Sex Differences in the Speed–Duration Relationship of Elite Runners across the Lifespan

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ABSTRACT

FULTON, T. J., C. W. SUNDBERG, B. E. ARNEY, and S. K. HUNTER. Sex Differences in the Speed–Duration Relationship of Elite Runners across the Lifespan. *Med. Sci. Sports Exerc.*, Vol. 55, No. 5, pp. 911–919, 2023. **Purpose:** To determine if the speed–duration relationship is altered with age and sex of elite Master's runners. **Methods:** The world's top 10 performances for men and women in three events (800, 1500, and 5000 m) across six age groups (18–34 yr, 40–49 yr, 50–59 yr, 60–69 yr, 70–79 yr, and 80–89 yr) were analyzed from public data to establish theoretical models of the speed–duration relationship. Critical speed (CS) and the curvature constant (*D′*) were estimated by fitting the average speeds and performance times with a two-parameter hyperbolic model. **Results:** Critical speed expressed relative to the 18- to 34-yr-olds, declined with age (92.2% [40–49] to 55.2% [80–89]; $P < 0.001$), and absolute CS was higher in men than women within each age group ($P < 0.001$). The percent difference in CS between the men and women progressively increased across age groups (10.8% [18–34] to 15.5% [80–89]). *D′* was lower in women than men in the 60–69 yr, 70–79 yr, and 80–89 yr age groups ($P < 0.001$), but did not differ in the 18–34 yr, 40–49 yr, or 50–59 yr age groups. **Conclusions:** Critical speed progressively decreased with age, likely due to age-related decrements in several physiological systems that cause reduced aerobic capacity. The mechanism for the larger sex difference in CS in the older age groups is unknown but may indicate physiological differences that occur with aging and/or historical sociological factors that have reduced participation opportunities of older female runners resulting in a more limited talent pool. **Key Words:** ATHLETES, AGING, EXERCISE, PERFORMANCE

The sustainable duration of running exercise is dependent on the intensity, or speed, at which the exercise is performed. This fundamental concept is known as the speed–duration relationship, and for exercise durations of ~2 to 40 min, can be modeled by a hyperbolic equation with two parameters, commonly known as critical speed (CS) and the curvature constant (*D′*) (1). Critical speed is the maximum speed that can be supported primarily by aerobic metabolism while still being able to achieve a metabolic steady state (1). As a result, CS is influenced by oxygen delivery and utilization (2) and is associated with both maximal oxygen uptake ($\dot{V}O_{2max}$) (3) and the proportional area of type I muscle fibers (4). The physiological underpinnings of *D′*, the constant describing the curvature of the hyperbolic relationship, are less clear but may be related to increased substrate level phosphorylation or the rate at which fatigue develops during exercise intensities (or running speeds) greater than CS (1,4). Thus, the speed–duration relationship is determined by the integration of multiple physiologic systems that influence exercise metabolism and metabolic homeostasis, providing a valuable model to evaluate the effects of acute and chronic perturbations, such as exercise training and aging on overall exercise capacity.

Age-related declines in exercise capacity are well known and can occur due to several mechanisms. For example, a primary central cardiovascular limitation that occurs with aging is a lower maximal heart rate (5), which causes reduced aerobic capacity ($\dot{V}O_{2max}$) in older endurance-trained adults. Another factor that may contribute to decrements in aerobic capacity with aging is lower hemoglobin levels (6,7). Impairments within the peripheral vasculature also occur in older adults, including lower blood flow through the large arteries compared with young adults (8) and reduced adenosine triphosphate release from red blood cells that attenuates local vasodilation (9). In addition, reductions in the ability of older adults to generate muscular power are well documented and attributed, at least in part, to the reductions in skeletal muscle mass, particularly the atrophy of type II fibers (10,11). Together, the age-related alterations to the heart, vasculature, and skeletal muscle impact the ability to perform and sustain high-intensity exercise and therefore would likely manifest as a shift in the speed–duration relationship. Indeed, there is evidence of lower CS and critical power (the cycling analog of CS) in older compared with young adults (12–14). These studies, however, do

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not include female subjects and/or do not directly examine sex differences, thereby providing only a limited understanding of potential sex differences in CS and D' across the lifespan.

Sex differences in running exercise performance, wherein men generally outperform women, are well known, with the magnitude of the sex difference increasing with age among elite runners (15,16). This widening of the sex difference with age may be due to differential effects of aging between men and women on major physiological determinants of endurance performance, such as maximal oxygen uptake (17), or due to societal and historical barriers to female participation (16,18). Although these findings add valuable insight into physiological performance differences with aging and between the sexes, these studies analyzed single long duration events (e.g., 10,000 m and marathon) that are performed at speeds slower than the critical speed and rely predominately on aerobic metabolism. An alternative approach is to estimate CS and D', which are derived mathematically using multiple exercise bouts of different durations (e.g., 800–5000 m track running events), all of which are performed at speeds faster than CS. Including shorter duration events (i.e., 800 m), which require substantial anaerobic energy production (19) and muscular power generation, allows for a more comprehensive examination of the effects of aging and sex on overall exercise capacity, including insight into exercise intensities where a metabolic steady state cannot be achieved.

One of the biggest challenges in human aging research is untangling the physiological changes occurring from the obligatory consequence of aging, *per se*, versus the myriad of other environmental and behavioral factors that arise across one's lifespan. A valuable approach used to address this issue is comparing performance records among elite Master's athletes, rather than comparing laboratory based measures of individuals from the local community. To our knowledge, only one study has used this approach to determine the effect of aging on the speed–duration relationship (14). Although an overall effect of sex on CS was observed in this study (CS of men was faster than women), sex differences across distinct age groups were not examined. Therefore, the purpose of this study was to determine how aging alters CS of top Master's runners in women compared with men. We hypothesized that CS would progressively decrease with increasing age in both sexes and that the age-related decrease in CS would be greater in women than men. In addition, we examined D' across the lifespan in both men and women to gain insight into potential sex differences that might occur with aging.

METHODS

Data Collection. The all-time top 10 performances for men and women in three outdoor track events (800 m, 1500 m, and 5000 m) across 6 age groups (18–34, 40–49, 50–59, 60–69, 70–79, and 80–89 yr) were analyzed from two public databases (https://www.worldathletics.org and https://www.mastersrankings.com). The performance lists were updated through January 2020 at the time of analysis.

Data Analysis. After compiling the performance times for men and women in each age group, the average speed during each performance was calculated using the following equation, $S = (D)/(t)$, where D is the event distance (m), t is the performance time (s), and S is the average speed (m·s^{-1}). The parameters (CS and D') of the speed–duration relationship for each performance ranking were estimated by fitting the average speed and event time data with a two-parameter hyperbolic model, $t = D'/(S - \mathrm{CS})$, where t is the performance time (s), D' is the curvature constant (m), S is the average speed (m·s^{-1}), and CS is the critical speed (m·s^{-1}). A residual minimizing iterative procedure was used to fit a hyperbolic model to three speed–duration coordinates from the same performance ranking within each age-sex cohort. For example, CS and D' were derived for the number one performance ranking in the 18- to 34-yr-old female cohort using the fastest 800 m performance, the fastest the 1500-m performance, and the fastest 5000 m performance of 18- to 34-yr-old women. Thus, the three data points are from different athletes. Using the all-time top 10 performances allowed us to determine the speed–duration relationship across athletes, not within an individual, which may be interpreted as an overall species assessment of aging, rather than an assessment of the effect of aging on any one individual.

Many laboratory-based studies that estimate CS (or critical power) use exercise trials between ~2 and ~15 min in duration to ensure that the exercise trials used to fit the hyperbolic model are all performed within the severe intensity domain (1,20). Our approach of using historical performance records to estimate critical speed prohibited the manipulation of the exercise intensities/durations. Thus, some of the 5000-m performances were longer than 15 min. Although many of the 5000-m performances were only slightly longer (e.g., 15–20 min), the 80- to 89-yr-old women had a median time to completion for the 5000 m of 27:06, which may be closer to the bound of exercise durations that are within the severe domain. We attempted to instead use the 3000-m performances for the 80- to 89-yr-old women in the hyperbolic modeling. However, the speeds of the 3000-m performances of this group were slower than the speeds of the 5000-m performances in 9 out of the 10 rankings (median 3000 m speed: 2.85 m·s^{-1}; median 5000 m speed: 3.08 m·s^{-1}). Therefore, we chose to include the 5000-m times in our modeling. See the *Experimental Considerations* section for details.

For each sex, 60 CS values and 60 D' values were calculated (10 values for each of the 6 age groups), which required 180 total data points (i.e., three running events were used to calculate one CS and one D' value). For men, the median R^2 for all models was 0.998 (interquartile range [IQR], 0.997–0.999), the median SEE for CS was 0.018 m·s^{-1} (IQR, 0.014–0.025 m·s^{-1}) or 0.4% of the absolute CS, and the median SEE for D' was 3.4 m (IQR, 2.9–4.4 m) or 9.7% of the absolute D'. For women, the median R^2 for all models was 0.998 (IQR, 0.996–0.999), the median SEE for CS was 0.016 m·s^{-1} (IQR, 0.009–0.022) or 0.3% of the absolute CS, and the median SEE for D' was 3.2 m (IQR, 2.5–3.2 m) or 9.1% of the absolute D'. These measures of model fit are within the bounds of recent recommendations (20). All curve fitting procedures were performed with commercially available software (SigmaPlot, Version 14; Systat Software, San Jose, CA).

The curvature constant D' represents the area encompassed by the CS asymptote and the hyperbolic line of best fit for the 800-, 1500-, and 5000-m speed–duration coordinates. Thus, D' is determined by the relative differences between the CS asymptote and the coordinates. To understand why D' might change with aging, we performed a *post hoc* analysis of sex and age differences in 800 m, 1500 m, and 5000 m speeds expressed as a percent of CS. Sex differences between age-matched men and women were largest for relative 800 m speed (0.2% [18–34 yr], 0.9% [40–49], 1.8% [50–59], 2.6% [60–69], 5.1% [70–79], 6.7% [80–89]), modest for relative 1500 m speed (0.4% [18–34 yr], 0.9% [40–49], 0.2% [50–59], 1.6% [60–69], 3.4% [70–79], 3.0% [80–89]), and smallest for relative 5000 m speed (0.1% [18–34 yr], 0.2% [40–49], 0.1% [50–59], 0.4% [60–69], 0.9% [70–79], 0.8% [80–89]). In addition, we calculated the sex difference between age-matched men and women in absolute performance times for the 800 m (12.5% [18–34 yr], 11.4% [40–49], 15.9% [50–59], 18.7% [60–69], 24.2% [70–79], 27.6% [80–89]), 1500 m (12.7% [18–34 yr], 11.1% [40–49], 14.2% [50–59], 18.0% [60–69], 21.6% [70–79], 24.5% [80–89]), and 5000 m (12.2% [18–34 yr], 12.0% [40–49], 14.2% [50–59], 15.7% [60–69], 19.0% [70–79], 19.7% [80–89]). Across age groups, the sex difference in relative 800 m speed was higher than the sex differences in relative 1500- and 5000-m speed. In addition, the sex difference in absolute performance times increased with aging in the 800 m more than the 5000 m. Therefore, we chose to report only on the relative 800-m speeds for clarity.

Statistical Analysis. Dependent variables were assessed for normality and homogeneity of variance using the Shapiro–Wilk test and Levene's test, respectively. There were moderate deviations from normality and the error variances were not equal across groups therefore nonparametric tests were used. Kruskal-Wallis tests were used to detect differences in CS, D', and 800 m speed across age within each sex. Dunn's procedure was used for *post-hoc* pairwise comparisons. Mann-Whitney tests were used to detect differences in CS, D', and 800 m speed between men and women within each age group. Bonferroni adjustments were used to correct for multiple comparisons and the resulting adjusted P values are reported. Data are reported as median values, and the IQR is reported for CS and D'. A linear regression was performed to test for associations between relative 800 m speed (% of critical speed) and D' in men and women. Statistical significance was set at $P < 0.05$. All statistical analyses were performed using SPSS (version 28, IBM, Chicago, IL).

RESULTS

Critical Speed. The median speed–time hyperbolic models for men and women in each age group are shown in Figure 1. CS was different between age groups in both men (H [5] = 57.5 $P < 0.001$) and women (H [5] = 57.1, $P < 0.001$). *Post hoc* pairwise comparisons between the 18- and 34-yr-old group and each older age group revealed a decline in the absolute CS with increasing age in both men and women (Fig. 2). Critical speed declined each decade in men (CS as a percent of the 18- to 34-yr-old group: 91.9% (40–49 yr), 84.4% (50–59), 77.0% (60–69), 68.2% (70–79), 56.4% (80–89), all $P < 0.001$]. Critical speed also declined each decade in women [CS as a percent of the 18- to 34-yr-old group: 91.8% (40–49 yr), 82.9% (50–59), 75.0% (60–69), 64.9% (70–79), 53.5% (80–89), all $P < 0.001$].

Critical speed was faster in men than women (5.11 [IQR, 1.48] vs 4.62 [IQR, 1.51] m·s^{-1}, $U = 1109$, $z = 3.6$, $P < 0.001$). Pairwise comparisons revealed faster CS in men than women within each age group (6.29 [0.05] vs 5.61 [0.05] m·s^{-1} [18–34 yr], 5.78 [0.11] vs 5.15 [0.08] m·s^{-1} [40–49], 5.31 [0.10] vs 4.65 [0.12] m·s^{-1} [50–59], 4.84 [0.06] vs 4.21 [0.12] m·s^{-1} [60–69], 4.29 [0.02] vs 3.64 [0.06] m·s^{-1} [70–79], 3.55 [0.05] vs 3.00 [0.18] m·s^{-1} [80–89], all $P < 0.001$). The sex difference across age groups, however, increased in the older decades. The CS of women, expressed relative to that of the age-matched men, was not different from the 18- to 34-yr-olds (89.2%) in the 40- to 49-yr-old (89.1%, $P = 1.000$) or 50- to 59-yr-old (87.6%, $P = 0.672$) age groups, but was less in the 60- to 69-yr-old (87.0,% $P = 0.030$), 70- to 79-yr-old (84.9%, $P < 0.001$), and 80- to 89-yr-old (84.5%, $P < 0.001$) age groups.

Curvature Constant. The curvature constants (D') for each age and sex are shown in Figure 3. The curvature constant was different between age groups in both men (H [5] = 18.1, $P = 0.003$) and women (H [5] = 36.8, $P < 0.001$). Pairwise comparisons between the 18- to 34-yr-old men and each older male age group revealed only one difference such that D' was greater in the 70- to 79-yr-old men (197 [15] m) compared with the 18- to 34-yr-old men (181 [3] m) ($P < 0.001$). D' was not different from the 18- to 34-yr-old men in any other age group (186 [6] m [40–49 yr], 186 [9] m [50–59], 182 [6] m (60–69), 178 [34] m [80–89], all $P = 1.000$). Pairwise comparisons among the women revealed that D' was lower in 60- to 69-yr-old (162 [6] m, $P = 0.045$), 70- to 79-yr-old (156 [9] m, $P = 0.005$), and 80- to 89-yr-old (143 [21] m, $P < 0.001$) women compared with 18- to 34-yr-old women (177 [3] m), but was not different in the 40- to 49-yr-old (197 [32] m, $P = 0.640$) or 50- to 59-yr-old (179 [4] m, $P = 0.768$) women.

The curvature constant was greater for men (185 [10] m) than women (168 [22] m, $U = 689$, $z = 5.8$, $P < 0.001$). Pairwise comparisons revealed a reduced D' in women compared with men in the 60- to 69-yr-old (162 [6] vs 182 [6] m, $P < 0.001$), 70- to 79-yr-old (156 [9] vs 197 [15] m, $P < 0.001$), and 80- to 89-yr-old (143 [21] vs 178 [34] m, $P < 0.001$) age groups. There were no differences in D' between women and men in the 18- to 34-yr-old (177 [3] vs 181 (3) m, $P = 0.258$), 40- to 49-yr-old (197 [32] vs 186 [6] m, $P = 1.000$), or 50- to 59-yr-old (179 [4] vs 186 [9] m, $P = 0.450$) age groups.

800 M Speed. Figure 3 shows the relative 800 m speed (800 m speed expressed as a percent of CS) for each age and sex. The relative 800 m speed was different between age groups for both men (H [5] = 43.6, $P < 0.001$) and women (H [5] = 47.2, $P < 0.001$). Pairwise comparisons between the 18- to 34 yr-old men and each older male age group revealed a faster relative

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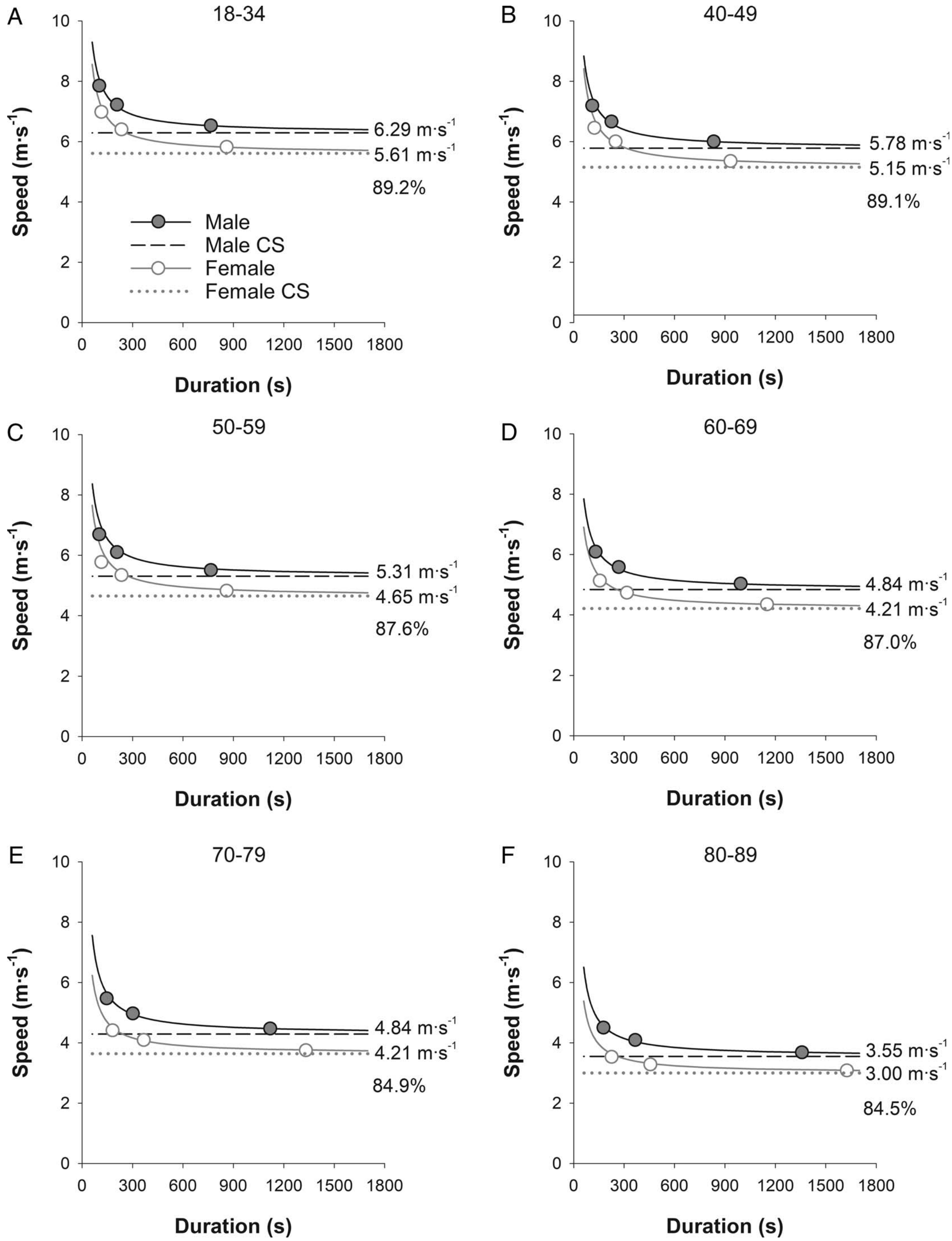

FIGURE 1—Sex differences in the speed–duration relationship. Median speed and duration data points for the 800-, 1500-, and 5000-m events, hyperbolic models (women: *gray solid lines*, men: I), and the CS asymptotes (women: *gray dashed lines*, men: black *dashed lines*) in (A) 18–34, (B) 40–49, (C) 50–59, (D) 60–69, (E) 70–79, and (F) 80- to 89-yr-old groups. On each curve, the 800 m is the leftmost point, the 1500 m the middle point, and the 5000 m the rightmost point. The variance around each curve is omitted for clarity. The values displayed to the right of the asymptotes on each panel are the median male and female CS for that age group. The percentages displayed below the median CS values correspond to each female age group's CS as a percentage of the age-matched men's CS.

800 m speed in the 70- to 79-yr-olds (128%) and 80- to 89-yr-olds (127%) compared with the 18- to 34-yr-olds (125%) (both $P < 0.001$). There were no differences between the 18- to 34-yr-old men and the other male age groups (124% [40–49], 126% [50–59], 125% [60–69], $P = 0.128$–1.000). Pairwise comparisons between the 18- to 34-yr-old women and each older female group revealed slower relative 800-m speed in the 70- to 79-yr-olds (121%, $P = 0.035$) and 80- to 89-yr-olds (119%, $P < 0.001$) compared with the 18- to 34-yr-olds (124%). There were no differences between the 18- to 34-yr-old women and the other female age groups (126% [40–49], 124% [50–59], 122% [60–69], $P = 0.135$–1.000).

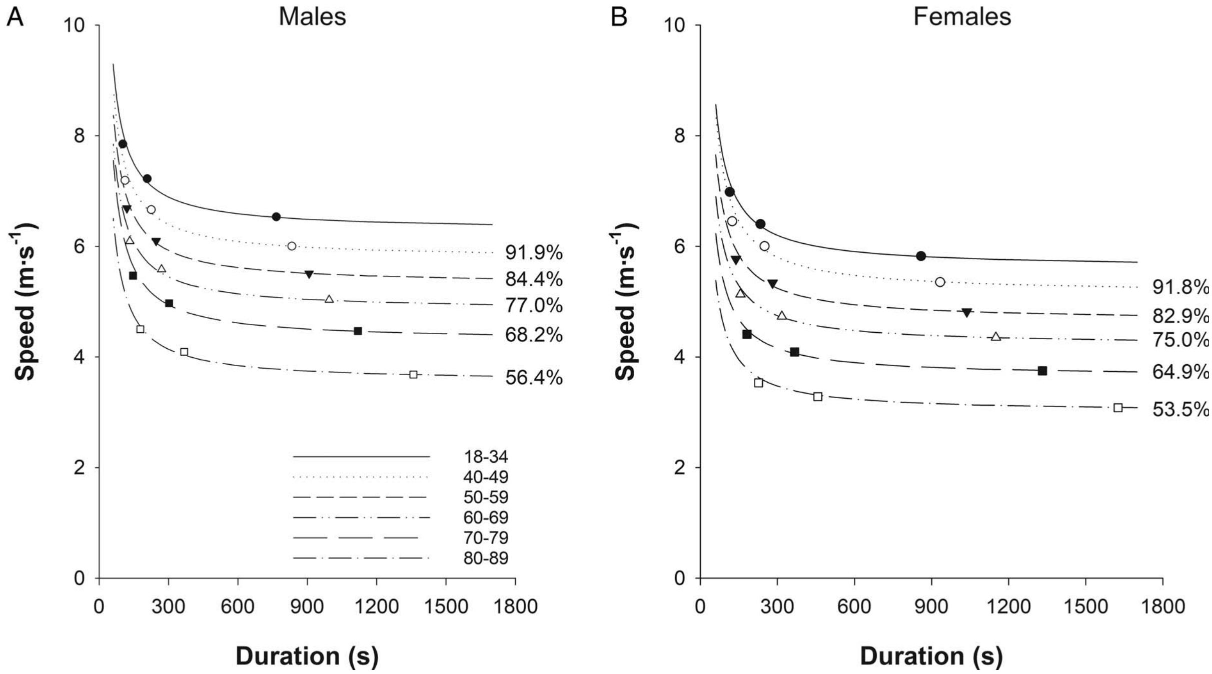

FIGURE 2—Age differences in the speed–duration relationship. Median speed and duration data points for the 800-, 1500-, and 5000-m events and corresponding hyperbolic models across the lifespan for (A) men and (B) women. On each curve the 800 m is the leftmost point, the 1500 m the middle point, and the 5000 m the rightmost point. The variance around each curve is omitted for clarity. The percentages displayed on the right side of each panel correspond to each age group's CS as a percentage of the 18- to 34 yr-old group's CS.

The relative 800-m speed was faster for men (125%) than women (123%) ($U = 578$, $z = 6.4$, $P < 0.001$). Pairwise comparisons revealed slower relative 800 m speed in women compared with men in the 50- to 59-yr-old (124% vs 126%, $P = 0.006$), 60- to 69-yr-old (122% vs 125%, $P < 0.001$), 70- to 79-yr-old (121% vs 128%, $P < 0.001$), and 80- to 89-yr-old (119 vs 127%, $P < 0.001$) age groups; however, relative 800-m speed was faster in women compared with men in the 40- to 49-yr-old (126% vs 124%, $P = 0.042$) age group. There was no difference in relative 800-m speed between women and men in the 18- to 34-yr-old (124% vs 125%, $P = 1.000$) age group. The relative 800-m speed was associated with D' for both men ($R^2 = 0.72$; $P < 0.001$) and women ($R^2 = 0.82$; $P < 0.001$).

DISCUSSION

The present study aimed to determine the effects of age and sex on the speed–duration relationship during running at speeds faster than CS using the all-time top 10 performances from three running events. This approach provides a unique view into sex- and age-related differences in overall exercise capacity. The findings demonstrate a progressive decline in CS with each decade of aging in both men and women, likely due to age-related reductions in aerobic capacity. Moreover, the magnitude of the sex difference in CS increased with aging, and a sex difference in the curvature constant appeared in the later decades of life. Collectively, our findings suggest that sex differences in the parameters of the speed–duration relationship are amplified with increasing age, which may be attributed to true physiological differences that occur with aging and/or historical sociological factors that have reduced participation opportunities of older female runners.

Critical speed and aging. There was a progressive reduction in CS with each decade of aging, which was consistent with our hypothesis. The 40- to 49-yr-old cohorts' CS was ~92% of the 18- to 34-yr-old age group, whereas the 80- to 89-yr-old cohorts' CS was almost halved (~55% of the 18- to 34-yr-olds). Some reports show a steeper decline across the lifespan such that older (mean ages of 66–71 yr) adults' critical power is ~53% to 65% of younger adults' critical power (12,13). It is likely that our experimental model, which used the all-time top 10 performance rankings to determine CS, buffered part of the steep decline previously observed in Overand et al. (12) and Neder et al. (13) as the 60- to 69-yr-old cohorts' CS was ~76% of the youngest cohort. Indeed, trained older adults have a higher critical power than untrained older adults (21), and lifelong endurance training can offset some of the age-related declines in aerobic capacity (5). However, there was a sharper decline in CS in the two oldest age groups (70- to 79-yr-olds and 80- to 89-yr-olds). A similar trend was observed in a recent investigation in Master's runners that demonstrated an annual decline in CS of ~0.5% through the sixth decade of life and then a decline of ~3.0% through the ninth decade of life (14). The reasons for this trend are unclear, although we speculate it is, in part, due to reduced training volume with aging that further decreases maximal aerobic capacity (22).

The physiological determinants of CS are strongly associated with those that influence $\dot{V}O_{2max}$ (3). Although this study was a data analytics study and we did not perform laboratory measurements on the runners, there is compelling evidence

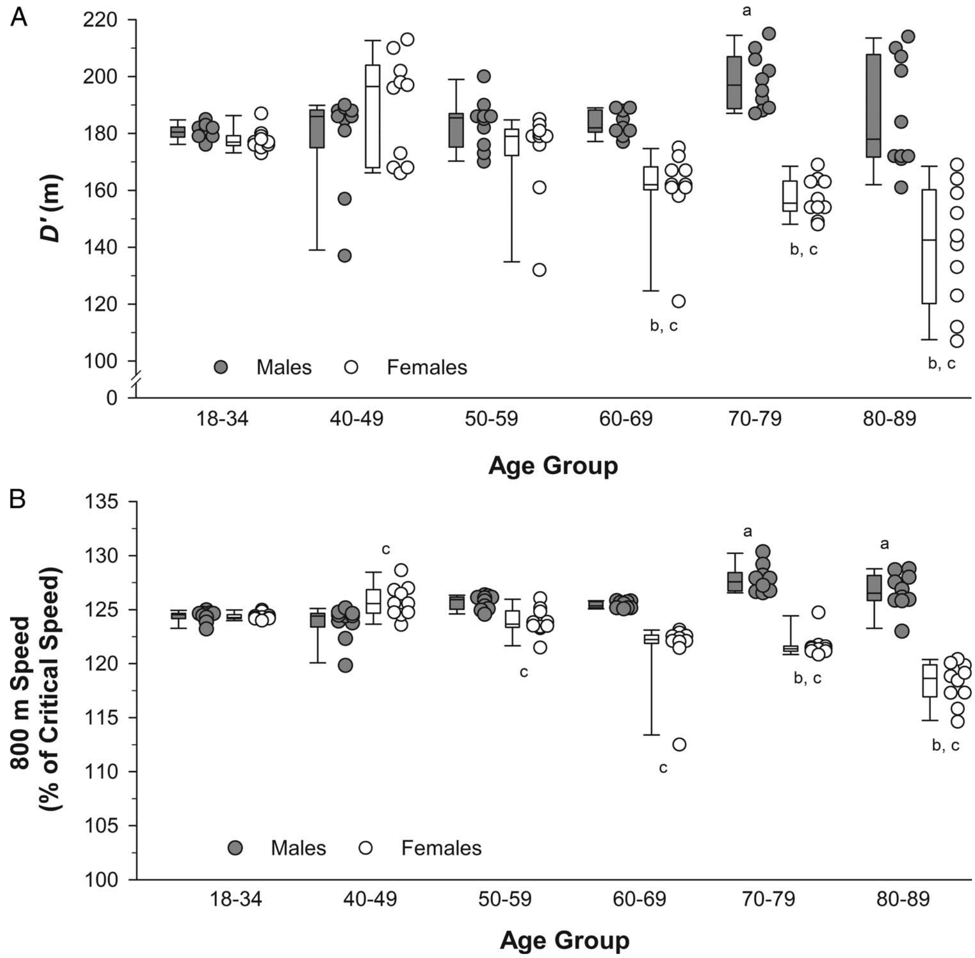

FIGURE 3—Age and sex differences in *D′* and 800 m speed. Individual data points and boxplots for men (*filled boxes*) and women (*open boxes*) for *D′* (panel A) and 800-m speed (panel B). [a]Different compared with 18- to 34-yr-old men ($P < 0.05$). [b]Different compared with 18- to 34-yr-old women ($P < 0.05$). [c]Different compared with age-matched men ($P < 0.05$).

that aging reduces $\dot{V}O_{2max}$ in healthy men and women (23). Two studies comparing Master's runners with younger counterparts demonstrate a 15%–19% lower $\dot{V}O_{2max}$ of Master's runners (~56–59 yr) primarily due to reductions in maximal heart rate (5). The magnitude of the reduction in $\dot{V}O_{2max}$ observed in the Master's runners of 15–19% is remarkably close to the reduction in CS we observed in the 50%- to 59-yr-old male cohort of ~16%. In addition, cross-sectional decade-by-decade data in healthy individuals suggest a 3.5-mL·kg^{-1}·min^{-1} decline in $\dot{V}O_{2max}$ per decade (24). Other factors that impact $\dot{V}O_{2max}$ (and are associated with critical power (25)), such as mitochondrial enzyme activity and capillary density, are reduced with age, at least in the non–endurance-trained population (26). Some evidence, however, suggests older and younger recreational active adults do not differ in *in vivo* measurements of muscle oxidative capacity (27). Moreover, when younger and older runners are matched for endurance performance and training volume, older runners have greater mitochondrial enzyme activity than younger runners (28). Thus, it is plausible that decreased oxygen delivery secondary to a decreased maximal heart rate and decreased cardiac output is a major physiological mechanism for reductions in CS with aging.

Critical speed and sex differences. As expected, critical speed was greater in men than women, regardless of age. The absolute sex difference in median critical speed was ~0.5 m·s^{-1}, which is similar with a previous report of championship-level runners (14) as well as recreational marathon runners (29). The mechanisms for the greater speed in men compared with women are likely related to physiological factors that cause sex differences in aerobic capacity. For example, healthy nontrained men, on average, have a higher $\dot{V}O_{2max}$ than women, and trained male runners have a higher $\dot{V}O_{2max}$ than trained female runners even when normalized to fat free mass (30,31). The sex difference in $\dot{V}O_{2max}$ is due primarily to the established greater hemoglobin mass in men compared with women (32), which may explain, in part, the sex difference in CS. This premise, however, needs direct substantiation through laboratory testing, because other factors influencing oxygen transport and utilization such as cardiac output, fiber type distribution, and skeletal muscle capillarity can influence CS (4,21,25).

Our experimental design of using the all-time top 10 performances allowed for a novel, decade-by-decade cross sectional comparison of men and women, which revealed that sex differences in CS are slightly greater with aging. Critical speed in the 18- to 34-yr-old and 40- to 49 yr-old women was ~89% of CS in age matched men, whereas CS in the 70- to 79-yr-old and 80- to 89-yr-old women was ~85% of CS in age matched men (Fig. 1). The widening of the sex differences with age that we observed has also been demonstrated in marathoners (16,33). Although the mechanisms for the increased sex difference with aging in the present study are unclear, one potential cause is the lower participation rates of older female runners compared with older men due to historical and sociological factors (16). Hunter and Stevens (14) showed that the lower participation rates of women were associated with larger sex differences in marathon performance and the participation rates explained most of the variability in the sex differences in performance (one third of the variance) outside that due to physiological differences between men and women (16). Thus, low participation rates of women relative to men will diminish the depth of the talent pool and therefore, on average, potentially reduce absolute running performance times and lower CS in this current data set among the older women. Future investigations are needed to uncover potential physiological and/or sociological mechanisms for the widening of the sex difference in CS with age.

Curvature constant, aging, and sex differences. Our analysis revealed novel findings wherein D' was similar between men and women in the three youngest age groups (i.e., 18–34, 40–49, and 50–59), but was less in females than males in the three oldest age groups (Fig. 3). Although the nonparametric statistical tests used in our analysis do not allow for the true testing of an age by sex interaction, we believe these results indirectly demonstrate an age by sex interaction effect. Mathematically, the reduction in D' in older women results from the compression of the area bound by the CS asymptote and the hyperbolic line of best fit for 800, 1500, and 5000 m speed–duration coordinates. We cautiously speculate the lower D' in older women could occur for two reasons. First, the magnitude of D' may be related to glycolytic (or anaerobic) energy contribution (4), which in turn is closely associated with thigh lean tissue volume across the lifespan for cycling exercise (34). Aging is associated with the atrophy of type II fibers with some evidence demonstrating that older women have a greater loss in type II cross-sectional area than men (10). It is possible that the exercise performance of older women in events such as the 800 m, which require substantial glycolytic energy production and muscular power generation (19), is reduced with aging to a greater extent than age-matched men. A greater reduction in 800 m event performance would cause a "downward" compression of D' and may provide indirect support for this thesis. Indeed, when we expressed the 800-m speed as a percent of CS, we observed no difference in the relative 800 m speed between the 18- to 34-yr-old men and women, nor a difference in D'; however, a sex difference in relative 800 m speed is apparent within the 60+ age groups that is qualitatively similar to the sex difference in D' (Fig. 3). An alternative explanation for the reduction in D' in older women may be an "upward" compression of D' wherein the CS asymptote is increased relative to event speeds. This could occur when the metabolic rate that is equivalent to CS is a greater percentage of $\dot{V}O_{2max}$, as has been demonstrated after endurance training (35). Although changes to the lactate threshold expressed as a percent of $\dot{V}O_{2max}$ can occur, no sex difference is apparent (36). Thus the "downward" compression seems more likely than the "upward" compression scenario. Clearly, more work is needed to elucidate the physiological determinants of D' and how it is altered by age and biological sex.

Experimental considerations. Estimates of CS and D' are traditionally derived for an individual using multiple exercise bouts of different durations. The current study used a different approach wherein three data points within the same top-10 ranking (i.e., world records for 800, 1500, and 5000 m) were used to estimate CS and D'. Thus, because the three data points are from different athletes, the findings of the current study should be interpreted as an overall species assessment of aging, rather than an assessment of the effect of aging on any one individual. In addition, the data analytics approach we used did not allow us to obtain laboratory based anatomical or physiological measures that may change with aging and thus might explain the observed sex and age differences in CS and D'. Future investigations that include measures of cardiac output, hemoglobin concentration, thermoregulation, or body composition in young and older adults may help elucidate the mechanisms for the observed sex and age differences in the speed–duration relationship.

Some of the 5000-m performances used (e.g., the median 5000 m times of the 80- to 89 yr old men and women were 22:38 and 27:08, respectively) are outside the 2- to 15-min suggested window for estimating critical speed, yet it is plausible that the performances were in the severe intensity domain. Exercise at speeds/intensities that are close to the critical speed asymptote (though still within the severe domain) can be sustained for relatively long durations beyond 2–15 min. For example, a recent study using track running distances of up to 10,000 m (~27 min) estimated critical speed and accurately predicted performance in world class athletes (37), whereas others have estimated critical speed using events up to the 15,000 m (~41 min) when the inclusion of the longer trials did not adversely affect the R^2 (38). In addition, some have proposed that critical speed/power can be sustained for up to 30 min (1) or possibly even 40 min (39). Together, this suggests that the 5000-m performances we used to estimate critical speed are likely within the severe domain. Importantly, a novel finding of the article, the increased sex difference in critical speed with aging, is the same even if the 80- to 89-yr-old groups (which have the longest 5000 m times) are removed. In fact, the sex difference in the 80- to 89-yr-old group of 14.5% is similar to the sex difference in the 70- to 79-yr-old group of 14.1%. Nevertheless, we suggest that the longer 5000 m performance times of the oldest groups, which may be closer to the bound of exercise durations that are within the severe domain, be considered when interpreting the results.

Practical considerations. Critical speed is a metabolic threshold such that exercising at speeds faster than CS will cause increased accumulation of fatigue-inducing metabolites and eventually task failure (40). We observed a substantial

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decrease in CS with aging, even in the elite Master's athletes whose running performances are in the top 10 performances ever. The decline in the metabolic threshold in the general, non–endurance-trained population is likely more pronounced than what we observed in elite level athletes who perform regular physical activity. This suggest that in older adults who are non–endurance-trained, fatigue may occur during tasks requiring absolute speeds slower than running speeds, such as walking-based activities of daily living.

CONCLUSIONS

The present study provides novel insight into decade-by-decade changes in the speed–duration relationship. The findings demonstrate a continual, deleterious effect of aging on critical speed which is likely due to age-related reductions in aerobic capacity. In addition, a widening of the sex difference in critical speed occurred with aging, along with the appearance of a sex difference in the curvature constant in the later decades of life. Collectively, these findings suggest that sex differences in the parameters of the speed–duration relationship are amplified with increasing age. These sex differences may indicate physiological differences that occur with aging and/or historical sociological factors that have reduced participation opportunities of older female runners.

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