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Declines in physiological functional capacity with age: a longitudinal study in peak swimming performance

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Abstract

We followed up swimming performance times of 321 women and 319 men who participated in the US Masters Swimming Championships over a 12-yr period. All swimmers placed in the top 10 in their age group over 3 yr (mean = 5 yr). A random coefficients model for repeated measures was used to derive a line of best fit from a group of regression lines for each subject. Both 50- and 1,500-m swimming performance declined modestly until ~70 yr of age, where a more rapid decline was observed in both men and women. Compared with 1,500-m swimming, the 50-m freestyle declined more modestly and slowly with age. The rate and magnitude of declines in swimming performance with age were greater in women than in men in 50-m freestyle; such sex-related differences were not observed in 1,500-m freestyle. Overall, the variability along a population regression line increased markedly with advancing age. The present longitudinal findings indicate that 1) swimming performance declines progressively until age 70, where the decrease becomes quadratic; 2) the rates of the decline in swimming performance with age are greater in a long-duration than in a short-duration event, suggesting a relatively smaller loss of anaerobic muscular power with age compared with cardiovascular endurance; 3) the age-related rates of decline are greater in women than in men only in a short-duration event; and 4) the variability of the age-related decline in performance increases markedly with advancing age.

Keywords

exercise performance; physical work capacity

Physiological Functional Capacity (PFC), defined as the ability to perform the physical tasks of daily life and the ease with which these tasks can be performed, is known to decline with advancing age even in healthy adults (2, 15, 22, 31, 40). This eventually can result in

increased incidence of morbidity and mortality, increased use of health care services, loss of independence, and reduced quality of life (1). Additionally, the decline in PFC may become a serious threat to individuals engaging in a physically demanding occupation, because physical demands of daily work do not normally change with age (42). This would force aging workers to labor closer to their maximal capacity and could lead to substantial stress, chronic fatigue, and health problems (42). The changing demographics of the aging population in the United States will result in an increasing number of older adults facing these adverse sequelae of age-related reductions in PFC. Thus understanding the rate and magnitude of decline in PFC with age and the factors that contribute to the decline is of critical importance.

One way to assess PFC in humans is to determine the changes in peak exercise performance with age in elite athletes (6, 39, 40). The primary experimental advantage of this approach is that confounding changes in physical activity levels, body composition, and degenerative diseases with age are either absent or markedly reduced in highly trained athletes compared with their sedentary peers. In this context, the analyses of swimming performance, in particular, provide a number of advantages for studies of aging and PFC. Swimming is a non-weight-bearing activity and, therefore, has a relatively low incidence of orthopedic injury even among older adults (20, 21). Additionally, unlike other athletic events in which male participants outnumber their female counterparts, swimming events attract similar numbers of male and female participants throughout the adult age range [US Masters Swimming (USMS) database]. This eliminates the influence of this potential “sociological” confound in the interpretation of results on sex (gender) comparisons.

In our earlier cross-sectional study, three key observations made by using this model were (40) 1) PFC, as assessed by peak swimming performance, decreases linearly until 70–80 yr of age, where the decline becomes exponential; 2) the rate and magnitude of the age-associated declines in both short- and long-duration events are greater in women than in men; and 3) these sex-related differences in the decline in swimming performance with age are greatest in short-duration events (40). Given the inherent limitations of cross-sectional comparisons, however, we reasoned that confirmation of these observations with a longitudinal study design was needed.

Accordingly, the primary aim of the present investigation was to determine the respective and interactive effects of age and sex on swimming performance. With the use of the USMS Championships database, we identified and analyzed the performance of 640 elite swimmers over a 12-yr period. The decline in PFC with advancing age is attributed to collective reductions in cardiovascular, respiratory, metabolic, and neuromuscular functions (6, 15, 40). We reason that this approach using peak swimming performance would provide insight into the functional (performance-based) consequences of age-associated declines in maximum muscular power, muscular endurance, and/or aerobic capacity.

METHODS

Analysis of swimming performance

Freestyle swimming data were collected from the USMS Championships over a 12-yr period of 1988–1999 (USMS database). All swimmers in the database placed in the top 10 in their age group in either 50- or 1,500-m freestyle events throughout the follow-up period (mean of 5 yr). Age of the swimmers included in the database ranged from 19 to 85 yr. Similar to our previous study (40), freestyle events were chosen because they were the fastest events, attracted the largest number of competitors, and have undergone the fewest number of rule and technical changes over the years. Detailed manual searches were conducted to locate as many swimmers as possible who competed in the same event over 3 yr (Table 1). As a result, we identified and followed up personal swimming performance times of 640 individuals (321 women, 319 men). We also collected data on the fastest world record times in men's and women's 50- and 1,500-m freestyle as of 2001. This allowed us to calculate the rate of age-related decline in performance relative to the world record time of a particular event.

Statistics

To determine the age-related longitudinal changes in swimming performance, a random coefficient model for repeated measures was used to derive a line of best fit from a group of regression curves for each subject (17). We fitted a population regression curve for each event by using a random coefficients mixed model for repeated measurements with swimming time (in minutes) as the outcome measures (17). The mixed model includes both fixed and random effects. The fixed component describes the population relationship of swim time and age, whereas the random component describes the variability of subjects about the population line. We fitted separate models to predict swimming times for the 1,500- and the 50-m events. For each swimming event, we allowed the relations between swimming performance time and age to differ by gender via fitting two lines with separate intercepts, slopes, quadratic terms, and additional quadratic terms for over age 70 as fixed effects. The inclusion of quadratic terms and quadratic terms over age 70 was motivated by several factors. For both races, plots of the raw data showed a slight decrease in swim time between age 19 and 30 followed by a gradual increase up to age 70 and a pronounced increase in both time and variability after age 70. If we had restricted the regression model to a linear relationship (i.e., a model with intercept and slope only), the resultant regression line would describe a relationship where the change in swim time does not vary by age. The quadratic term allowed us to fit a model in which swimming times decrease initially and increase thereafter. The additional quadratic term after age 70 allowed us to model an even faster rate of decline after age 70. As random effects, we included an intercept, slope, quadratic, and additional quadratic after age 70 yr for each gender. We used a backward, stepwise process to first model the random effects and then the fixed effects. We compared the model described above with a similar model that excluded the quadratic terms over age 70. We compared the 32 log likelihood of the two models and found the more complex model to be significantly better. In a similar manner, we compared our original model with a model that excluded the quadratic terms, a model that excluded the slope terms, and a model that excluded the intercept terms. If two models were not found to be significantly different,

we selected the model with fewer terms. We used linear contrasts to test for gender differences in swimming performance over time and in the rate of increase. For all tests, we used $P < 0.05$ for statistical significance.

RESULTS

Figure 1 illustrates 1,500-m freestyle swimming performance with advancing age. Long-duration swimming performance times increased (performance declined) curvilinearly with age in both sexes. Peak performance times were maintained until ~35 yr of age, followed by a progressive increase until ~70 yr of age. Thereafter, swimming time increased substantially, which was characterized by a steep quadratic term ($P < 0.0001$). The average rates of age-related changes in swimming performance times were not different between men and women in 1,500-m events. There was, however, considerable overlap between men and women throughout the age range when the individual regression lines were plotted (Fig. 1*B*). In both sexes, variability associated with the swimming performance times increased significantly with increasing age ($P < 0.0001$).

Changes in 50-m freestyle swimming with age are depicted in Fig. 2. Similar to 1,500-m freestyle swimming, short-term swimming performance times increased curvilinearly in both men and women. Compared with the 1,500-m freestyle event, however, smaller overall increases in swimming performance times were observed ($P < 0.0001$). Increases in 50-m freestyle times were modest until 70 yr of age; thereafter, substantially steeper quadratic increases in swimming time occurred in both sexes ($P < 0.0001$). The average rate of increase in 50-m swimming time with age was significantly greater in women than in men ($P < 0.0001$). There was little or no overlap between men and women at any age in 50-m events (Fig. 2*B*). Intersubject variability also increased with advancing age in the 50-m event ($P < 0.0001$).

Figure 3 displays the instantaneous rate of changes in swimming performance times in relation to the current world record time. Overall, swimming performance times increased progressively until 70 yr of age followed by substantially greater rises. Until 70 yr of age, the rate and magnitude of increases in swimming performance times were greater in the 1,500-m events (6–12%; percent changes in swimming performance time for fixed time interval) than in the 50-m events (3–8%) for both men and women ($P < 0.0001$). In the 50-m freestyle, the increase in swimming performance time was greater in women (15–16%) than in men (13–14%) after age 70 ($P < 0.0001$). In 1,500-m free-style swimming, no such sex-related differences were observed.

DISCUSSION

The salient findings of the present longitudinal study are as follows. First, the best-fitting model showed that swimming performance declines (performance time increases) progressively until ~age 70, where the decrease becomes quadratic. Second, the rates of the declines in swimming performance with age are greater in long-duration than in short-duration events. Third, female swimmers experience greater declines in sprint, but not endurance, swimming performance than their male counterparts. Fourth, the variability of

the age-related decline in performance increases markedly with advancing age for both short- and long-duration events. The present findings using a longitudinal study design demonstrate that 1) the age-related reduction in PFC is biphasic with accelerated decline around age 70, and 2) sex and exercise-duration interact to determine the age-related declines in PFC as assessed by swimming performance.

Since the Nobel laureate A. V. Hill effectively used athletic world record data to gain insight into peak exercise performance and functional capacity in humans in the 1920s (10), a number of investigators have studied the influence of aging on PFC in humans. Master athletes represent an effective experimental model because changes observed with advancing age are thought to reflect primarily the results of physiological aging. In the present study, PFC, as assessed by swimming performance, declined with advancing age curvilinearly at primarily two different rates in both men and women. Specifically, swimming performance decreased progressively until ~70 yr of age, followed by a markedly accelerated rate of decline. It is not clear as to why there appears to be an accelerated decline in PFC after ~70 yr of age. Our findings, however, are consistent with previous studies conducted in the area of functional ability and aging. For example, freely chosen walking speed declines relatively little up to ~60–70 yr of age followed by sudden decreases (11). Additionally, muscular strength, as assessed by Olympic weight-lifting capacity, declines linearly until approximately age 70, after which the rates increase significantly (24). Thus it is tempting to speculate that fundamental changes in biological aging processes may occur around the age of 70, as previously suggested by Joyner (15). Alternatively, this also might be the age at which “biobehavioral” changes (e.g., reductions in motivation to train at high levels) may occur. It is interesting to note that one of the age-related biobehavioral changes, the reductions in spontaneous activity with age, is a common characteristic of many different animal species since they have been observed in insects (35), rodents (13), and humans (8, 12, 29).

Previous cross-sectional studies comparing short- and long-duration exercise events have produced inconsistent findings regarding the influence of age on peak exercise performance. Shorter exercise duration was associated with greater (25) and smaller (37, 40) declines in performance with advancing age. We believe that the results of the present study, which utilizes longitudinal study samples, provide more definitive insight into this issue. We found that the rate of decline in swimming performance was greater in long-duration than in short-duration events. We could only speculate as to why task duration modulates the rate of decline in PFC. The most likely explanation is that the respective physiological determinants of short- and long-duration exercise performance decrease at different rates with advancing age. The anaerobic power of the upper body muscles is a primary determinant of sprint or 50-m freestyle swimming (33, 38), whereas maximal oxygen consumption contributes importantly to success in endurance or 1,500-m swimming events (7, 19). In this context, findings of several cross-sectional studies indicate that peak muscular power exhibits a considerably less rapid rate of decline with age than maximal aerobic capacity (2, 9, 18). Moreover, voluntary muscle function appears to decline less rapidly in the upper limbs compared with the lower limbs (9, 23). Thus the slower rate of decline in sprint swimming performance may be attributed to a less rapid rate of decline in anaerobic power of upper body muscles.

In contrast to our previous cross-sectional study (40), in the present investigation, sex differences in age-related declines in swimming performance only were evident in short-duration events. It is possible that a greater decline in training intensity and/or volume with age occurred in the women compared with the men participating in sprint racing but not in endurance events. Alternatively, the age-associated declines in the physiological determinants of sprint and endurance performance may occur at different rates in men and women. In this regard, it is noteworthy that the relative (%) rates of decline in maximal oxygen consumption (i.e., a major determinant of endurance swimming performance) are similar between men and women (12), whereas women appear to experience greater declines in muscular strength and power (i.e., a primary determinant of sprint performance), particularly in the upper extremities, than men (28, 30, 34). The larger decreases in muscular strength in women appear to be due to the greater reduction in maximal voluntary strength per cross-sectional area (28).

For both short- and long-duration events and both men and women, the variability of the age-related decline in performance increased markedly with advancing age. Such variability has been reported previously for particular expressions of physical function in the general population of healthy adults (14, 26). The results of the present study extend these observations to highly trained athletes and suggest that even within a physically elite population of healthy humans, there may be markedly varying degrees of “successful” aging (32) as it relates to PFC.

The effects of aging on PFC in humans have been examined by using cross-sectional and longitudinal approaches. Both study designs have inherent, methodological limitations that could influence PFC independent of the aging process per se. For example, cross-sectional comparisons are influenced by genetic and constitutional factors (e.g., cohort difference), whereas longitudinal designs are subject to confounds such as the practice/rehearsal effect and changes in lifestyle factors within individual subjects (e.g., reductions in training volume due to injury, increases in body weight due to dietary changes, etc.) (3). We reason that our complementary approaches using both cross-sectional (40) and longitudinal approaches (present study) reduce as much as possible these respective limitations. Although we are unable to quantitatively compare the present results with the previous findings because of the use of different statistical techniques, the results of the present longitudinal study are generally and qualitatively consistent with the findings of our previous cross-sectional study, strengthening our conclusions regarding the age and sex interactions on PFC. As we have demonstrated here, it is tempting to hypothesize that well-conducted cross-sectional studies, which are easier to perform, may yield qualitatively, if not quantitatively, similar results to longitudinal studies when the relation between age and PFC is examined. It is interesting that key determinants of short- and long-duration PFC (muscular strength and maximal oxygen consumption) also demonstrate similar rates of decline with age when examined cross sectionally or longitudinally (8, 16, 24).

Because of the major role that habitual exercise plays in determining PFC (e.g., maximal oxygen consumption), it is tempting to speculate that the rate of decline in swimming performance with age may reflect the decrease in the overall training volume. Although the lack of complete data preclude us from drawing any definite conclusions, it is interesting to

compare running and swimming performance data in this regard. Empirical data suggest that the training volume of older Masters swimmers is considerably lower than those of the young peers (36), whereas many of the top Masters runners continue to train with high volume at least through middle age (27). In contrast to this trend, we have previously reported that the magnitude of overall reduction in swimming performance with age is smaller than those observed in running performance (39, 40). Thus training volume data do not appear to explain the age-related decline in PFC. A more likely explanation for the smaller age-related decline in swimming vs. running performance may be a greater reliance on biomechanical technique in swimming as demonstrated by the strong correlation between free-style swimming performance and distance per stroke (5). An interesting observation was made in a case study of one swimmer who achieved the best freestyle swimming times at age 50 despite the fact that he was an accomplished collegiate swimmer (4, 41).

In conclusion, the present longitudinal findings support the hypothesis that sex and task duration are at least two important factors that selectively affect PFC with advancing age in healthy adult humans. Our results also confirm that an accelerated reduction in PFC after age 70 in both men and women exists. Finally, the interindividual variability in PFC increases markedly with age, consistent with different rates of aging among individuals in the primary physiological determinants of PFC.

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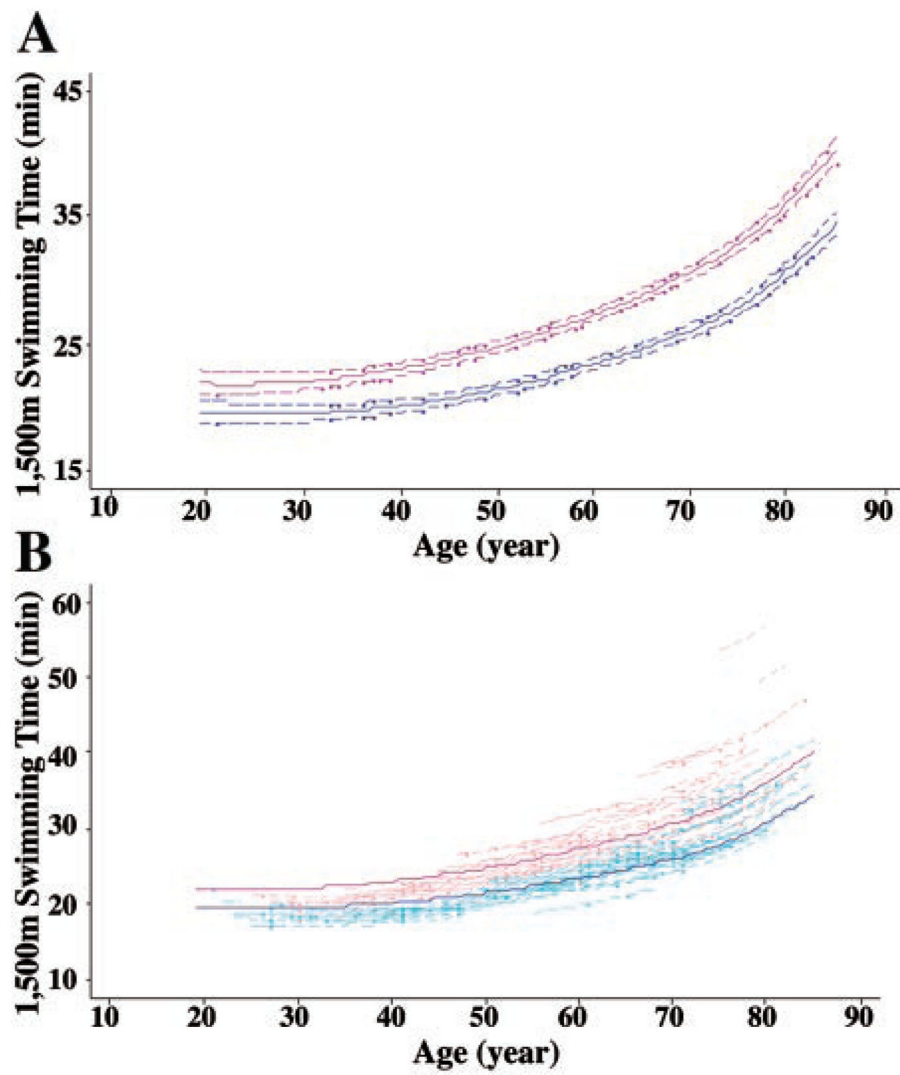


Fig. 1. US Masters Swimming 1,500-m freestyle performance times with advancing age. *A*: mean (population) quadratic line and 95% confidence intervals. *B*: average quadratic line and individual regression lines. Pink identifies women, and blue identifies men.

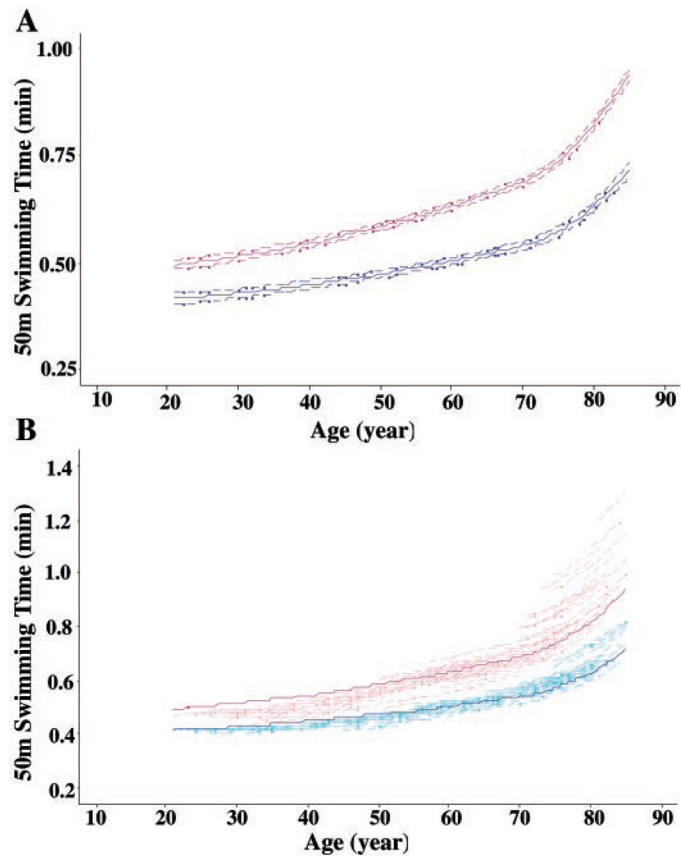


Fig. 2. US Masters Swimming 50-m freestyle performance times with advancing age. *A*: mean (population) quadratic line and 95% confidence intervals. *B*: average quadratic line and individual regression lines. Pink identifies women, and blue identifies men.

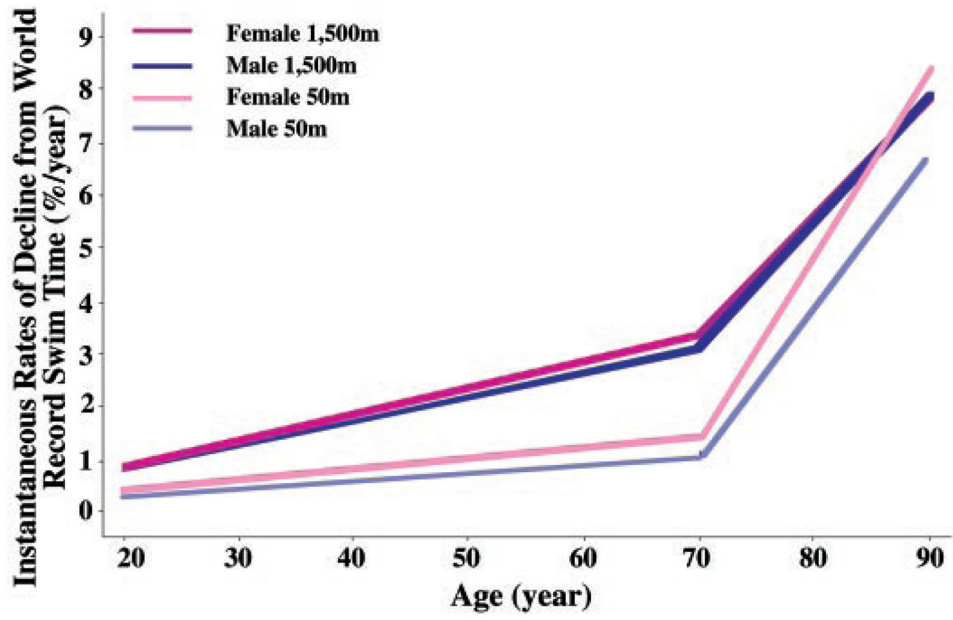


Fig. 3.
The instantaneous (relative) rate of changes in swimming performance times in relation to the present fastest world record time.

Table 1

Number of swimmers divided into years of participation in the Master's swimming competition

No. of Years	No. of Women		No. of Men	
	50 m	1,500 m	50 m	1,500 m
3	60	50	61	60
4	23	35	30	23
5	21	19	23	29
6	17	11	13	14
7	13	12	12	17
8	7	8	13	4
9	10	5	3	5
10	5	4	4	2
11	7	4	3	1
12	5	5	2	0
Total	168	153	164	155

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