



The relationships between age and running performance variables in master runners

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Received: 19 December 2018 / Accepted: 5 March 2019 / Published online: 15 March 2019
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Abstract

Purpose Peak aerobic capacity ($\dot{V}O_{2\text{peak}}$) declines with age, but running economy (RE) may not. We evaluated $\dot{V}O_{2\text{peak}}$ and RE in master runners and determined whether age is associated with these measures.

Methods In a cross-sectional study, runners completed two running tests within 4 weeks of a goal race of 10–26.2 miles. Subjects ran for 5 min at 88% of predicted maximum heart rate, approximating a marathon-intensity effort (MIE), then performed a $\dot{V}O_{2\text{peak}}$ test. Running economy in the MIE was measured using oxygen cost with body mass scaled allometrically ($\text{allo}\dot{V}O_2$); energy cost (EC), determined using caloric equivalents; and percent of $\dot{V}O_{2\text{peak}}$ ($\%\dot{V}O_{2\text{peak}}$). 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) had a mean $\dot{V}O_{2\text{peak}}$ of 52.5 ± 7.9 ml O_2 kg^{-1} min^{-1} . Age was significantly correlated with $\dot{V}O_{2\text{peak}}$ ($r = -0.580$, $p = 0.001$) and $\text{allo}\dot{V}O_2$ ($r = -0.454$, $p = 0.034$). Age was related to EC in females ($r = 0.649$, $p = 0.042$) and MIE $\dot{V}O_2$ in males ($r = -0.600$, $p = 0.039$).

Conclusions In this population, age was negatively associated with $\dot{V}O_{2\text{peak}}$ and $\text{allo}\dot{V}O_2$. Females showed a positive relationship between age and EC, while males had a negative correlation between age and MIE $\dot{V}O_2$. Aerobic capacity declines with age, but there may be sex differences in age-related alterations to submaximal running.

Keywords Aging · Peak aerobic capacity · Running economy · Energy cost · Sex differences

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 [1, 2]. Athletes over the age of 50 have increased participation in these events more than younger athletes [1, 3], and masters may comprise a majority of the field in marathons and ultra-marathons [2]. Furthermore, as the increase in numbers of female master endurance athletes outpaces that of males, the sex gap in performance is shrinking [1, 4]. 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 [1, 2].

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 [3, 5–9]. The main cause of slowing in older distance runners is a decline in peak aerobic capacity ($\dot{V}O_{2\text{peak}}$) [10], a key predictor of performance in long-distance running. In groups of female and male master athletes heterogeneous for $\dot{V}O_{2\text{peak}}$, $\dot{V}O_{2\text{peak}}$ may be a crucial running performance predictor [11].

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 ($\dot{V}O_2$) in ml kg body weight⁻¹ min^{-1} [12]. Among athletes with similar $\dot{V}O_{2\text{peak}}$ values, RE can account for performance differences [13–15], and faster runners typically

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have better RE than slower runners [14, 16]. However, these relationships have primarily been demonstrated in younger runners, not in masters. In contrast to $\dot{V}O_{2\text{peak}}$, RE may be preserved with age. At a given absolute speed [17] or relative intensity level, e.g., 10-km race pace [18], RE—as assessed through $\dot{V}O_2$ —has been found to have no relationship with age in runners of both sexes.

Despite the predominance in running performance literature of submaximal $\dot{V}O_2$ 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 $\dot{V}O_2$ with mass, body mass should be scaled to a power of -0.66 to -0.75 ($\text{allo}\dot{V}O_2$) [12, 19, 20]. Furthermore, oxygen cost does not serve as an accurate proxy for energy cost. More oxygen is required to oxidize lipids than carbohydrates, raising $\dot{V}O_2$. 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 $\dot{V}O_2$. Therefore, energy cost (EC) should instead be measured in units including kcal [12]. In addition, the percent of $\dot{V}O_{2\text{peak}}$ ($\%\dot{V}O_{2\text{peak}}$) at which an athlete can complete a given effort is also important for race performance and is related to RE [21].

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 $\dot{V}O_{2\text{peak}}$ decreases similarly in sedentary and endurance-trained males, female athletes may exhibit a steeper decline than sedentary counterparts [3, 9]. Additionally, evidence suggests that age-related performance decrements differ by age, with athletes experiencing relative stability between the mid-30 s and age 50, and larger changes thereafter [3, 5–9].

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 with a more practical measure than simply $\dot{V}O_2$. Because $\dot{V}O_{2\text{peak}}$ and RE are key determinants of running performance, it is important to investigate whether these markers change with age in master runners. Therefore, the major aim of this study was to determine whether age is related to $\dot{V}O_{2\text{peak}}$, submaximal $\dot{V}O_2$, $\text{allo}\dot{V}O_2$, EC, or $\%\dot{V}O_{2\text{peak}}$ in master runners training for long-distance races. Additionally, we sought to determine whether these relationships differ between females and males. We hypothesized that in this group of runners, when considering both sexes, age would be negatively associated with $\dot{V}O_{2\text{peak}}$. In contrast, we hypothesized that age would not be significantly correlated with measures of RE (i.e., submaximal $\dot{V}O_2$, $\text{allo}\dot{V}O_2$,

EC, or $\%\dot{V}O_{2\text{peak}}$). Furthermore, we hypothesized that when male and female runners were considered separately, they would demonstrate different relationships between age and these running performance variables. To investigate these hypotheses, we used a cross-sectional study of master runners in training for a long-distance race.

Methods

Study design

To address our aims, we conducted a cross-sectional study. 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 4 weeks of each master athlete's goal race. At the visits, all runners completed a treadmill marathon-intensity effort (MIE) and $\dot{V}O_{2\text{peak}}$ test.

Peak 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% of maximal aerobic capacity ($\dot{V}O_{2\text{max}}$) [22]. Eighty percent of $\dot{V}O_{2\text{max}}$ corresponds to a heart rate of 88% of the MHR [23, 24].

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 long-distance race, defined here as between 10 miles and a marathon in distance. They also needed to have been running consistently, defined as three or more times per week, for at least five years. 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 1. This study was approved by the Institutional Review Board at the University of Minnesota, and all subjects provided informed consent before enrolling in the study.

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.

Table 1 Descriptive characteristics of the subjects

<i>N</i> (% 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
$\dot{V}O_{2\max}$ (ml kg ⁻¹ min ⁻¹)	52.5 ± 7.9
Weekly training distance (km)	47.2 ± 23.0

Values are reported as mean ± SD unless otherwise indicated

BMI body mass index; $\dot{V}O_{2\text{peak}}$ peak aerobic capacity

Participants were asked not to eat, consume caffeine or alcohol, or use tobacco within three h 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 h of their visits.

Anthropometric measurements

Height was measured to the nearest 0.25 inch using a stadiometer (ACCUSTAT™ Stadiometer, Genentech, San Francisco, CA, USA), and weight was measured to the nearest 0.1 pound on an electronic scale (Etekcity, Anaheim, CA, USA). 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, USA). 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, USA). Competitive runners complete a marathon race at approximately 80% of $\dot{V}O_{2\max}$ [22], which corresponds to 88% of MHR [23, 24]. Each subject was allowed to warm-up for several minutes at a 1% incline and speed of their choice. This warm-up was at a self-selected pace and duration and was unique to each individual. 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 [25]:

$$\text{MHR} = 208 - (0.7 \times \text{age}).$$

Participants ran for 5 min 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 5-min 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 [26]. If athletes exhibited a RER consistently at or above 1.0, we ended the MIE run early so as not to cause undue fatigue.

Peak aerobic capacity testing

Participants performed an incremental treadmill test to exhaustion to determine their $\dot{V}O_{2\text{peak}}$. This test occurred approximately 10 min after the end of the RE test. The speed for this test was based on subjects' self-reported estimated current 5-km race pace [27]. Subjects began by walking for one min 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 min. All subsequent stages lasted 1 min. 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 [28] 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 peak and submaximal exercise tests. Participants also wore a heart rate monitor (Polar, Bethpage, NY, USA) throughout treadmill testing. Peak aerobic capacity was determined using BreezeSuite breath-by-breath software.

Data analysis

Peak 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 ($\dot{V}O_2$) and was also calculated with allometric scaling of body mass to the -0.66 power, i.e., ml kg^{-0.66} min⁻¹ (allo $\dot{V}O_2$). The energy cost (EC) of running, in kcal kg⁻¹ km⁻¹, in the MIE was also calculated [29]. Average respiratory exchange ratio (RER) over the five-min running test was used to determine a caloric equivalent value in kcal l O₂⁻¹ [26]. This value was multiplied by $\dot{V}O_2$ and divided by each participant's average speed in m/min to find EC. Finally, the percent of $\dot{V}O_{2\text{peak}}$ (% $\dot{V}O_{2\text{peak}}$) that the MIE required was calculated as mean $\dot{V}O_2$ divided by $\dot{V}O_{2\text{peak}}$ and multiplied by 100%.

Statistical analyses

To determine demographic parameters for the athletes, we calculated mean and standard deviation for age, mass, height, body mass index, and $\dot{V}O_{2\text{peak}}$. The Shapiro–Wilk test was used to check that each variable was normally distributed.

Correlation was used to evaluate the relationships between age and $\dot{V}O_{2peak}$, submaximal $\dot{V}O_2$, $allo\dot{V}O_2$, EC, and $\% \dot{V}O_{2max}$. 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.

We used Statistical Package for the Social Sciences (SPSS; IBM, Armonk, NY, USA), version 23, for all statistical analyses. The alpha level for significance for tests was set at $p < 0.05$.

Results

Thirty-one participants, including 13 females and 18 males, were enrolled in the study. All runners completed the $\dot{V}O_{2peak}$ 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 $\dot{V}O_2$, $allo\dot{V}O_2$, 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 $\dot{V}O_{2peak}$ ($r = -0.580$, $p = 0.001$). $allo\dot{V}O_2$ 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 1 depicts the relationships between age

and $\dot{V}O_{2peak}$, submaximal $\dot{V}O_2$, $allo\dot{V}O_2$, EC, and $\% \dot{V}O_{2peak}$ among all subjects.

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 $\dot{V}O_{2peak}$ ($r = -0.720$, $p = 0.001$), MIE $\dot{V}O_2$ ($r = -0.600$, $p = 0.039$), and MIE $allo\dot{V}O_2$ ($r = -0.730$, $p = 0.007$), while females did not. Figures 2 and 3 show the relationships between age and running performance variables in females and males, respectively.

Discussion

In this cross-sectional study, we found that peak aerobic capacity and allometrically scaled $\dot{V}O_2$ 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 relationship of $\dot{V}O_{2peak}$ to age is unsurprising given consistent findings in previous studies on older athletes.

As expected, based on a wide body of literature on the effects of aging on exercise, $\dot{V}O_{2peak}$ decreased with age (Fig. 1). Other studies have consistently found that $\dot{V}O_{2peak}$ is lower in older than younger people [2, 3, 7–10, 30–37]. As others have noted, cross-sectional studies of master athletes do not necessarily represent $\dot{V}O_{2peak}$ trends in the general population due to selection bias: older people who enroll

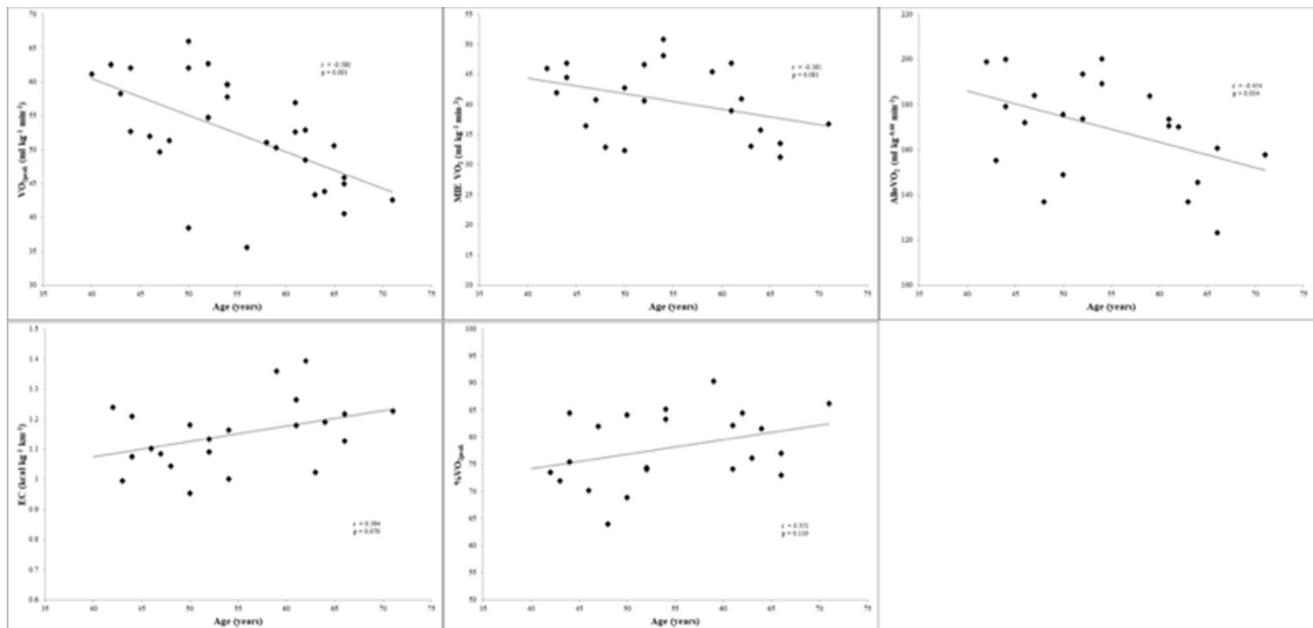


Fig. 1 Relationships between age and running performance variables in all participants. $\dot{V}O_{2peak}$ peak aerobic capacity, MIE marathon-intensity effort, $\dot{V}O_2$ oxygen consumption, $allo\dot{V}O_2$ allometrically scaled $\dot{V}O_2$, EC energy cost, $\% \dot{V}O_{2peak}$ percent of $\dot{V}O_{2peak}$

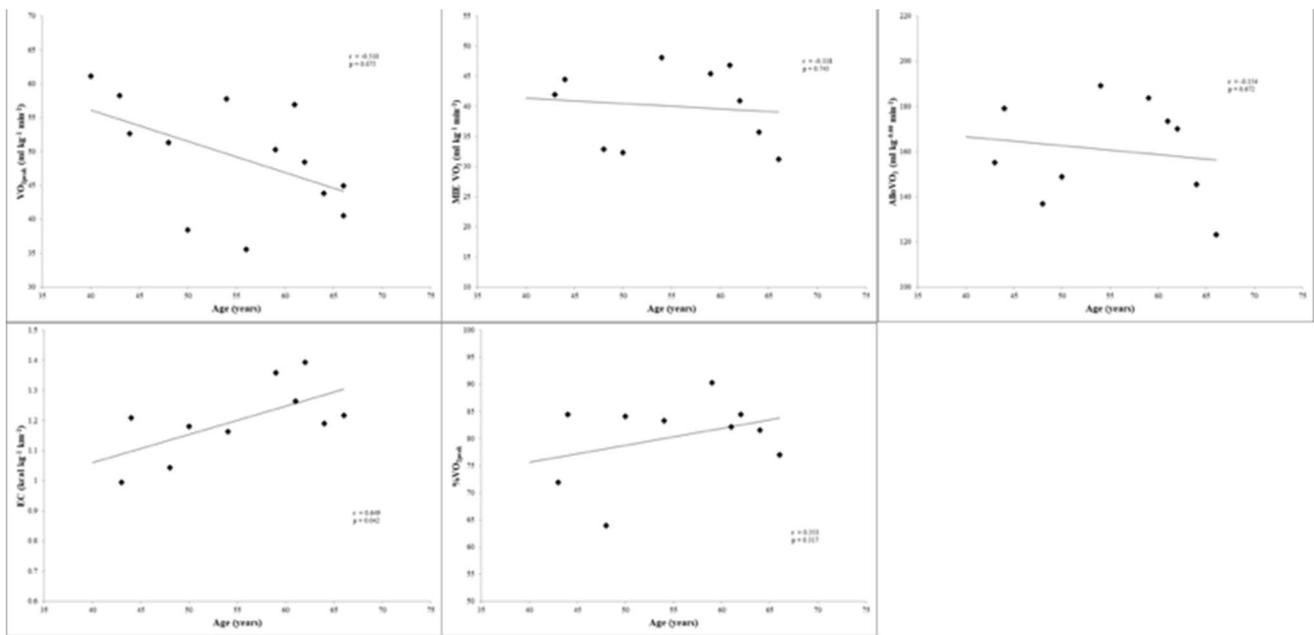


Fig. 2 Relationships between age and running performance variables in female masters. $\dot{V}O_{2peak}$ peak aerobic capacity, *MIE* marathon-intensity effort, $\dot{V}O_2$ oxygen consumption, *allo* $\dot{V}O_2$ allometrically scaled $\dot{V}O_2$, *EC* energy cost, $\% \dot{V}O_{2peak}$ percent of $\dot{V}O_{2peak}$

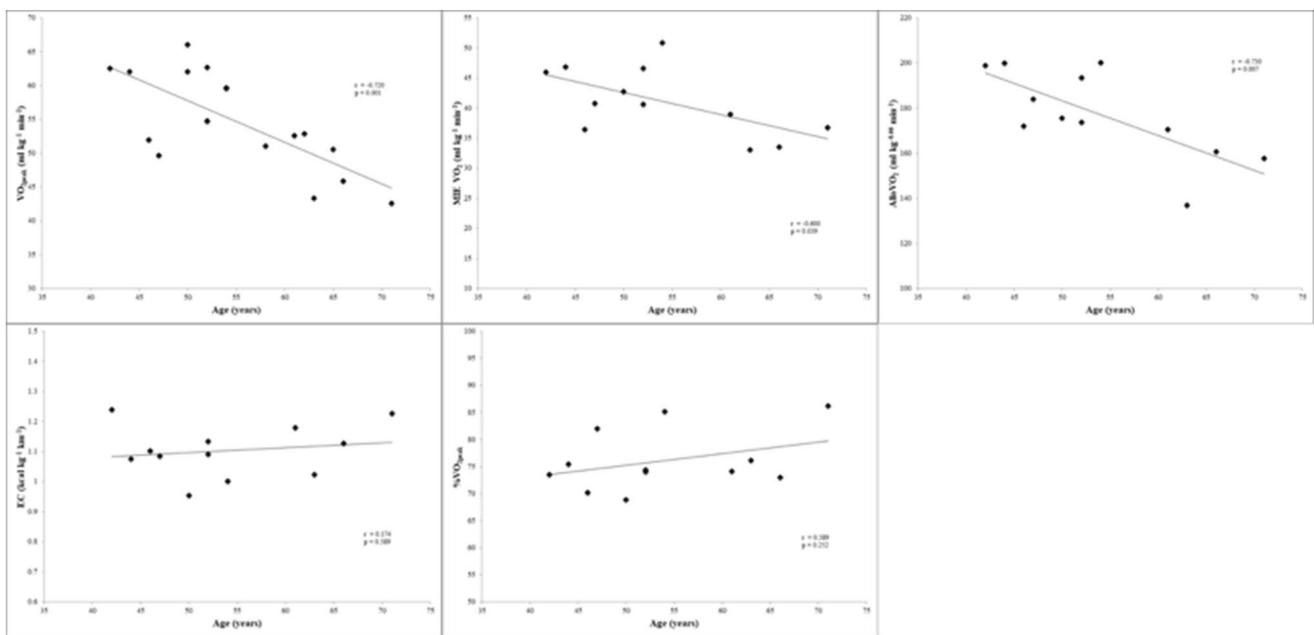


Fig. 3 Relationships between age and running performance variables in male masters. $\dot{V}O_{2peak}$ peak aerobic capacity, *MIE* marathon-intensity effort, $\dot{V}O_2$ oxygen consumption, *allo* $\dot{V}O_2$ allometrically scaled $\dot{V}O_2$, *EC* energy cost, $\% \dot{V}O_{2peak}$ percent of $\dot{V}O_{2peak}$

in studies that require strenuous exercise testing tend to be healthy and fit [3, 8, 9, 33]. Therefore, our finding of an average decrease in $\dot{V}O_{2peak}$ of $-0.580 \text{ ml kg}^{-1} \text{ min}^{-1} \text{ year}^{-1}$ in both sexes between the ages of 40 and 71 might be lower than the true value in the population of this age range.

Our finding of a significant relationship between *MIE* *allo* $\dot{V}O_2$ and age, but not *MIE* $\dot{V}O_2$ and age, across the whole group supports the use of allometric scaling of body mass in the use of $\dot{V}O_2$ to quantify RE. Because $\dot{V}O_2$ does not increase linearly with body mass, scaling body mass to the

–0.66 or –0.75 power allows comparison of RE among runners with different body mass [19, 20]. 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 $\dot{V}O_2$, has not been significantly related to age [17, 18, 38]. Interestingly, however, we observed a significant negative relationship between MIE $\dot{V}O_2$ and age in male master runners, but not in their female counterparts. Males alone also showed a significant negative association between age and $\dot{V}O_{2peak}$, while this relationship was not significant in females. These patterns would mean that males lose peak aerobic capacity with age, but become more economical at lower exercise intensities. Perhaps hormone-related differences in aging, as discussed below [33], can account for the apparently distinct effects of aging on running performance variables between the sexes.

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 $\dot{V}O_2$ at submaximal speeds [17, 18, 38]. However, compared to using $\dot{V}O_2$ as a measure of RE, EC presents an advantage. While $\dot{V}O_2$ depends on substrate oxidation [26], 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 [29]. This group tested trained male runners at three submaximal speeds and evaluated both $\dot{V}O_2$ and EC in $\text{kcal kg}^{-1} \text{km}^{-1}$. The oxygen cost of running was not significantly different at each speed, but EC increased with speed [29]. Similarly, we saw no significant change in $\dot{V}O_2$ ($\text{ml kg}^{-1} \text{min}^{-1}$) 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 (Fig. 2). Running economy depends on metabolic, cardiopulmonary, neuromuscular, and biomechanical factors [19]. A key biomechanical attribute associated with high RE is musculotendinous stiffness in the lower legs [19, 39]. Such stiffness enables efficient storage and use of elastic energy, which can reduce submaximal $\dot{V}O_2$ by lowering horizontal and vertical oscillations unnecessary for the motion of running [40]. Among elite endurance athletes, larger horizontal and vertical forces are related to reduced RE and slower 3-km running time [41]. Cavagna et al. [42] 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 [42]. 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.

We observed three sex differences in the effects of age on running performance variables (Figs. 2, 3): namely, that EC during a MIE run increased with age in females, and $\dot{V}O_{2peak}$ and MIE $\dot{V}O_2$ decreased with age in males. Others have found conflicting results regarding sex differences and athletic performance. In a cross-sectional examination of national-level master track athletes, females had larger performance decreases than males [43]. In contrast, Fleg and Latakka [44] observed no sex difference in the rate of $\dot{V}O_{2peak}$ decline with age. Our findings regarding MIE $\dot{V}O_2$ 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 [33]. The lack of research on endurance-trained female masters athletes inhibits making firm conclusions regarding sex differences in running performance with age.

The present study has several potential limitations. We must consider the possibility that MHR does not change according to the predictions of Tanaka et al. [25], 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 [22], trained open-age runners use approximately 80% of $\dot{V}O_{2max}$ 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.

We did not evaluate body composition in the study participants. Sarcopenia, the age-related reduction in muscle mass, causes a decrease in muscular strength [10]. Beginning around age 50 or 60, individuals progressively lose muscle mass and strength; approximately 40% of muscle mass is lost by age 80 [45]. In sarcopenia, type II fibers are lost preferentially, negatively affecting explosive power and strength [5]. Although our running tests did not directly measure muscular strength or explosive power, changes in lean body mass with age may have confounded our findings of significant relationships between age and running performance variables.

The relationship between $\% \dot{V}O_{2\max}$ 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 $\dot{V}O_{2\max}$ [23, 24]. In older runners, 80% of $\dot{V}O_{2\max}$ 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 $\dot{V}O_{2\max}$.

We did not perform an a priori power calculation to determine the sample size needed for each of the parameters assessed in our population. We performed a post hoc power calculation for the r values in the population that were not statistically significant. Using a two-tailed alpha of 0.05 and a beta of 0.20 and our findings of a Pearson's r of -0.381 , 0.394 , and 0.351 [for age and MIE $\dot{V}O_2$ ($p=0.081$), age and EC ($p=0.070$), and age and $\% \dot{V}O_{2\text{peak}}$ ($p=0.110$)], respectively, we determined that we would need sample sizes of 52, 48, and 61 to determine an effect, if an effect is present. Given these results, for the population as a whole we would have needed a sample size greater than 60 to determine an effect for each of the parameters assessed. Therefore, future studies with a larger sample should focus on these measures.

Our study has several additional limitations. Not all participants were tested at exactly the same point in their training relative to their goal races. We tested subjects within 4 weeks of their races; training periodization might have affected the $\dot{V}O_{2\text{peak}}$ values that we measured [46]. Nevertheless, we attempted to control for training status by requiring that subjects refrain from high-intensity workouts in the 24 h 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 h 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 [26] which would affect the measurement of $\dot{V}O_2$ and calculation of EC.

In conclusion, we have found that peak 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 $\dot{V}O_2$ 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.

Practical applications

We found that the EC of submaximal running, expressed as $\text{kcal kg}^{-1} \text{ km}^{-1}$, is positively related to age in female master runners. Therefore, as female runners age, they may need to change their fueling practices during extended periods of exercise, i.e., increase their caloric intake, to account for a greater energy expenditure. However, older female runners must note that changes in body mass and/or running speed may also play a role in determining EC. Male master runners demonstrated a significant negative relationship between age and $\dot{V}O_{2\text{peak}}$. Thus, male runners may be able to better maintain running performance with aging if they incorporate training strategies to improve or preserve their aerobic capacity.

Compliance with ethical standards

Conflict of interest This study was funded by NIH grant R01 HL208962-05. The authors have no conflicts of interest to report.

Statement of human rights All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This study was approved by the Institutional Review Board at the University of Minnesota.

Informed consent Informed consent was obtained from all individual participants included in the study.

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