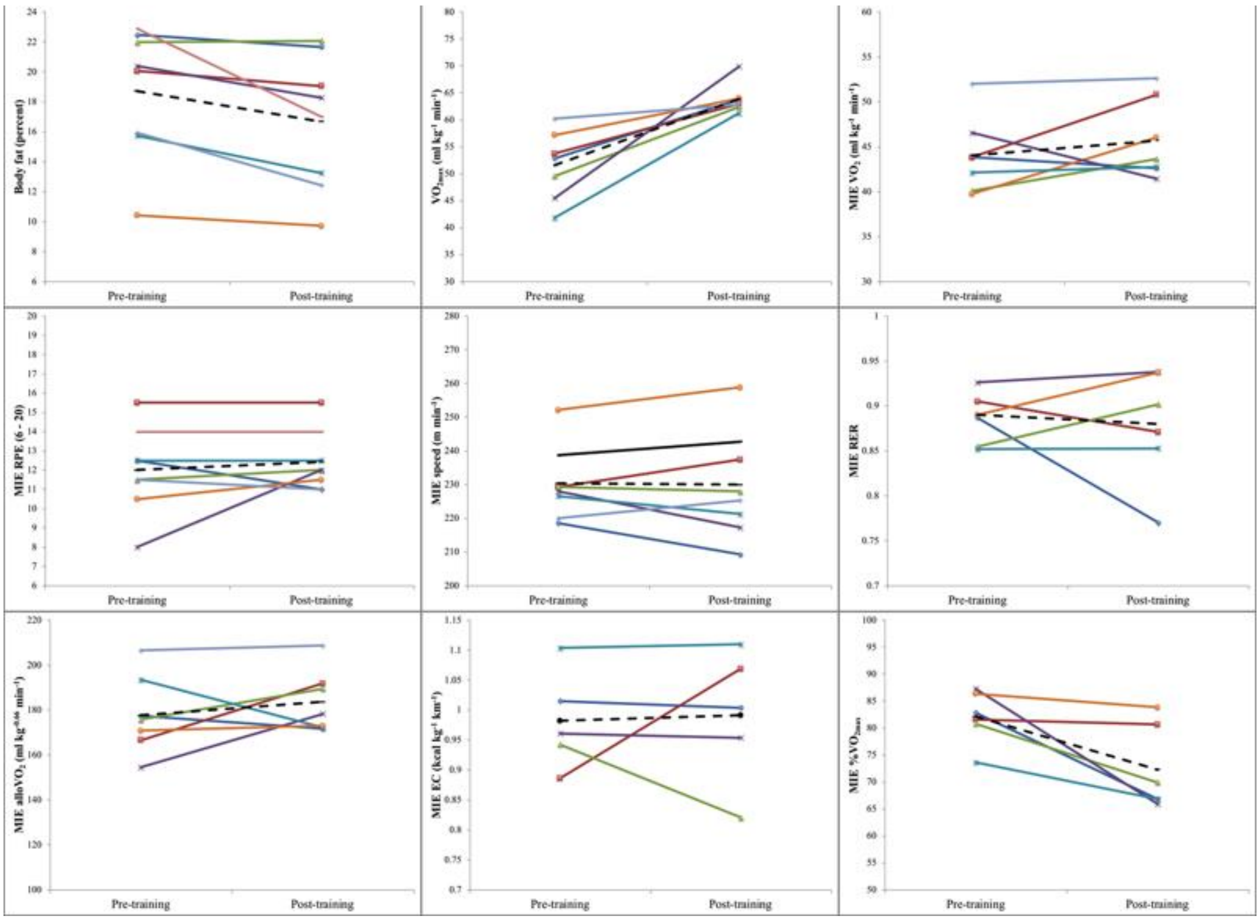
RESULTS

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.

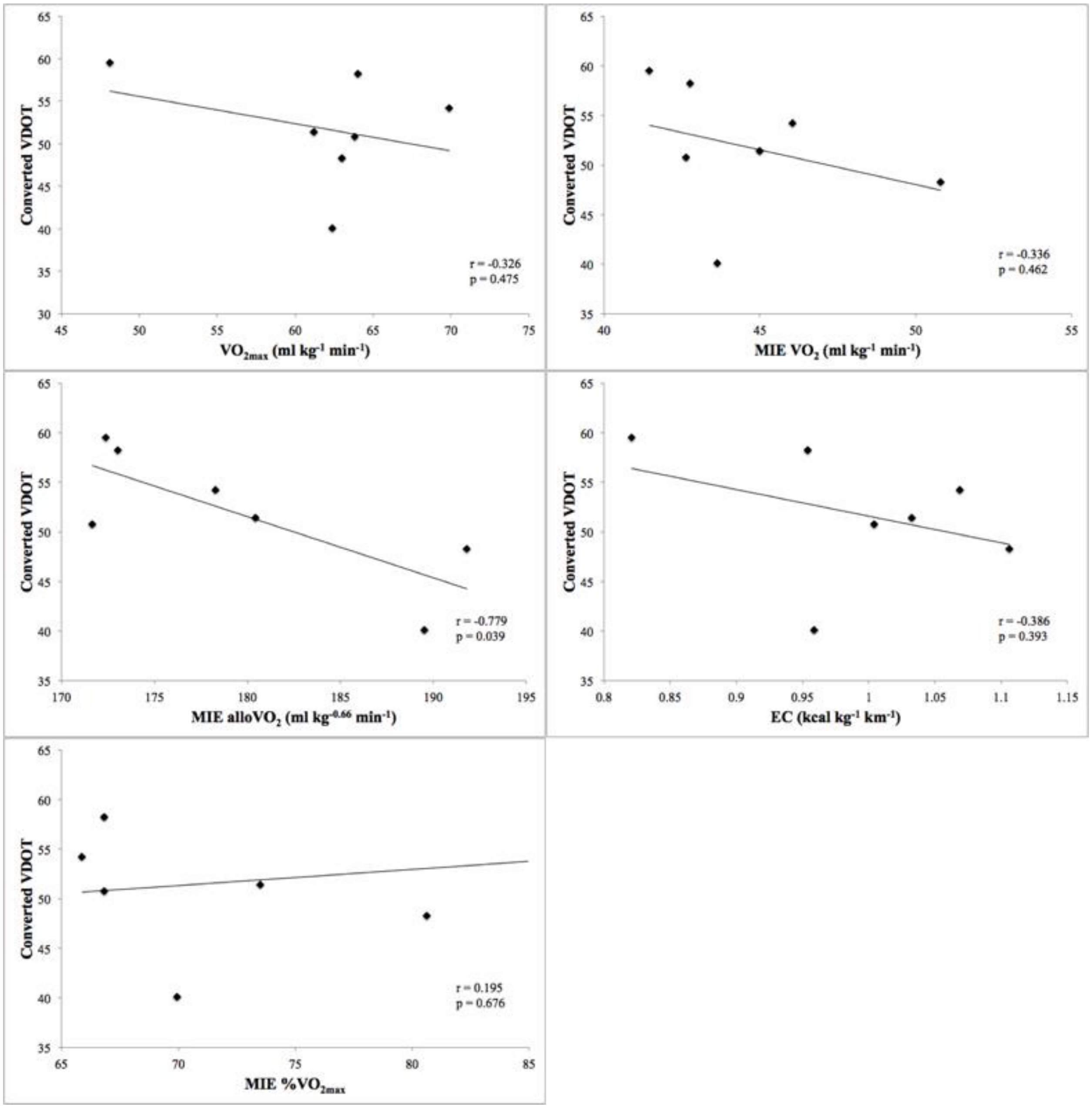
Subject demographics at baseline are reported in Table 1. Following approximately eight weeks of marathon training in our participants, we observed a significant decrease in %BF, from 18.7 ± 1.5% to 16.7 ± 1.6% ($p = 0.020$). Maximal aerobic capacity increased significantly, from 51.56 ± 2.43 ml kg^{-1} 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.



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. VO_{2max}: maximal aerobic capacity; MIE: marathon-intensity effort; VO_2: oxygen consumption; RPE: rating of perceived exertion; RBR: respiratory exchange ratio; alloVO_2: allometrically scaled VO_2; EC: energy cost; %VO_{2max}: percent of VO_2max.

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

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 shows these relationships.



VO_{2max}: maximal aerobic capacity; MIE: marathon-intensity effort; VO_2: oxygen consumption; alloVO_2: allometrically scaled VO_2; EC: energy cost; %VO_{2max}: percent of VO_{2max}.

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

All participants 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. 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.

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 difference 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 (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 favourably 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 submaximal 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, McNaughton, & Jones, 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 musculotendinous stiffness (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 in the present study, 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, Demarle, Slawinski, Paiva, & Koralsztein, 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 participant 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 participant in the post-training MIE. Therefore, comparison of VO_{2max} was only made in seven participants; 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.

CONCLUSIONS

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 favourably in trained runners 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.

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