Age and gender interactions in physiological functional capacity: insight from swimming performance

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Tanaka, Hirofumi, and Douglas R. Seals. Age and gender interactions in physiological functional capacity: insight from swimming performance. J. Appl. Physiol. 82(3): 846–851, 1997.—One experimental approach to studying the effects of aging on physiological functional capacity in humans is to analyze the peak exercise performance of highly trained athletes with increasing age. To gain insight into the relationships among age, gender, and exercise task duration with use of this model, we performed a 5-yr (1991–1995) retrospective analysis of top freestyle performance times from the US Masters Swimming Championships. Regression analysis showed that in both men and women endurance swimming performance (i.e., 1,500 m) declined linearly from peak levels at age 35–40 yr until ∼70 yr of age, whereas performance declined exponentially thereafter. In both genders, the variability among the top 10 winning times in each 5-yr age interval increased markedly with advancing age. Compared with the 1,500-m freestyle, performance in the 50-m freestyle (short-duration task) showed only a modest decline until ages 75 and 80 yr in women and men, respectively. The rate and magnitude of the declines in both short- and long-duration swimming performance with age were significantly (P < 0.05) greater in women than in men. In the women, the percent decline in swimming performance over a 50-yr age period from the 19- to 24-yr to the 69- to 74-yr age groups became progressively greater from the shortest distance (50 m) to the two longest distances (800 and 1,500 m), whereas in men, no differences were observed in the magnitude of performance decline with age among the five longest distance events (i.e., 100–1,500 m). The percent gender difference in performance throughout the age range studied became progressively smaller (P < 0.05) with increasing distance from 50 m (19 ± 1%) to 1,500 m (11 ± 1%). The findings in this cross-sectional study indicate that from peak levels at age 35–40 yr, physiological functional capacity, as assessed by swimming performance, decreases linearly until ∼70–80 yr of age, whereas the decline becomes exponential. Moreover, the rate of decline with advancing age appears to be associated with event duration and gender.

aging; gender difference; exercise mode specificity

Physiological functional capacity (PFC) is of critical importance in determining our ability to perform the tasks of daily life. PFC declines at some point with advancing age in humans, reducing the rate at which we can perform a particular physical task and, in some cases, completely preventing us from performing certain tasks (1, 7, 13).

Determination of the effects of aging per se on PFC in humans is difficult by using cross-sectional age comparisons of the general population, for several reasons. First, the most frequently used measure of PFC in such comparisons, i.e., peak or maximal oxygen consumption, although an important indicator of short-term maximal aerobic power (10, 21, 22, 24), provides limited insight into other expressions of PFC such as endurance under sustained submaximal working conditions. Second, the interpretation of aging effects is confounded by reductions in physical activity levels (deconditioning), changes in body composition (i.e., increases in body fatness and reductions in fat-free mass), and the development of chronic degenerative diseases with age, all of which reduce PFC, independent of the aging process (5, 10–12, 21, 23).

Because of such limitations, another experimental approach to studying the effects of aging on PFC in humans is to analyze the peak exercise performances of highly trained athletes with increasing age. If carefully selected, changes in physical activity levels, body composition, and overt disease with age are markedly reduced or eliminated in these athletes compared with the general population (5, 10, 12, 23). Thus any changes observed with advancing age are considered to be primarily the result of aging per se (5, 12).

Using this approach, Dempsey and Seals (5), Evans et al. (6), and others (2, 12, 18) have studied age-related changes in PFC by examining endurance running performance. In a recent study, Dempsey and Seals observed that 10-km running time increased (performance declined) with age in a curvilinear manner. Specifically, performance times were maintained until ∼35 yr of age, followed by modest increases until the middle-to-late 50s, with progressively steeper increases thereafter. Importantly, we found that the increases in performance times with advancing age were up to threefold greater in women compared with men, with the largest differences noted at >60 yr of age (5). Thus an age and gender interaction was documented, suggesting that declines in endurance running capacity with aging might be greater in women.

Although previous studies on running performance (2, 5, 12, 18) establish a clear pattern of age- and gender-related changes in PFC as it pertains to endurance leg exercise, considered more broadly, there are many different elements that contribute to overall PFC. As such, we cannot assume that changes in endurance running performance accurately reflect aging and gender interactions in other types of human performance. For example, the type and duration of the physical task performed could affect these relationships. Given this, one could place greater confidence in the data obtained on long-distance running if the results could be confirmed with other types of physical activity.

In this regard, we believe that analysis of swimming performance represents an intriguing alternative model to running in several respects. First, swimming is primarily an upper body task (25, 27). Second, it is
performed in a different medium than running (i.e., water) and in the supine rather than the upright posture, resulting in a zero-gravity situation. Third, it is known to have an equivalent male-to-female participation ratio [US masters swimming (USMS) report], enhancing its generalizability. Finally, because of its non-weight-bearing nature, swimming has a much lower rate of orthopedic injury than does running (16). This is particularly important in the present context because the interpretation of age-related decrements in running performance is confounded by an increased incidence of orthopedic injuries with advancing age, which limits the training volume of many older runners (6, 12, 21, 22). Therefore, age-associated changes in swimming performance should be influenced to a much lesser extent by this factor.

Accordingly, the aim of the present study was to determine swimming performance with increasing age in adult men and women. To accomplish this, we performed a retrospective analysis of top freestyle performance times from the USMS Championships. To ensure that the possible effects of task duration were considered, changes in swim performance with age were determined over a full range of distances.

METHODS

Analysis of swimming performance. To determine whether the relationships among age, gender, and endurance swimming performance were similar to those we have observed previously with endurance running performance (5), 1,500-m freestyle swimming data were collected from the USMS Championships over the 5-yr period of 1991–1995 (USMS database). Participants were divided into 5-yr age intervals from ages 19 to 99 yr. Top 10 winning times within each 5-yr age interval for each distance were plotted against age for men and women. We also collected the data on world record times in 1,500-m freestyle in both men and women over the adult age range (World Masters Swimming) to provide a secondary database with which to examine this issue.

To address the question of whether swimming performances across ages and genders are similar in freestyle events of different distances, 50-m freestyle swimming performance data were analyzed from the USMS Championships over the 5-yr period described above. Comparison with the results of the 1,500-m analysis revealed differences. Therefore, to examine the entire continuum of freestyle-event distances for both men and women, 100-, 200-, 400-, and 800-m performance data from the 1995 USMS Championships were subsequently analyzed. For each of these distances, the mean percent decline in performance (i.e., increase in swimming time) over a 50-yr age period from the 19- to 24-yr age interval to the 69- to 74-yr age interval (the largely linear period of performance decline) was used to address this question.

Statistics. Regression analyses and Pearson coefficient of correlation were performed to describe the relationship between swimming performance and age for each gender. One-way analysis of variance was used to determine differences in the rate of decline in performance with age among the various freestyle-event distances. In the case of a significant main effect, a post hoc test using Tukey’s procedure was used to identify significant differences among mean values. The probability level of statistical significance was set at \( P < 0.05 \) in all comparisons. Descriptive statistics were expressed as means ± SE.

RESULTS

Age and gender effects in endurance swimming performance. Figure 1A illustrates 1,500-m freestyle swim performance with advancing age. Peak performance times were observed from \( \sim 25 \) to 40 and from \( \sim 30 \) to 35 yr of age in the men and women, respectively. Swimming times were slower at the younger adult ages for both genders. After \( \sim 40 \) yr of age in the men, swimming time increased (performance declined) somewhat linearly until \( \sim 70 \) yr of age, whereupon performance time increased exponentially thereafter. The same general pattern was observed in the women; after \( \sim 35 \) yr of age average swimming time appeared to increase progressively and linearly until \( \sim 70 \) yr of age, followed by an exponential increase. In both genders, the variability among the top 10 winning times in each 5-yr age interval increased markedly with advancing age. Over the largely linear respective periods of performance-time increase over 50 yr, the average rate of increase in
swimming time with age was significantly greater ($P < 0.05$) in women ($38 \pm 3\%$) than in men ($31 \pm 2\%$). There was, however, considerable overlap between the men and women throughout the adult age range studied.

The general pattern of decline in endurance swimming performance with age observed in USMS Championships data was similar to that obtained in the age-based world record data (Fig. 2A). However, when the percent increase in performance times was expressed relative to the fastest world record times in each gender (Fig. 2B), there were no differences between men and women in the rate of performance deterioration with age up to \( \sim 70 \) yr; thereafter, the rate of age-related increase in swimming times became progressively greater in women.

Age and gender effects in short-duration swimming performance. Changes in 50-m freestyle swimming time with advancing age in men and women are depicted in Fig. 1B. In contrast to the 1,500-m distance, peak performance in the 50-m freestyle was observed at age 20–30 yr (i.e., the 2 youngest age groups analyzed) and was maintained until age 40–45 yr in both men and women. Moreover, compared with the 1,500-m distance, only modest increases in swimming times were observed from age 40–45 until 75 and 80 yr of age in the women and men, respectively; thereafter, exponential increases in swimming performance times occurred in both groups. In this shorter event, age-related increases in the variability of the individual winning times largely were confined to the women. Similar to that observed in the 1,500-m event, the average rate of increase in 50-m swimming time over the linear portion of the aging curve was greater in the women ($31 \pm 1\%$) than in the men ($26 \pm 1\%; P < 0.05$). However, unlike the longer event (i.e., 1,500 m), there was little or no overlap in performance between the men and women at any age.

Influence of event duration on age-related changes in swimming performance. The magnitude of the increase in swimming performance times over a 50-yr age period from the youngest age interval studied (i.e., 19–24 yr) to the 69- to 74-yr age interval as a function of swimming distance is presented in Fig. 3. The percent increase in swimming performance times over this period was greater in the 1,500-m freestyle swimming event than in the 50-m event for both genders. However, analysis of the intermediate freestyle swimming distances (i.e., 100, 200, 400, and 800 m) indicates a gender-specific interaction between the percent decline in performance with age and swimming distance. Specifically, in the women, the percent increase in swimming performance times with age became progressively greater from the shortest distance (50 m) to the two longest distances (800 and 1,500 m). In contrast, in the men, no significant differences were observed in the magnitude of performance decline with age among the five longest distance events (i.e., 100–1,500 m).

Gender-event distance interactions in swimming performance. Gender differences in performance as a function of freestyle swimming distance are depicted in Fig. 4A. Gender differences were greatest in the shorter events (i.e., 50 and 100 m) and became progressively smaller with increasing distance such that the smallest gender difference was observed in the 1,500-m freestyle event. There were significant differences ($P < 0.05$) between any paired swimming distances except for 50 vs. 100 m and 800 vs. 1,500 m.
The major new findings from this study are as follows. First, endurance swimming performance also decreases with age in men and women, although the pattern of decline is somewhat different from that previously observed with long-distance running (2, 5, 12). Peak performance was maintained until ~35–40 yr of age and then declined progressively and linearly, followed by exponential declines. However, we noted that the pattern of decline is somewhat different than that observed with long-distance running in several aspects. First, the magnitude of overall reduction in swimming performance with advancing age appears to be smaller than those observed in running performance (2, 12, 26). Second, the age at which exponential declines start occurred later with swimming (~70 yr of age) compared with running (~60 yr of age). The exact reasons for these task-specific differences are not clear, but it could be explained by the observation that the swimming performance is relatively more dependent on biomechanical techniques than is running (4). It is not uncommon to see masters swimmers achieve their personal best time at 40–50 yr of age (2). An alternative explanation for the smaller age-related reduction in swimming vs. running performance is a lower prevalence of orthopedic injury during swimming (16). In running, the decline in exercise performance with age has been partly attributed to an increased incidence of orthopedic injuries with advancing age, which limits the training volume of many older runners (6, 12, 21). It is possible that swimming performance was influenced to a much lesser extent by this factor.

ThedeclineinPFCwithadvancingageisattributed to collective reductions in cardiovascular, respiratory, metabolic, and neuromuscular functions (5, 7, 9, 11). What might be the physiological mechanisms or determinants that contribute to age-related reductions in endurance swimming performance? Two possibilities are likely. First, it is generally agreed that maximal oxygen uptake is one of the best single indicators of endurance performance because it establishes the upper limit of maximal energy production through oxidative pathways (12, 24). In studies of long-distance runners, the decline in 10-km running times was parallel to the age-related reduction in maximal oxygen uptake (6, 8, 23). Similar to running, a high correlation between maximal oxygen uptake and endurance swimming performance of over 400 m has been reported (3). Second, findings on competitive runners (1, 7) indicate that age-related declines in lactate threshold, defined as the absolute exercise velocity at which blood lactate increases significantly above baseline, were the best correlates of the decline in running performance. It is tempting to speculate that the progressive reductions in maximal oxygen uptake and/or lactate threshold with age are primarily responsible for the age-related decline in endurance swimming performance. However, because these physiological determinants have not been determined in swimmers of various ages, their respective contributions to age-related declines in swimming performance are unknown at present.
Task duration and age-related changes in performance. The temporal pattern and overall magnitude of decline in swimming performance in short-duration events were different than in long-duration events. Peak performance appeared to be maintained to a slightly older age range in the short-duration events, and the rate and overall magnitude of performance declines were smaller. Moreover, when we performed an analysis of the magnitude of decline in swimming performance over a 50-yr age span, we found that, at least in the women, the magnitude of the age-related decline was increasingly greater with increases in swimming distance.

It is not clear why task duration exerts an influence on performance-related PFC with age. One possibility is based on the fact that events of varying durations necessitate different levels of involvement of the various energy-producing pathways in skeletal muscle. There is some evidence to suggest that there is a relatively smaller loss of “anaerobic power”-related PFC with age (9, 14). Findings from several cross-sectional studies indicate that the declines in muscular power with age are considerably more delayed than that in cardiovascular endurance (9, 14). Larsson et al. (14) reported that there is little loss of maximal isokinetic power up to the age of 50 yr. It has also been reported that voluntary muscle function deteriorates less rapidly in the upper limbs (major working muscles during swimming) than in the lower limbs (9, 17). The anaerobic power of the upper body muscles is an important contributor to success in sprint swimming (i.e., 50 m; Refs. 25, 27), as indicated by the strong correlation coefficient (r = 0.90) between anaerobic power output measured on a biokinetic swim bench ergometer and freestyle sprint swim (25). Thus the slower decline in 50-m, compared with 1,500-m, swimming performance with age may be attributed to a less-rapid decline in upper body anaerobic power.

Age-related changes in performance in men vs. women. We found that the rate of decline in swimming performance with age was greater in women than in men in both short- and long-duration events. The greater decline in performance-derived PFC between genders is in agreement with previous studies that examined long-distance running performance (5, 12). The previous study of Dempsey and Seals (5) and that of Joyner (12) indicated that from ~40 yr of age on, the rate of decline in running performance was greater in women than in men.

However, interpretation of such cross-sectional analysis of performance times across ages must be made carefully. It is possible that factors independent of true physiological aging changes, e.g., sociological factors, may contribute to these observations. For example, it has been speculated that the widening of gender differences with advancing age in long-distance running is partly due to the fewer number of female runners in the older age groups (12). However, unlike running in which the number of male participants is greater than the number of female participants, swimming competition attracts approximately equal numbers of men and women throughout the adult age range (USMS report). For this reason, selection bias likely did not contribute significantly to the gender differences observed in the present study. This may explain the much smaller gender-related differences in the average rate of increases in swimming times with advancing age compared with those previously reported in running (5, 12). Furthermore, unlike running performance, when we expressed the world record data as a percent decline, we did not observe the greater rate of increases in swimming time in women until ~70 yr of age.

Gender differences in performance and event distance. In the present study employing swimming as a model, the gender difference in performance times progressively became smaller as swim distance increased. To address the question of whether the trend of smaller gender differences in longer swim distances could also be observed in running events, we collected running performance data from the United States of America National Masters Track and Field Championships in 1995 (National Masters News). The results showed that, in contrast to swimming, gender differences in running performance were independent of running distance (Fig. 4B). One plausible explanation for the mode differences is that the higher economy of female swimmers contributes more to the determinants of performance as the swim distance increases. In contrast to running where the oxygen cost of running at a given speed by male and female runners appears to be similar (2, 19), the energy cost of swimming the freestyle has been shown to be significantly higher (i.e., lower economy) for men than for women performing similar training programs (20). The higher economy of women has been attributed to smaller body size (resulting in smaller body drag), smaller body density, and greater fat percent and shorter legs (resulting in a more horizontal and streamlined position) (15, 20). It is not known whether the gender difference continues to become smaller as the event duration further increases. However, an interesting observation is that the world record of swimming the English Channel had been held by a female swimmer until very recently.

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