Critical Speed throughout Aging: Insight into the World Masters Championships

JAYSON R. GIFFORD[1,2], and JESSICA COLLINS[1]

[1]*Department of Exercise Sciences, Brigham Young University, Provo, UT; and* [2]*Program of Gerontology, Brigham Young University, Provo, UT*

ABSTRACT

GIFFORD, J. R., and J. COLLINS. Critical Speed throughout Aging: Insight into the World Masters Championships. *Med. Sci. Sports Exerc.*, Vol. 53, No. 3, pp. 524–533, 2021. **Purpose:** This study aimed to determine how the speed–distance relationship, described by critical speed (CS) and distance prime (D'), is altered with aging. **Methods:** Official race data from the past eight World Masters Athletics Indoor Track and Field World Championships were used for this study. CS and D' were calculated for female and male athletes (35–90 yr of age) who registered times for the 800-, 1500-, and 3000-m runs during a single championship to determine the relationship between age and CS and D'. Twenty-six athletes completed sufficient races in multiple championships to retrospectively assess the change in CS and D' over time. **Results:** Cross-sectional data indicated that CS continuously decreases after age 35 yr in a curvilinear manner with advancing age ($R^2 = 0.73$, $P < 0.001$, $n = 187$), with even greater decreases in CS occurring after ~70 yr of age. D' also changed in a curvilinear manner with age ($R^2 = 0.45$, $P < 0.001$, $n = 103$), such that decreases were observed between 35 and 70 yr, followed by an increase in D' thereafter. Retrospective, longitudinal data, with an average follow-up of 6.38 ± 1.73 yr, support these findings, indicating that the annual decrease in CS grows with advancing age (e.g., ~1% vs ~3% annual decrease in CS at age 55 vs 80 yr, respectively) and that D' shifts from an annual decrease (e.g., ~2.5% annual decrease at 55 yr) to an annual increase (e.g., ~2.5% annual increase at 80 yr) around 70 yr of age. Importantly, the relationship between CS and race pace was unaffected by age, supporting the relevance of CS throughout aging. **Conclusion:** Even among world-class athletes, CS decreases and D' changes with aging. These adaptations may contribute to the diminished exercise ability associated with aging. **Key Words:** CRITICAL SPEED, CRITICAL POWER, DISTANCE PRIME, AGING, MASTERS ATHLETES

Nearly 100 yr ago, the Nobel prize–winning physiologist A.V. Hill examined the relationship between running speed and race distance by plotting the reigning world-record speeds (event distance/total race time) for various foot races of different distances (1). The plot revealed a hyperbolic relationship, in which the highest race speed was observed during the shortest events (e.g., 200-yd dash) with the lowest speeds being observed in the longest events (e.g., 10 miles, 100 miles). An important feature of this relationship was that although the record speeds for shorter races differed dramatically (e.g., 1000-yd dash was ~25% slower than the 200-yd dash), the record speeds for longer distance events were minimally different. For example, the record speed for the 6-mile race was only ~5% less than the record speed for the 2-mile event, despite being 7040 yd longer.

In the nearly 100 yr since Hill's articulate interpretation of world-record race times, researchers have confirmed the hyperbolic relationship between distance and speed and mathematically described it with the term distance prime (D') representing the curvature constant and the term critical speed (CS) representing asymptote of the hyperbolic curve (2–4). In physiological terms, CS, or its analog critical power (CP), is understood to represent the maximum metabolic rate, often simplified into terms of speed or power, at which a person can achieve steady-state conditions (i.e., maximal metabolic steady state) (5), whereas D', or its analog work prime (W'), represents the finite amount of work that can be performed and tolerated above CS.

CS is an important threshold for fatigue (2). Although one's rate of maximum oxygen consumption ($\dot{V}O_{2max}$) represents the greatest rate of oxygen consumption that is achievable, CS, which varies considerably between people with the same $\dot{V}O_{2max}$ (2), represents the greatest metabolic rate (e.g., percentage of $\dot{V}O_{2max}$) that is sustainable (5). Exercise at or below CS is predominantly fueled by oxidative phosphorylation and sustainable rates of anaerobic glycolysis (CS is above the lactate threshold), which allows for prolonged endurance (e.g., professional marathoners reportedly run very close to their

Address for correspondence: Jayson R. Gifford, Ph.D., Department of Exercise Sciences, Brigham Young University, Provo, UT 84602; E-mail: jaysongifford@byu.edu.
Submitted for publication May 2020.
Accepted for publication August 2020.

0195-9131/20/5303-0524/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000002501

CS [4]). Exercise above CS also uses oxidative phosphorylation; however, exercise above CS is also reliant on finite stores of phosphocreatine and high rates of anaerobic glycolysis to meet the high ATP demand of the exercise. With phosphocreatine stores becoming increasingly depleted and high rates of anaerobic glycolysis being associated with the accumulation of fatigue-inducing metabolites (e.g., acid, inorganic phosphate, and potassium), exercise above CS inexorably leads to fatigue (2,5,6). D' is the quantification of how much work, often simplified into meters, that can be performed or tolerated above the CS threshold before fatigue occurs.

As exercise performance and tolerance clearly decline with aging (7), it is not surprising that CS and CP decline with age. In one of the only studies to compare the CP of young and older individuals, Neder et al. (8) found that sedentary ~65-yr-old males exhibited a CP that was approximately 47% less than that of their young, sedentary counterparts (~22 yr old). Such a decline in CP represents increased the susceptibility of the elderly to fatigue at lower exercise intensities, which would likely impair exercise performance. As the subjects in the study by Neder et al. (8) were sedentary males, it is unclear if similar declines in CP would be observed in an active population or among females. Moreover, it is not clear if CP decreases linearly over time, or if it declines at greater rates in advancing age, such as $\dot{V}O_{2max}$ (9). The determination of CS and D' in an active aging population, such as masters athletes, may provide insight into the effect of age on CS and D'.

The World Masters Athletics (WMA) has sponsored the World Masters Indoor Track and Field Championships approximately every 2 yr since 2004. During these championships, an international selection of athletes ranging from 35 to 90 yr and older run events from 60 m to the half marathon. The athletes participating in these events represent some of the best athletes in the world for their age (10), as evidenced by the 39 age-based world records that were broken during the 2019 games alone (11). Fortuitously, during each championship, several athletes register times for multiple different distances (e.g., 800, 1500, and 3000 m), allowing for calculation of CS and D' (12–14). Therefore, the purpose of this study was to use race results from the World Masters Indoor Track and Field Championships to examine the effect of age on the speed–distance relationship, CS, and D' in an active aging population.

METHODS

All procedures for this study were approved by the Institutional Review Board at Brigham Young University and given exempt status before data were collected. Data were obtained from publicly available race results (https://world-masters-athletics.com/championships/results-championships-indoor) (11) from the 2004, 2006, 2008, 2010, 2012, 2014, 2017, and 2019 WMA Indoor Track and Field World Championships. As described in greater detail below, race speed, CS, and D' were then derived from these data.

About the WMA World Championships. According to the association's Web site, WMA is the "organization designated by the International Association of Athletics Federations (IAAF) to sanction World Masters Athletic Championships" and "ratify and register world masters 5-yr age-group records" (15). The WMA sponsors Indoor Track and Field Championships every 2 yr. Athletes ranging from 35 to 90 yr and older from ~80 different countries participate in the championships every 2 yr. Events ranging from 60 to 3000 m are held on a 200-m indoor track, whereas longer races, including the 8000-m cross-country race and the half marathon, are generally held on outdoor courses through the surrounding area (16). Athletes were sorted and competed in 5-yr age-groups starting at 35 yr of age (e.g., 35–39 yr old, 40–44 yr old, etc.). Although there are technically no qualifying standards for the WMA championships, the pool of athletes represents a relatively fit and active population, as evidenced by 39 age-based world records that were set during the 2019 championships alone (11).

Assessing the speed–distance relationship throughout aging. The results of the 2019 championships were used to examine the effect of age on the speed–distance relationship. Specifically, the times for top finishers for the 60-, 200-, 400-, 800-, 1500-, 3000-, and 10,000-m events for each 5-yr age-group and sex were converted into average race speed by dividing the race distance by race time. For most races, the top 8 times for males and top 8 times for females in the finals of each event were used to explore how the speed–distance relationship changes with age. In a few races for the older age-groups, there were fewer than eight finishers because of lower participation or completion (e.g., females 75-yr age-group, 1500 m, $n = 4$). As described below, univariate ANOVA was used to explore the effect of age on the speed–distance relationship.

Determination of CS and *D'*. CS is most commonly determined in a laboratory over the course of several days by having participants run at multiple (e.g., 3–5) given speeds until exhaustion (12). Multiple field measurements have also been found to accurately calculate CS and D' by examining the time required to run multiple fixed distances lasting between ~2 and 15 min (12–14). Therefore, race results for all WMA indoor championships were examined for individuals who completed the 800-, 1500-, and 3000-m races with times falling between 2 and ~15 min during a single championship. Over the course of the eight championships considered, 189 unique athletes completed all three races during a single championship.

Ultimately, CS and D' were calculated with linear regression from an athlete's times from the three events with the distance–time method (i.e., race distance = (CS × race time) + D') (3). Only CS values that registered an SEE <5% were included in the CS analysis (12). Because of considerably more variation in the D', only values of D' associated with an SEE <20% were included in the analysis.

Cross-sectional examination of CS and *D'* throughout aging. The relationship between CS, D', and aging was examined with mixed model analysis. Specifically, CS or D' were entered as dependent variables, whereas age (entered in 5-yr bins) and sex were entered as fixed-factor, independent variables. To account for the potential effect of race year or location, the year in which the races were completed was entered

APPLIED SCIENCES

as a random-factor variable in the model. To explore the possibility of a quadratic or cubic relationship between age and CS or D', age^2, and age^3 were also entered into the model. The model with the greatest significant fit (i.e., greatest significant R^2) was selected as the model of best fit. Note that for individuals who registered more than one CS or D' over the course of the eight championships (e.g., CS and D' could be calculated during the 2004 and 2008 events), only one set of CS and D' was used for this cross-sectional analysis. In such cases, for athletes ≤65 yr of age, the value calculated at the athlete's youngest available age was used, and for athletes >65 yr of age, the value calculated at the athlete's oldest available age was used.

Retrospective examination of change in CS and *D′* over time. Several individuals completed the 800, 1500, and 3000 m in more than one championship (e.g., an individual completed the three races in 2004 and again in 2010). Therefore, the change in CS and D' over time was examined for individuals registering values for CS and D' separated by at least 4 yr. Specifically, values registered at their youngest and oldest available ages were used to assess the effect of change of CS and D' over time (i.e., value at oldest age − value at youngest age)/years elapsed). Ultimately, the percent change per year in CS or D' was related to the initial age with linear regression. CS and D' were calculated and screened for SEE as described above.

Relationship between CS and race speed for different distances throughout aging. Many individuals who completed the three races required to calculate CS also completed additional races ranging in distance from 400 m to the half marathon. Therefore, the relationship between CS and average race speed during events ranging from 400 m to a half marathon was examined by representing an athlete's race speed as a percentage of their CS. Ultimately, linear regression was used to determine whether the percentage of CS at which a race is run remains constant or changes throughout aging.

Predicting CS with three versus two time points. Some studies (14,17) have suggested that as few as two distances can be used to calculate CS and D'. Therefore, CS and D' were recalculated using data from only two events (1500 and 3000 m), instead of the three events used for the rest of the study (800, 1500, and 3000 m) to determine whether CS and D' could be accurately predicted with data from just two distances. Subsequently, paired *t*-tests and linear regression were used to determine the utility of a two-event approach.

Statistical analysis. All statistical analyses were completed using JMP Pro version 15 (SAS, Carey, NC). As mentioned, univariate ANOVA, with age, sex, and distance entered as independent variables and speed as the dependent variable, was used to explore the effect of age on the speed–distance relationship. In the event of a significant omnibus ($P < 0.05$), a Bonferroni-corrected *post hoc* test was used to determine differences between race speeds for the different age-groups. As mentioned, mixed model analysis with age, age^2, age^3, and sex entered as independent fixed factors and race year entered as an independent random factor was used to model the relationship between age and CS or D'. Linear regression was used for retrospective analysis of the relationship between change in CS or D' over time and to determine whether race pace, represented as a percentage of CS, is altered with aging. Data are expressed as the mean ± SD, and alpha was set to $P \leq 0.05$, unless otherwise stated.

RESULTS

The speed–distance relationship throughout aging. As illustrated in Figure 1, a hyperbolic relationship between race distance and average race speed was observed in all age-groups (main effect of distance: $F = 931$, $P < 0.001$; note that only 35-, 55-, and 75-yr-old curves are illustrated in Fig. 1 for clarity). A main effect of age on race speed was also observed ($F = 1510$, $P < 0.001$) such that race speed tended to decrease with age, regardless of distance. It is also notable that there was a main effect of sex ($F = 837$, $P < 0.001$), such that, on average, females exhibited lower race speeds, regardless of distance. A comparatively small yet significant interaction between age and distance was also observed ($F = 8.3$, $P < 0.001$). *Post hoc* analysis indicated that race speed for a given distance was not always different between the highlighted age-groups (35, 55, and 75 yr old). For example, despite being visually lower than the average race speed for the 35-yr-old group in the 800-m event, the 55-yr-old group did not perform significantly slower than the 35-yr-old group when Bonferroni corrected for multiple comparisons (mean difference 0.47 ± 0.08 m·s^{-1}, $P = 0.22$). By contrast, the speed for the 75-yr-old group was significantly slower than the 55-yr-old group (mean difference 1.9 ± 0.8 m·s^{-1}, $P < 0.001$).

Relationship between age and CS and *D′* from a cross-sectional sample. CS was calculated from 189 subjects who registered times for the 800, 1500, and 3000 m events during the same championship. The average SEE for the CS derived from the linear regression between distance and time was 1.78% ± 1.09%, with all but two subjects, who were ultimately excluded from subsequent analysis, yielding SEE <5%. For 189 subjects, the average SEE for the D' derived from the linear regression between distance and time was 19.68% ± 10.99%, whereas the average correlation coefficient for the whole regression including all subjects was $R^2 = 0.99 \pm 0.11$. To reduce error surrounding the calculation and interpretation of D', only subjects with an SEE for $D' \leq 20\%$ were used for data analysis ($n = 103$), reducing the average SEE for the D' used in the analyses to 11.84% ± 5.27%.

As illustrated in Figure 2A, the relationship between age and CS was found to be curvilinear ($y = 8.86 - 0.21 \times \text{age} + 0.0036 \times \text{age}^2 - 0.0000239 \times \text{age}^3$ + [female: −0.25, male: +0.25], $R^2 = 0.73$, $P < 0.001$, $n = 187$). A main effect of sex was detected, such that, on average, males exhibited a 0.50-m·s^{-1} greater CS than females ($F = 77.90$, $P < 0.0001$). Age, age^2, and age^3 all significantly contributed to the equation (F = 1.76, 5.96, and 6.39; P = 0.015, 0.012, and 0.002, respectively). No sex–age interaction was detected ($F = 0.83$, $P = 0.51$). Race year/location did not significantly affect the equation ($F = 1.76$, $P = 0.10$).

APPLIED SCIENCES

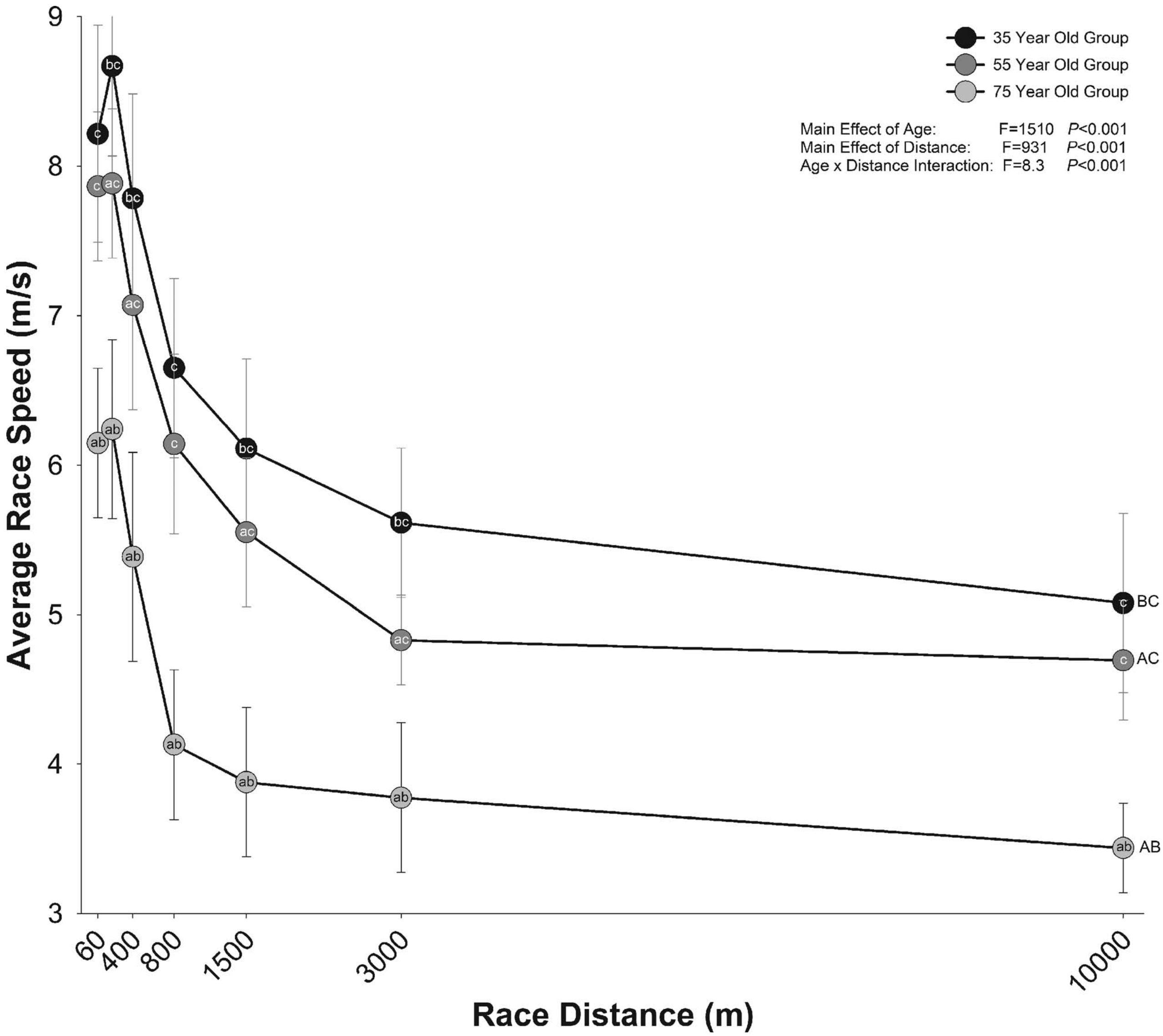

FIGURE 1—The relationship between race distance and average running speed in the 35, 55, and 75-yr-old age-groups participating in the 2019 WMA Indoor Track and Field World Championships. Data are the mean ± SD of top 8 male and top 8 female finishers for each distance. A, Group curve is significantly different than that of the 35-yr-old group. B, Group curve is significantly different than that of the 55-yr-old group. C, Group curve is significantly different than that of the 75-yr-old group. Data point significantly different from corresponding data point of 35-yr-old group (a); data point significantly different from corresponding data point of 55-yr-old group (b); data point significantly different from corresponding data point of 75-yr-old group (c).

As illustrated in Figure 2B, the relationship between age and D' was also found to be cubic in nature ($y = -78.82 + 16.84 \times \text{age} - 0.35 \times \text{age}^2 + 0.0022 \times \text{age}^3 + [\text{female: } -13.85, \text{male: } +13.85]$, $R^2 = 0.45$, $P < 0.001$, $n = 103$). A main effect of sex was detected, such that, on average, males exhibited a 27.70-m greater D' than females ($F = 31.52$, $P < 0.0001$). F values and P values for age, age^2, and age^3 are as follows: $F = 1.79$, 3.15 and 4.59; $P = 0.18$, 0.08 and 0.03 respectively. No interaction between age and sex was detected ($F = 1.46$, $P = 0.18$). Race year/location did not significantly affect the equation ($F = 1.65$, $P = 0.13$).

Retrospective examination of change in CS and *D′* over time. Twenty-six athletes competed in the 800, 1500, and 3000 m in two different championships separated by at least 4 yr, making it possible to retrospectively analyze the change in CS and D' in a subset of athletes over time. The average time elapsed between assessments of CS and D' was 6.38 ± 1.73 yr with a minimum follow-up period of 4 yr and a maximum follow-up period of 9 yr. Figure 3A illustrates the change in CS for each individual during the follow-up period. To investigate if the rate of change in CS was constant or accelerated with aging, the relationship between annual percent change for each individual and their initial age was investigated. As illustrated in Figure 3B, the annual percent change in CS increased with age in a linear fashion ($R^2 = 0.51$, $P < 0.001$), such that a 50 yr old may anticipate a ~0.5% decrease per year, whereas an 80 yr old may anticipate a ~3% decrease in CS per year.

Figure 3C illustrates the change in D' for each individual during the follow-up period. The relationship between an athlete's annual percent change in D' and their initial age was investigated. As illustrated in Figure 3D, the annual rate of change in D' exhibited a positive linear relationship ($R^2 = 0.17$, $P = 0.04$)

APPLIED SCIENCES

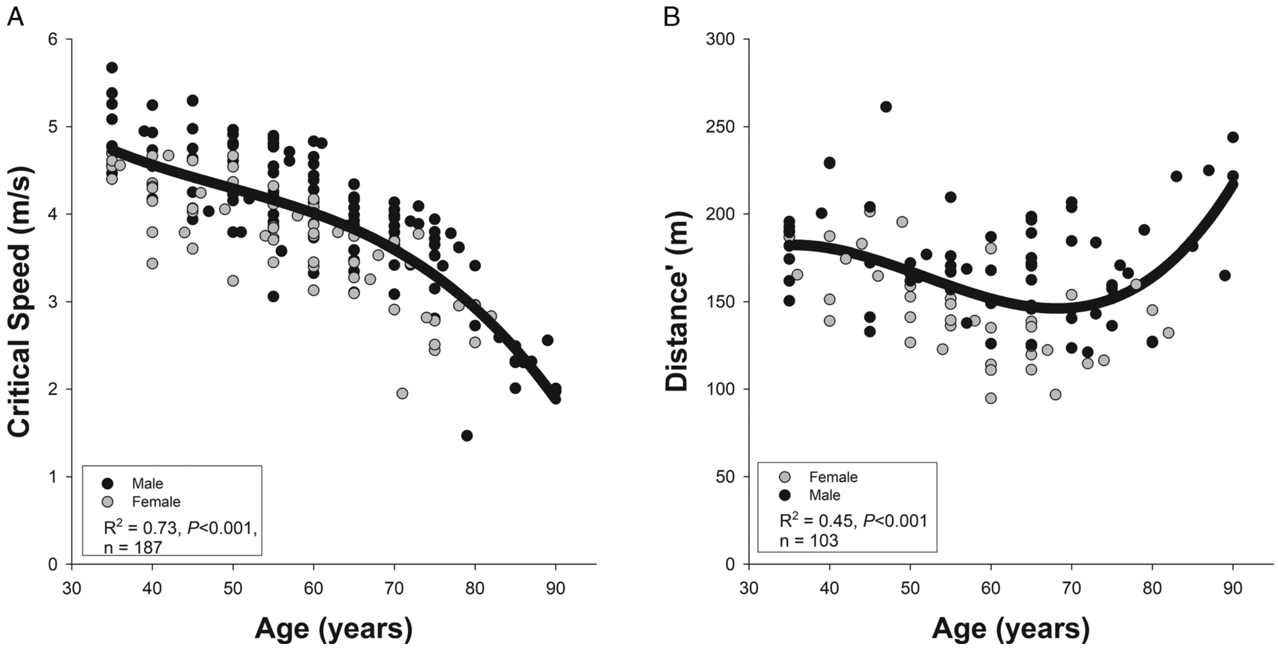

FIGURE 2—The relationship between age and CS (A) and *D′* (B) in a cross-sectional sample of masters athletes competing in the World Masters Indoor Track and Field Championships from 2004 to 2019.

with age, such that a 50 yr old might anticipate an annual ~2% decrease in *D′*, whereas an 80 yr old might anticipate an annual ~2% increase in *D′*.

Relationship between CS and different race distances across age. The relationship between CS and average race speed across age for various distances was examined by representing average race speed for each distance as a percentage of CS. This was subsequently correlated with age for each distance. As illustrated in Figure 4, age was completely unrelated to the %CS at which the various events are run ($R^2 = 0.001–0.02$, $P = 0.15–0.78$), indicating that the relationship between CS and race pace is constant with aging.

Noting the consistent relationship between CS and race speed across age, the relationship between CS, *D′*, and race times for individuals who also registered times for the 400 or 8000 m was examined. These two distances were chosen because they were not included in the regression equation for CS and *D′*. Interestingly, for the 400-m event, CS exhibited a strong inverse relationship with the 400-m race time ($r = −0.86$, $P < 0.001$, $n = 24$), such that a greater CS was associated with a faster 400-m race time. By contrast, *D′* was positively related to the 400-m race time ($r = 0.53$, $P = 0.035$, $n = 24$), such that a greater *D′* was associated with a slower 400-m race time across the sample. For the 8000-m cross-country event, CS exhibited a strong inverse relationship race time ($r = −0.86$, $P < 0.001$, $n = 67$), such that a greater CS was associated with a faster 8000-m race time. *D′* was unrelated to the 8000-m race time ($r = 0.05$, $P = 0.79$, $n = 67$).

Predicting CS with three versus two time points. CS and *D′* were recalculated using data from only two events (1500 and 3000 m) instead of the three events used for the rest of the study (800, 1500, and 3000 m) to determine whether CS and *D′* could be accurately predicted with data from just two distances. Linear regression indicated that CS calculated from data of the two races was very strongly predictive of CS calculated from data of the three races ($y = 1.01x − 0.01$; $R^2 = 0.99$, $P < 0.0001$, $n = 237$). Residuals of the regression equation were not significantly correlated to the true CS ($R^2 = 0.01$, $P = 0.09$). Paired *t*-test revealed a small yet significant offset, with the CS calculated from two races underestimating the true CS calculated from three races by 0.05 $m \cdot s^{-1}$ ($P < 0.001$).

Linear regression indicated that *D′* calculated from data of the two races was predictive of the true *D′* calculated from data of the three races ($y = 0.61 + 50.34$; $R^2 = 0.79$, $P < 0.0001$, $n = 103$). On average, the *D′* calculated from two races overestimated the true *D′* by 20.93 m ($P < 0.001$). However, residuals of the regression were correlated with *D′* ($R^2 = 0.21$, $P < 0.001$), indicating a level of bias, such that *D′* calculated from two events overestimated the true *D′* to a greater extent as the true *D′* increased.

DISCUSSION

The purpose of this study was to use race results from the WMA Indoor Track and Field World Championships to explore the effect of age on the speed–distance relationship, CS, and *D′*. These data indicate that CS and *D′* change throughout aging in a curvilinear manner in active adults, such that the annual decrease in CS appears to accelerate with advancing age, whereas *D′* decreases from age 35 to ~70 yr, after which it exhibits an exponential increase. Nevertheless, the relationship between CS and race speed for the various events appears constant throughout aging. The implications of these findings will be discussed below.

Is the speed–distance relationship altered with aging? Most people know from personal experience that the longer an event, the slower the average speed. However,

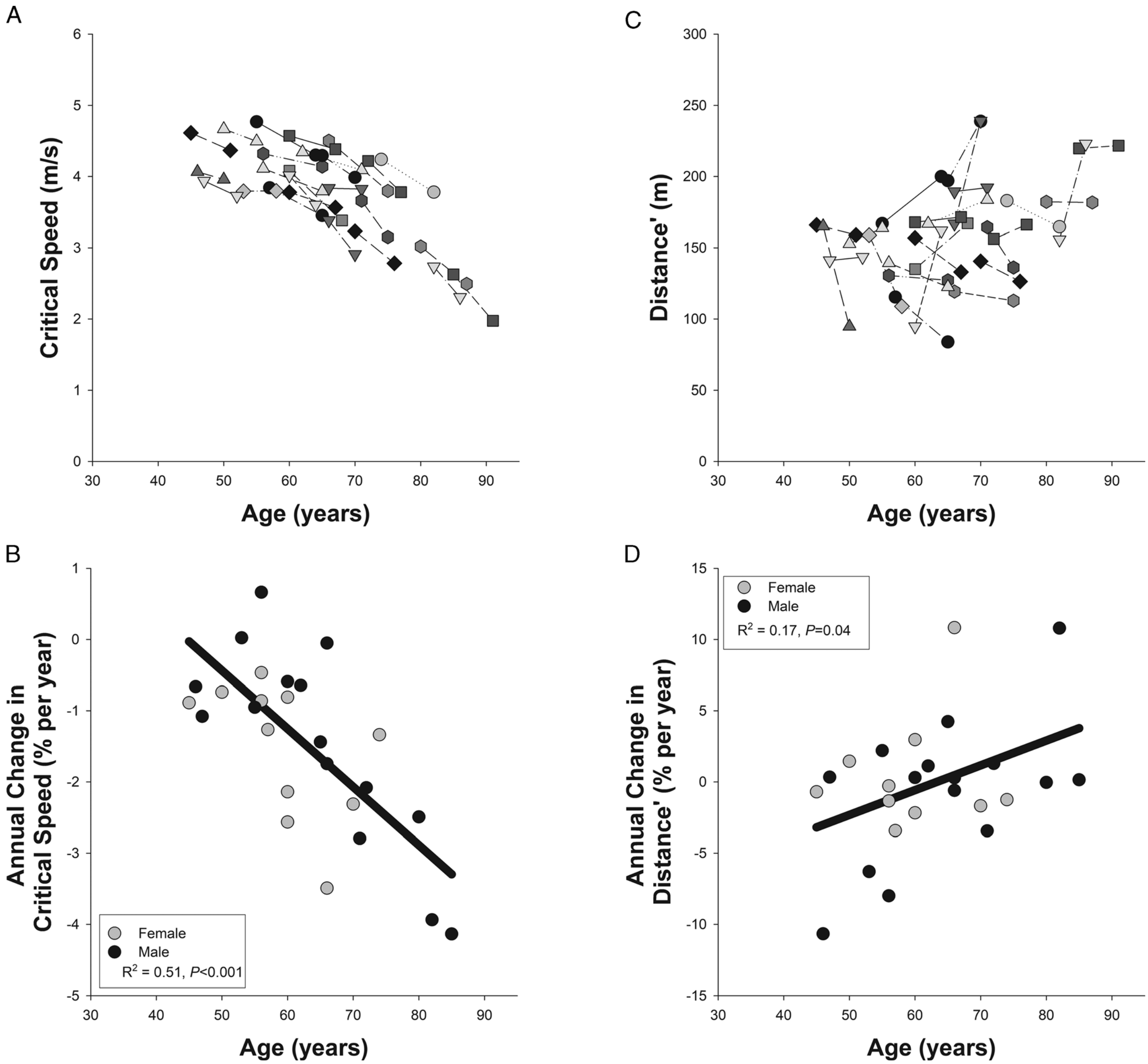

FIGURE 3—The change in CS and *D′* for 26 athletes who competed in 2 WMA Indoor Track and Field World Championships. A, CS at the initial and follow-up time points. B, The annual percent change in CS for each individual plotted against their initial age. C, *D′* at the initial and follow-up time points. D, The annual percent change in *D′* for each individual plotted against their initial age. The average follow-up period was 6.38 ± 1.73 yr with a minimum follow-up period of 4 yr and a maximum follow-up period of 9 yr.

contrary to what one might casually think, the inverse relationship between speed and distance is not linear. Hill (1) and multiple others since (3) have consistently demonstrated a hyperbolic relationship when plotting race speed (vertical axis) against sustainable time or distance (horizontal axis) in which a steep curve and large changes in race speed are observed between shorter distance events (e.g., 100–1500 m), whereas average speeds of longer distance events (e.g., 5-km marathon) vary relatively little as they approach what appears to be an asymptote. Consistent with previous findings (8,18), Figure 1 illustrates that this hyperbolic relationship between speed and distance is retained throughout the life span, whether 35 or 75 yr old.

Although previous data have made it clear that the speed–distance relationship persists throughout aging (8,18), the question of how the curve is shifted at different ages has remained unanswered. In this regard, Figure 1 proves insightful. The speed–distance curve shifts downward and leftward with aging (19), such that older individuals run a given distance at a slower speed than younger individuals. Nevertheless, the downward shift of the speed–distance curve does not appear to occur at a constant rate throughout aging. As illustrated in Figure 1, the downward shift of the speed–distance curve associated with 20 yr of aging from age 55 to 75 yr is visibly greater than the downward shift of the curve associated with 20 yr of aging from 35 to 55 yr. As discussed below, CS, which represents the asymptote of the speed–distance curve, and *D′*, which represents the curvature constant of the curve, were quantified to gain a better understanding of how the speed–distance relationship varies with aging.

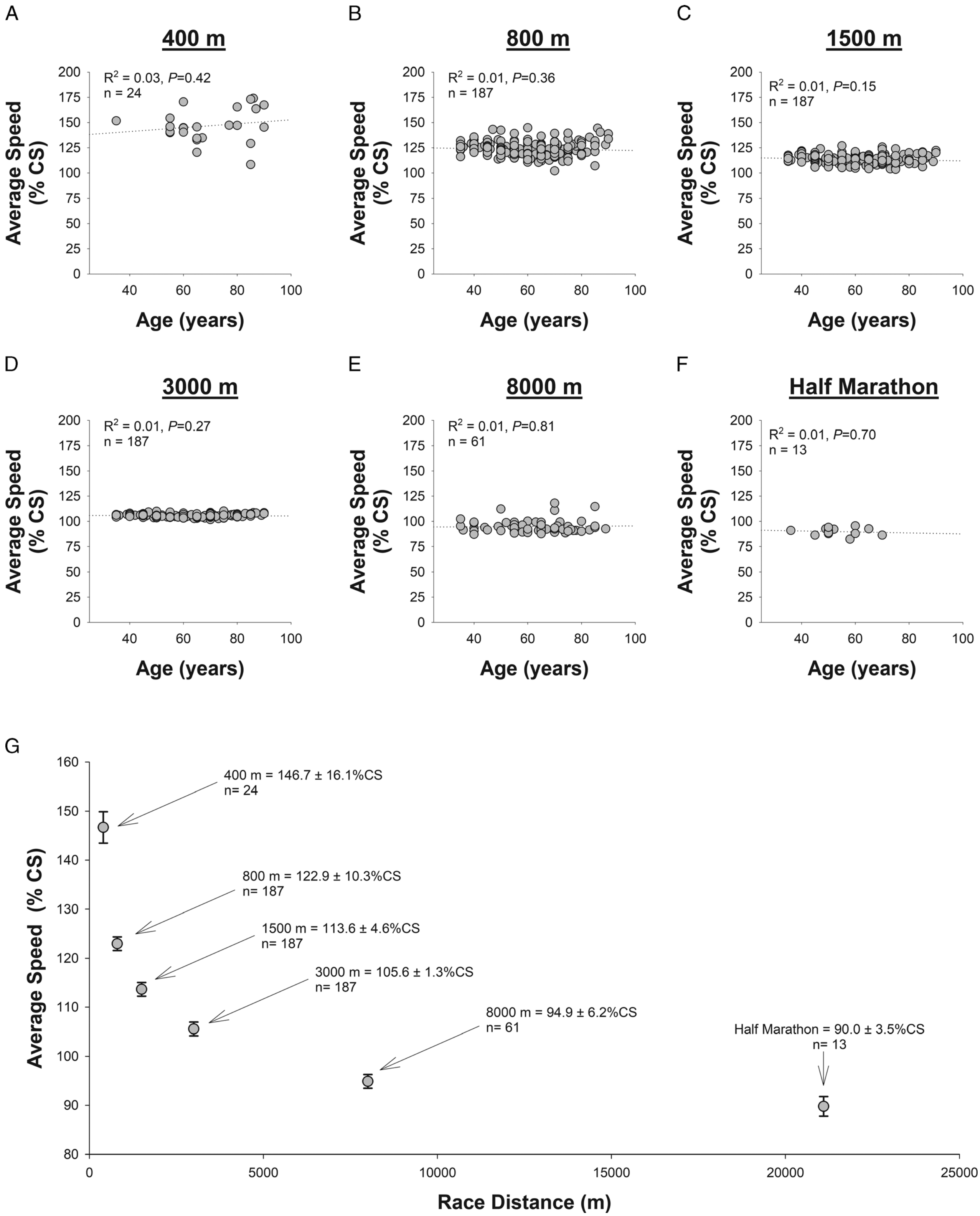

FIGURE 4—The relationship between age and average race pace, expressed as a percentage of CS, during the 400-m (A), 800-m (B), 1500-m (C), 3000-m (D), 8000-m (E), and half marathon (F) races. G, Average race speed and SD, expressed as a percentage of CS, for masters athletes participating in the masters world championships for events ranging from 400 m to the half marathon.

How does CS vary throughout aging? The current data support the findings of Neder et al. (8), indicating that CS declines with age, even among physically active masters athletes. Importantly, as illustrated in Figure 2A, the cross-sectional data from athletes of various ages indicate that the decline in CS does not occur at a constant rate (i.e., not a linear decrease) but that the rate of decline in CS varies with age, with steep declines being observed between the 35- and the ~40-yr age-groups and another steep decline beginning around 70 yr of age. Recent analysis of 100-, 400-, and 10,000-m race times support the observation of greater losses in performance between the ages of 30 and 40 yr and again after ~70 yr (20). Notably, a main effect of sex was observed, such that men tend to have a CS 0.50 $m \cdot s^{-1}$ greater than their female counterparts; however, the exponential decline in CS was observed in both males and females.

Fortuitously, several athletes competed in multiple championships over the span of 4–9 yr, providing an opportunity to retrospectively determine how CS and *D′* change within a longitudinal cohort over time. As illustrated in Figures 3A and 3B, this longitudinal analysis supports the cross-sectional data, indicating that the rate of change in CS is not constant throughout aging but accelerates with advancing age. For example, 70-yr-olds may anticipate a greater annual decrease in CS than they did when 40 or 60 yr old. Indeed, Leyk et al. (21), who investigated the relationship between age and performance on half/full marathons, which are run near CS (4), for over 300,000 participants, reported much greater slowing of average marathon times after 50 yr old than before. An accelerated loss of endurance performance after ~70 yr has also been reported for swimming (22).

At this point, it is important to remember that CS is not merely an index of performance but also an important fatigue threshold (2), with speeds just above CS leading to fatigue exponentially faster than speeds just below CS (2). Moreover, although described in terms of speed, CS actually represents a metabolic rate. Although the speed associated with CS is unlikely to be reached during daily activities on flat ground, the metabolic rate associated with CS may potentially be reached when performing activities, such as stair climbing or carrying objects, which elicit an increased metabolic rate for a given speed (23). With this in mind, the exponential decline in CS with aging means that increasingly lower speeds or intensities of exercise will elicit fatigue in an elderly person each year, such that activities that are very sustainable 1 yr (e.g., climbing stairs) can rapidly become fatiguing the next. Therefore, the rapidly declining CS in advanced age represents increased susceptibility to fatigue that may lead to loss of function and independence.

When interpreting these data, it is very important to keep in mind that the declines in CS illustrated in Figures 2 and 3 were obtained from masters athletes competing in the world championships—which may represent a best-case scenario for active aging (10). It is possible that the active lifestyle of masters athletes delayed or blunted the decline in CS and function (Figs. 2 and 3) that may be observed in sedentary aging. Indeed, Neder et al. (8), who used cycle ergometry to assess CP in a group of younger (~22 yr old) and older (~66 yr old) sedentary males, observed a ~47% decrease in CP associated with ~40 yr of sedentary aging. By contrast, in the current data, 40 yr of aging (35 to 75 yr) was associated with only a ~33% reduction in CS. The blunted decreased observed in the current study may be related to protective effects of physical activity or to decreases in CS between ages 20 and 35 yr that were not captured in the current study. On the other hand, evidence indicates that $\dot{V}O_{2max}$, which is related to CS (2), declines more rapidly with age in trained compared with untrained adults (24–26). Despite the more rapid decline in $\dot{V}O_{2max}$, the trained generally maintain a greater $\dot{V}O_{2max}$ and function compared with untrained elderly throughout aging (24–26). Clearly, further research examining the effect of physical activity on the rate of the age-related decline in CS or CP may prove useful in understanding the role of exercise in extending physical function and independence into advanced age.

The current study does not allow for an examination of the physiology related to the decline in CS with age. However, with CS being related to $\dot{V}O_{2max}$ (2), the same physiological changes that elicit the age-related decline in $\dot{V}O_{2max}$, such as alterations in cardiac capacity, vascular health, and mitochondrial function (27–30), are likely also at play in the age-related decline in CS. Indeed, like CS, $\dot{V}O_{2max}$ reportedly undergoes an exponential decline with aging, such that the rate of decrease in $\dot{V}O_{2max}$ per year is much smaller before age 30 yr than after age 70 yr (9). It is also possible that decreased training volume or intensity, which reportedly decrease with age and contribute to the age-related decline in $\dot{V}O_{2max}$ in masters athletes (7,24–26), contributes to the decrease in CS observed with age. Altered body composition (e.g., reduced muscle mass or increased body mass) may also contribute to the decrease in CS observed with age (30).

How does *D′* vary throughout aging? *D′* describes the curvature constant of the speed–distance relationship (2) and is thought to represent a finite buffer of work that can be done above CS before task failure. Consequently, detriments in *D′* could also contribute to the reduced exercise performance observed with aging. As illustrated in Figure 2B, *D′* undergoes nonlinear changes with aging. Despite a main effect of sex, such that males tend to have a slightly greater *D′* than their female counterparts, both males and females exhibited the same curvilinear relationship between age and *D′*. In contrast to CS, which exhibited a persistent decline with aging (Figs. 2A, 3A, and 3B), *D′* exhibits an initial ~11% decline from ages 35 to ~70 yr of age followed by a steep increase thereafter (Fig. 2B). That *D′* initially declines is in agreement with findings of Neder et al. (8), who observed a ~38% decrease in *W′* in ~65-yr-old males compared with ~22-yr-old males. However, the magnitude of the decrease observed in Neder's sedentary subjects (~38%) was substantially greater than what was observed in the active subjects in the current study, potentially because of differences in physical activity of the subjects or methods of data collection.

The rebound in *D′* as age advances past ~70 yr is a novel observation. As illustrated in Figure 3D, longitudinal data that retrospectively followed the change in *D′* in a subset of subjects over time support the transition from a decreasing *D′* to an increasing *D′* with advancing age. The physiological reasons for this transition are unclear and cannot be addressed by the current data. Nevertheless, it seems possible that the shift in D' may be influenced by the relationship between CS and $\dot{V}O_{2max}$. Previous research has indicated that the magnitude of W' is inversely related to the gap between CP and $\dot{V}O_{2max}$ (31), such that factors that decrease CP more than $\dot{V}O_{2max}$ tend to augment W'. Thus, it may be that the exponential increase in D' after age 70 yr is the consequence of widening gap between CS and $\dot{V}O_{2max}$ (e.g., greater decrease in CS than $\dot{V}O_{2max}$). Research comparing the rates of change in CS and $\dot{V}O_{2max}$ may provide insight into why D' changes with age.

Does age affect the relationship between CS and race pace? Jones et al. (4) recently reported that elite marathoners compete at ~95% of their estimated CS, without necessarily knowing their official CS. Recognizing the influence of CS on race pace, we sought to determine whether the relationship between race pace and CS was altered with age. First, the relationship between CS, D', and race time for the 400- and 8000-m events were examined to explore the relationship between CS, D', and two race distances with very different metabolic requirements (e.g., magnitude of aerobic vs anaerobic reliance), which were not included in the initial regression to determine CS and D'. CS was strongly inversely related to 400-m time ($r = -0.86$, $P < 0.001$) and 8000-m time ($r = -0.86$, $P < 0.001$). Interestingly, D', which has previously been thought of as an "anaerobic work capacity," was positively related with 400-m time ($r = -0.53$, $P = 0.04$), meaning that a greater D' was actually associated with a slower 400-m race time. This suggests that a high D' may not always be beneficial and that D' is more than a measure of anaerobic capacity, as has been suggested (32,33). Considering the relatively small distance that can be accounted for by D' (100–300 m in the current study), it is not surprising that D' was not related to race performance for a long distance such as 8000 m ($r = 0.05$, $P = 0.79$).

Noting that CS was related to race performance for two very different distances, we next sought to determine whether the relationship between CS and race speed for various distances was altered with aging. As illustrated in Figure 4, there was no relationship between age and average race speed/pace for several events when speed was expressed as a percentage of CS. Thus, whether 35 or 80 yr old, a 1500-m event is run at ~114% of CS, whereas a 3000-m event is run at ~106% of CS and the 8000-m event is run at ~95% of CS. That the percentage of CS at which a race is run remains constant throughout aging supports the physiological relevance of CS.

Can data from two races predict CS and D'? With relatively few individuals completing the three events needed to calculate CS (800, 1500, and 3000 m) each championship, we sought to determine whether CS and D' calculated from just the 1500- and 3000-m data would accurately reflect the true CS and D' calculated from the three races used for the rest of the study. Indeed, CS calculated from 1500 and 3000 m exhibited a very strong, nearly one-for-one relationship with the true CS ($R^2 = 0.99$, $P < 0.001$), with a small yet significant offset of just 0.05 $m \cdot s^{-1}$ (1.0% to 2.5% overestimation for the data in the current study). Thus, in agreement with previous research (14,17), it appears that CS can be calculated with a strong degree of accuracy from just two trials (e.g., 1500- and 3000-m events), making future investigation into CS potentially more feasible. D' calculated from the two events was also very strongly related to the true D' calculated from the three events ($R^2 = 0.79$, $P < 0.001$), but there was a substantial amount of error and bias in the prediction, with the overestimation of D' being substantially greater for individuals with larger D'. Thus, D' predicted from just two points may potentially be used to track relative changes in D' but may not accurately reflect that absolute value of the true D'. Indeed, based on the magnitude of error in D' observed in the current study, data from more than three events may be required to obtain a sufficiently accurate D'.

Experimental considerations. The data used in this study were collected retrospectively from the official race times of the WMA Indoor Track and Field World Championships. This approach has several strengths, in that it provides information on the relationship between speed and distance across a wide age range of presumably active adults. Nevertheless, the approach carries limitations that should be considered when interpreting the data and extrapolating it to other populations.

First, the population represents relatively fit individuals, who are likely more fit than most individuals their age. Nevertheless, as physical activity or training load was not measured, it is not possible to rule out the possibility that part of the change in variables such as CS and D' in the older subjects was due to decreased physical activity, training, or participation and not age (34–36). Indeed, Fitzgerald et al. (26) and Tanaka et al. (24) have indicated the training volume typically decreases with age in masters athletes and that this reduction in training volume partially explains the age-related decline in $\dot{V}O_{2max}$.

The calculation of CS and D' from race data assumes a maximal effort. It is possible that participants did not exhibit a maximal effort during these world championships. Nevertheless, with the error of the estimates for CS and D' being close to those of laboratory-based measurements (37), submaximal effort does not seem to have been an issue.

Exercise shortly before a race has the potential to affect CS and D' (12), and it is unknown how well rested each subject was before each race. Although the race schedule of the championships was arranged in such a way to allow rest between events for each age-group, it is possible that athletes were not well rested before the races. In general, D' appears to be more sensitive to rest duration than CS (13), which could explain some of the variability observed in D'.

CONCLUSIONS

Even among some of the fittest and presumably active individuals in the world, age is associated with a downward shift in the speed–distance relationship and a concomitant exponential decrease in CS that accelerates in advanced age. Despite undergoing an increasingly precipitous annual decline in CS with advanced age, the relationship between CS and race pace is impressively preserved throughout aging, such that a race of a given distance is run at a given percentage of CS, regardless of age. D' also varies with age in a curvilinear manner, such that it tends to decline from 35 to ~70 yr and then increase exponentially thereafter. Given the influence of CS on physical function and fatigability (2), interventions attempting to improve exercise tolerance in aging populations should seek to minimize the effect of aging on CS and D'.

The authors thank Dr. Dennis Eggett for his assistance with the statistical analysis. They also thank Erik Cruz for his assistance transcribing the data. Finally, they also thank the editor and peer reviewers for their constructive critiques of this manuscript. The authors have no conflicts of interest to report. This study is not funded. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation, and the results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Hill PA. The physiological basis of athletic records. *Nature*. 1925;116(2919):544–8.
2. Poole DC, Burnley M, Vanhatalo A, et al. Critical power: an important fatigue threshold in exercise physiology. *Med Sci Sports Exerc*. 2016;48(11):2320–34.
3. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical power: implications for determination of $\dot{V}O_{2max}$ and exercise tolerance. *Med Sci Sports Exerc*. 2010;42(10):1876–90.
4. Jones AM, Vanhatalo A. The ‘critical power’ concept: applications to sports performance with a focus on intermittent high-intensity exercise. *Sports Med*. 2017;47(s1):65–78.
5. Jones AM, Burnley M, Black MI, Poole DC, Vanhatalo A. The maximal metabolic steady state: redefining the ‘gold standard. *Physiol Rep*. 2019;7(10):1–16.
6. Burnley M, Vanhatalo A, Jones AM. Distinct profiles of neuromuscular fatigue during muscle contractions below and above the critical torque in humans. *J Appl Physiol*. 2012;113(2):215–23.
7. Suominen H. Ageing and maximal physical performance. *Eur Rev Aging Phys Act*. 2011;8(1):37–42.
8. Neder JA, Jones PW, Nery LE, Whipp BJ. The effect of age on the power/duration relationship and the intensity-domain limits in sedentary men. *Eur J Appl Physiol*. 2000;82(4):326–32.
9. Fleg JL, Morrell CH, Bos AG, et al. Accelerated longitudinal decline of aerobic capacity in healthy older adults. *Circulation*. 2005;112(5):674–82.
10. Geard D, Reaburn PRJ, Rebar AL, Dionigi RA. Masters athletes: exemplars of successful aging? *J Aging Phys Act*. 2017;25(3):490–500.
11. World Masters Athletics. *Official Results—8*. Torun, Poland: World Masters Athletics Championships Indoor; 2019. Available from: https://world-masters-athletics.com/results/.
12. Muniz-Pumares D, Karsten B, Triska C, Glaister M. Methodological approaches and related challenges associated with the determination of critical power and curvature constant. *J Strength Cond Res*. 2019;33(2):584–96.
13. Galbraith A, Hopker J, Lelliott S, Diddams L, Passfield L. A single-visit field test of critical speed. *Int J Sports Physiol Perform*. 2014;9(6):931–5.
14. Denadai B, Gomide EB, Greco C. The relationship between onset of blood lactate accumulation, critical velocity, and maximal lactate steady state in soccer players. *J Strength Cond Res*. 2005;19(2):364–8.
15. World Masters Athletics. ABOUT US—World Masters Athletics. Available from: https://world-masters-athletics.com/about/.
16. Arena Toruń—World Masters Athletics Championships Indoor[date unknown]. Available from: https://wmaci2019.com/arena-torun/.
17. Kordi M, Menzies C, Galbraith A. Comparison of critical speed and D' derived from 2 or 3 maximal tests. *Int J Sports Physiol Perform*. 2019;14(5):685–8.
18. Mezzani A, Corrà U, Giordano A, Colombo A, Psaroudaki M, Giannuzzi P. Upper intensity limit for prolonged aerobic exercise in chronic heart failure. *Med Sci Sports Exerc*. 2010;42(4):633–9.
19. Craig JC, Vanhatalo A, Burnley M, Jones AM, Poole DC. *Critical Power*. Elsevier Inc.; 2019. 159–181 p. Available from: http://dx.doi.org/10.1016/B978-0-12-814593-7.00008-6.
20. Aguiar S da S, Sousa CV, Sales MM, et al. Age-related decrease in performance of male masters athletes in sprint, sprint–endurance, and endurance events. *Sport Sci Health*. 2019; (0123456789). Available from: https://doi.org/10.1007/s11332-019-00613-6. doi: 10.1007/s11332-019-00613-6.
21. Leyk D, Erley O, Ridder D, et al. Age-related changes in marathon and half-marathon performances. *Int J Sports Med*. 2007;28(6):513–7.
22. Tanaka H, Seals DR. Age and gender interactions in physiological functional capacity: insight from swimming performance. *J Appl Physiol*. 1997;82(3):846–51.
23. Teh KC, Aziz AR. Heart rate, oxygen uptake, and energy cost of ascending and descending the stairs. *Med Sci Sports Exerc*. 2002;34(4):695–9.
24. Eskurza I, Donato AJ, Moreau KL, Seals DR, Tanaka H. Changes in maximal aerobic capacity with age in endurance-trained women: 7-yr follow-up. *J Appl Physiol*. 2002;92(6):2303–8.
25. Tanaka H, Seals DR. Invited review: dynamic exercise performance in masters athletes: insight into the effects of primary human aging on physiological functional capacity. *J Appl Physiol*. 2003;95(5):2152–62.
26. Fitzgerald MD, Tanaka H, Tran ZV, Seals DR. Age-related declines in maximal aerobic capacity in regularly exercising vs. sedentary women: a meta-analysis. *J Appl Physiol*. 1997;83(1):160–5.
27. Valenzuela PL, Maffiuletti NA, Joyner MJ, Lucia A, Lepers R. Lifelong endurance exercise as a countermeasure against age-related $\dot{V}O2_{max}$ decline: physiological overview and insights from masters athletes. *Sport Med*. 2020;50(4):703–16.
28. Betik AC, Hepple RT. Determinants of $\dot{V}O_{2max}$ decline with aging: an integrated perspective. *Appl Physiol Nutr Metab*. 2008;33(1):130–40.
29. Gifford JR, Garten RS, Nelson AD, et al. Symmorphosis and skeletal muscle $\dot{V}O2_{max}$: *in vivo* and *in vitro* measures reveal differing constraints in the exercise-trained and untrained human. *J Physiol*. 2016;594(6):1741–51.
30. Tanaka H, Tarumi T, Rittweger J. Aging and physiological lessons from master athletes. *Compr Physiol*. 2020;10(1):261–96.
31. Parker Simpson L, Jones AM, Skiba PF, Vanhatalo A, Wilkerson D. Influence of hypoxia on the power–duration relationship during high-intensity exercise. *Int J Sports Med*. 2014;36(2):113–9.
32. Vanhatalo A, Black MI, DiMenna FJ, et al. The mechanistic bases of the power–time relationship: muscle metabolic responses and relationships to muscle fibre type. *J Physiol*. 2016;594(15):4407–23.
33. Vanhatalo A, Fulford J, DiMenna FJ, Jones AM. Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Exp Physiol*. 2010;95(4):528–40.
34. Pollock ML, Foster C, Knapp D, Rod JL, Schmidt DH. Effect of age and training on aerobic capacity and body composition of master athletes. *J Appl Physiol*. 1987;62(2):725–31.
35. Trappe SW, Costill DL, Vukovich MD, Jones J, Melham T. Aging among elite distance runners: a 22-yr longitudinal study. *J Appl Physiol*. 1996;80(1):285–90.
36. Speakman J, Westererp K. Associations between energy demands, physical activity, and body composition in adult humans between 18 and 96 y of age. *J Clin Nutr*. 2010;92:826–34.
37. Triska C, Prinz B, Tschan H, et al. Reliability of the parameters of the power–duration relationship using maximal effort time-trials under laboratory conditions. *PLoS One*. 2017;12(12):e0189776.