Meta-analysis of the age-associated decline in maximal aerobic capacity in men: relation to training status

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Wilson, Teresa M., and Hirofumi Tanaka. Meta-analysis of the age-associated decline in maximal aerobic capacity in men: relation to training status. Am. J. Physiol. Heart Circ. Physiol. 278: H829–H834, 2000.—Based on cross-sectional data, we recently reported that, in contrast to the prevailing view, the rate of decline in maximal oxygen consumption (VO2max) with age is greater in physically active compared with sedentary healthy women. We tested this hypothesis in men using a meta-analytic study of VO2max values in the published literature. A total of 242 studies (538 subject groups and 13,828 subjects) met the inclusion criteria and were arbitrarily separated into sedentary (214 groups, 6,231 subjects), active (159 groups, 5,621 subjects), and endurance-trained (165 groups, 1,976 subjects) populations. Body fat percent increased with age in sedentary and active men (P < 0.001), whereas no change was observed in endurance-trained men. VO2max was inversely and strongly related to age within each population (r = −0.80 to −0.88, all P < 0.001) and was highest in endurance-trained and lowest in sedentary populations at any age. Absolute rates of decline in VO2max with age were not different (P > 0.05) in sedentary (−4.0 ml·kg⁻¹·min⁻¹·decade⁻¹), active (−4.0), and endurance-trained (−4.6) populations. Similarly, there were no group differences (P > 0.05) in the relative (%) rates of decline in VO2max with advancing age (−8.7, −7.3, and −6.8% decade⁻¹, respectively). Maximal heart rate was inversely related to age within each population (r = −0.88 to −0.93, all P < 0.001), but the rate of age-related reduction was not different among the populations. There was a significant decline in running mileage and speed with advancing age in the endurance-trained men. The present cross-sectional meta-analytic findings do not support the hypothesis that the rate of decline in VO2max with age is related to habitual aerobic exercise status in men.

aging; exercise

SINCE A CLASSIC STUDY by Robinson in 1938 (20), it has been well recognized that the functional capacity of the cardiovascular system, as assessed by maximal oxygen consumption (VO2max), declines with advancing age. This reduction results in a decrease in physiological functional capacity that would contribute to a loss of independence, increased incidence of disability, and reduced quality of life with age (10, 27). Additionally, maximal aerobic capacity is an independent risk factor for cardiovascular and all-cause mortality (1, 2). Moreover, an age-related decline in VO2max has recently been shown to influence the reduction in cognitive function observed with advancing age (26).

A currently prevailing concept based on some evidence in men is that the rate of age-related decline in VO2max is up to 50% less in endurance-trained compared with sedentary adults (3–6). In marked contrast to this view, we recently reported that the absolute rate of age-related decline in maximal aerobic capacity with advancing age was greater in highly physically active women compared with their sedentary peers (5, 23). The results of recent longitudinal studies in endurance-trained men support our observation and suggest as great or greater rates of reduction in VO2max as those previously reported in sedentary men (7, 18, 25). However, the relatively small sample sizes, limited age ranges, and lack of sedentary control groups in these studies preclude drawing any conclusions concerning this issue.

Accordingly, the primary aim of the present investigation was to determine the relationship between habitual aerobic exercise status and the rate of decline in VO2max with age in men. Our hypothesis was that the rate of age-related decline in VO2max is greater in endurance-trained than in sedentary healthy men. To address this aim, we used a meta-analytic approach in which a large number of mean VO2max values were collected from the published literature (5). We reasoned that the use of a large population approach may provide new and greater insight into this controversial issue.

METHODS

General procedure. Meta-analysis is a set of quantitative procedures for systematically integrating and analyzing the findings of previous research. Meta-analysis in the present study was conducted as described previously in detail by our laboratory (5). As an initial step, an extensive literature search was conducted to identify as many studies as possible in which VO2max was measured in men. Initially, this was done by using computer searches (via Sport Discus and Medline) using key words such as aerobic power, physical fitness, maximal oxygen consumption, VO2max, and exercise training. In addition, extensive hand searching and cross-referencing were done using bibliographies of already retrieved studies. Moreover, journals considered likely to have pertinent research were examined (American Journal of Physiology, European Journal of Applied Physiology, International Journal of...
nal of Sports Medicine, Journal of Applied Physiology, and Medicine and Science in Sports and Exercise. All mean values from previous studies meeting the following criteria for inclusion were analyzed: 1) English language studies published in peer-reviewed journals; 2) data on men reported separately from women; 3) data in which age groups were separated; 4) data with at least five subjects per group; 5) studies with only the most recently published results used and are on a particular population; 6) studies with subject groups consisting of adult men (i.e., 18–89 yr of age); 7) studies in which VO\textsubscript{2max} was directly measured (not estimated); 8) studies in which VO\textsubscript{2max} was obtained by using at least one objective criterion (e.g., plateau in VO\textsubscript{2max}, maximal respiratory exchange ratio >1.10; see Ref. 11); 9) studies in which exercise protocols were performed either on treadmills or cycle ergometers; and 10) studies in which only healthy populations were used (i.e., no overt disease). A list of papers included in the meta-analysis can be obtained from the authors upon request.

Coding variables. Subsequently, the important characteristics of all of the relevant studies located in the literature search were classified and coded. To integrate the differing methodologies (subjects, results, etc.), a coding sheet was constructed. Primary variables coded included the following: 1) study characteristics (journal, country, etc.), 2) physical characteristics of subjects (body mass, body fat, etc.), 3) exercise program characteristics (treadmill, cycle ergometer, etc.), and 4) VO\textsubscript{2max} and maximal heart rate values.

Group assignment. Because the studies included in the meta-analysis used different terms to describe the aerobic exercise status of their subject groups, we separated and analyzed the groups in the following three arbitrarily defined categories: 1) endurance-trained, referring to regular performance of vigorous endurance exercise (e.g., running, cycling, cross-country skiing) ≥3 times/wk for >1 yr; 2) active, referring to occasional or irregular performance of aerobic exercise (e.g., walking, basketball, dancing) ≥2 times/wk; and 3) sedentary, referring to no performance of any aerobic exercise.

Statistical analysis. Data from treadmill and cycle ergometer exercise were evaluated together and separately. There were no differences in results between the two analyses. Therefore, data from both exercise modes were pooled and are presented together. Because we have previously shown that weighted results (by sample size) were not significantly different from unweighted results (5), no weighing scheme was used in the present meta-analysis. Of the key dependent variables, complete data were available for age, VO\textsubscript{2max} and body mass on all groups. Because maximal heart rate values were missing in 10–15% of the subject groups, analysis for this variable was performed on the available database only. To gain insight into the possible influence of age-related changes in exercise training on VO\textsubscript{2max}, a limited amount of training data were obtained in endurance-trained men (runners). Running intensity, mileage, frequency, and years of training were available in 16 groups (5 studies), 52 groups (28 studies), 16 groups (11 studies), and 43 groups (28 studies), respectively. Because training intensity and duration are markedly different among different activities (e.g., running vs. cycling), only data on runners were included in this analysis.

Linear regression analyses were performed to determine the association among variables. In all cases, age was used as the predictor variable. Pearson product-moment correlation coefficients were used to indicate the magnitude and direction of relations among variables. One-way ANOVA was used to determine differences in the dependent variables (e.g., VO\textsubscript{2max}) among populations. When overall significance was indicated, the Tukey’s method for multiple comparisons was used to differentiate among the three group means. The slopes of regression lines were compared using analysis of covariance. Stepwise multiple regresional analyses were used to identify significant, independent determinants for the age-related declines in VO\textsubscript{2max}. Because only a limited number of values are available in the training factors, they were not included in the stepwise regression analyses. All data are reported as pooled means ± SD. The statistical significance level was set at P < 0.05 for all analyses.

RESULTS

Subject characteristics. A total of 242 studies, 538 groups, and 13,828 subjects met the criteria for inclusion. There were 214 groups (n = 6,231) in the sedentary category, 159 groups (n = 5,621) in the active category, and 165 groups (n = 1,976) in the endurance-trained category (Table 1). Overall mean age was 5–6 yr greater in the sedentary men compared with the physically active populations. Body fat percentage was 6–8% less in the endurance-trained compared with the active and sedentary men. As expected, VO\textsubscript{2max} was lowest in the sedentary men, higher in the active men, and highest in the endurance-trained men.

Table 1 presents mean values for selected subject characteristics. In all three populations, body mass did not change with advancing age. Body fat percent increased with age in both sedentary and active populations (P < 0.001), whereas no change was observed in the endurance-trained population.

Rate of decline in VO\textsubscript{2max}. Figure 1 shows the decline in VO\textsubscript{2max} in three subject populations. VO\textsubscript{2max} was strongly and inversely related to age in each of the three populations (r = −0.80 to −0.88, all P < 0.001). The rate of decline in VO\textsubscript{2max} with increasing subject group age was similar among the three subject populations. When the data were expressed as percent decrease from mean levels at age ~25 yr, the rate of decline in VO\textsubscript{2max} also was not different among three groups (Fig. 2). At any age, VO\textsubscript{2max} was highest in the endurance-trained and lowest in sedentary men. Rate of decline in maximal heart rate. As shown in Fig. 3, maximal heart rate was strongly and inversely related to subject group age in each of the three populations (r = −0.88 to −0.93, all P < 0.001). The
Age-related declines in maximal heart rate were not different in the three populations.

Age-related changes in training factors in the endurance-trained men. Figure 4 shows exercise training data in the endurance-trained men. Weekly running mileage and running speed were inversely related to age \( r = -0.60 \) to \( 0.77, P < 0.001 \), whereas years of training were positively associated with age \( r = 0.66, P < 0.001 \). Weekly running frequency was similar across the age range. There were significant relations between \( \dot{V}O_2\max \) and both running mileage \( r = 0.73, P < 0.001 \) and speed \( r = 0.91, P < 0.001 \).

Correlates of the age-related decline in \( \dot{V}O_2\max \). Table 3 presents significant predictor variables of the age-related reductions in \( \dot{V}O_2\max \) as assessed by forward stepwise multiple regression analysis. Age was the

<table>
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<th>Variable</th>
<th>20–29</th>
<th>30–39</th>
<th>40–49</th>
<th>50–59</th>
<th>60–69</th>
<th>&gt;70</th>
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<td>No. of groups</td>
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<td>31</td>
<td>22</td>
<td>26</td>
<td>50</td>
<td>9</td>
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<td>Age, yr</td>
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<td>45 ± 3</td>
<td>55 ± 3</td>
<td>65 ± 2</td>
<td>74 ± 4</td>
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<td>Height, cm</td>
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<td>174 ± 5</td>
<td>174 ± 5</td>
<td>176 ± 2</td>
<td>173 ± 5</td>
<td>172 ± 3</td>
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<tr>
<td>Body mass, kg</td>
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<td>77.8 ± 6.1</td>
<td>78.0 ± 7.7</td>
<td>81.1 ± 5.8</td>
<td>78.5 ± 7.0</td>
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</tr>
<tr>
<td>Body fat, %</td>
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<td>20 ± 3</td>
<td>20 ± 3</td>
<td>22 ± 4</td>
<td>23 ± 5</td>
<td>25 ± 0</td>
</tr>
</tbody>
</table>

| No. of groups  | 80    | 18    | 17    | 16    | 25    | 3   |
| Age, yr        | 24 ± 3| 34 ± 4| 45 ± 3| 56 ± 3| 65 ± 3| 73 ± 3|
| Height, cm     | 176 ± 5| 174 ± 6| 177 ± 3| 176 ± 4| 175 ± 3| 174 ± 1|
| Body mass, kg  | 73.2 ± 5.4| 76.8 ± 6.9| 78.5 ± 4.4| 76.5 ± 3.6| 75.9 ± 3.9| 74.4 ± 2.5|
| Body fat, %    | 15 ± 3| 18 ± 4| 21 ± 5| 21 ± 4| 21 ± 4| 30 ± 0|

| No. of groups  | 93    | 16    | 14    | 14    | 25    | 3   |
| Age, yr        | 25 ± 3| 34 ± 2| 46 ± 2| 56 ± 3| 64 ± 2| 72 ± 2|
| Height, cm     | 178 ± 3| 176 ± 5| 171 ± 7| 171 ± 7| 171 ± 6| 168 ± 9|
| Body mass, kg  | 69.8 ± 4.5| 67.9 ± 5.0| 65.8 ± 7.9| 65.4 ± 6.1| 66.7 ± 6.8| 62.4 ± 5.0|
| Body fat, %    | 10 ± 3| 12 ± 2| 13 ± 2| 13 ± 3| 14 ± 3| 14 ± 2|

Values are means ± SE.

Fig. 1. Relations between maximal oxygen consumption (\( \dot{V}O_2\max \)) and increasing subject group age in the three study populations. Rates of decline in \( \dot{V}O_2\max \) with age were not different among the three populations.

Fig. 2. Mean rates of decline in \( \dot{V}O_2\max \) with advancing age in the three study populations. Both absolute rate of decline (A) and percent rate of decline (B) were similar.
primary predictor of VO\textsubscript{2max} in all populations, accounting for 65–75% of the total variance. The secondary predictor of endurance-trained and active groups was body mass, which accounted for an additional 3 and 10% of the variance, respectively. In the sedentary group, maximal heart rate appeared as the secondary predictor and accounted for an additional 2% of the variance. Because percent body fat and fat-free mass values were missing in 10–20% of the subject groups, separate analyses were performed with and without these variables included. The results were essentially the same.

**DISCUSSION**

The primary finding of the present study is that, in contrast to our previous study in women, the rate of decline in VO\textsubscript{2max} with advancing age was not different among the subjects varying in habitual exercise status. These results suggest that sedentary men who are healthy and who undergo successful aging demonstrate similar rates of decline in VO\textsubscript{2max} as highly endurance-trained men.

In the area of aging, exercise, and cardiovascular function, the concept has been established and widely promoted that the rate of decline in maximal aerobic capacity with age is markedly attenuated in adults who perform regular aerobic exercise. In contrast, our present findings indicate that both absolute and relative rates of decline in maximal aerobic capacity were not different in endurance-trained, active, and sedentary healthy men. There are at least three independent lines of evidence to support our finding. First, as early as 1977, Hodgson and Buskirk (9) reported dissertation...
data showing no association between endurance training status and an age-associated rate of decline in VO$_{2\text{max}}$. Second, in a review paper, Saltin (22) presented unpublished data demonstrating that the average rate of decline in VO$_{2\text{max}}$ with age was essentially the same in endurance-trained orienteers and in healthy controls. Third, recent longitudinal studies in endurance-trained men reported similar rates of decline in VO$_{2\text{max}}$ to those previously reported in sedentary men (7, 18, 25). Taken together, these results suggest that the age-related rate of decline in VO$_{2\text{max}}$ is not associated with habitual exercise status in healthy men.

We want to emphasize that, although the rate of decline in VO$_{2\text{max}}$ with age was similar among the three groups, the endurance-trained men possess higher absolute levels of physiological functional capacity than do sedentary men at any age. Thus men who regularly engage in aerobic exercise are capable of performing physical tasks that cannot be performed by their sedentary peers (27). Additionally, based on epidemiological data (1, 2, 10), physically active men are at lower risk of premature mortality and functional disability.

The present results in men differ from our previous findings in women (5, 23). As described above, we previously found that the absolute, but not the relative, rate of decline in VO$_{2\text{max}}$ with age is greatest in the most physically active women and smallest in the least active women. Interestingly, the gender-dependent difference in age-related reduction in VO$_{2\text{max}}$ is in agreement with a previous study by Ogawa et al. (14). Ogawa et al. studied only young and older men and women (i.e., no continuous age distribution), but the construction of a linear regression using their mean data indicates that endurance-trained women demonstrated a 50% greater absolute rate of decline in VO$_{2\text{max}}$ compared with their sedentary peers. In contrast, the age-related rate of decline in VO$_{2\text{max}}$ was similar in endurance-trained and sedentary men (14). Taken together, these results indicate that the relation between habitual exercise status and the age-related rate of decrease in VO$_{2\text{max}}$ may depend on gender. It is tempting to speculate that the greater reductions in VO$_{2\text{max}}$ in physically active women than in men may be responsible for the greater rates of decline in endurance performance with age previously observed in women (4, 24).

It is not clear why the association between endurance training and an age-related decrease in VO$_{2\text{max}}$ is gender-dependent. One possibility is that endurance-trained women undergo a larger age-related reduction in maximal stroke volume because of its effect on maximal cardiac output and subsequently VO$_{2\text{max}}$. In this context, the aforementioned study by Ogawa et al. (14) reported that the rate of age-related decline in stroke volume (ml/kg) was ~60% greater in trained vs. sedentary women, whereas in men, the magnitude of reduction was similar between the two groups. Similarly, in the present meta-analysis, when we plotted a limited number of maximal cardiac output values available in sedentary (5 studies, 7 groups) and endurance-trained (5 studies, 12 groups) men, the rates of decline were similar in the sedentary (−2.6 l·min$^{-1}$·decade$^{-1}$) and endurance-trained (−2.4 l·min$^{-1}$·decade$^{-1}$) men (data not shown). Alternatively, it is also plausible that factors independent of true physiological changes (e.g., sociological factors) may contribute to these observations. For example, well-trained and competitive older women are fewer in numbers than their male counterparts. This could contribute to the greater rate of decline in maximal aerobic capacity with age in endurance-trained women (13).

The slower decline in maximal heart rate with advancing age in trained adults is thought to be a primary factor contributing to the slower rate of decline in VO$_{2\text{max}}$ (6, 8). In the present study, there were no group differences in the rate of decrease in maximal heart rate with age. The present findings are consistent with our previous study in women (5, 23). In fact, the age-associated rates of decline in maximal heart rate and regression equations were very similar in men and women. Taken together, these results suggest that the rate of decline in maximal heart rate is not associated with habitual exercise status and gender.

Habitual exercise plays a major role in determining VO$_{2\text{max}}$ (16). In the present study, running duration and intensity declined significantly and progressively with advancing age. Running mileage, for example, declined in excess of 50% from age 20 to age 70 yr. These observations support the view that overall aerobic exercise levels decline markedly with age in endurance-trained adults (19, 23). Additionally, we observed strong and significant associations between VO$_{2\text{max}}$ and both running mileage and intensity in the endurance-trained men. Because, conceptually, sedentary men are not performing any aerobic exercise across the age range, the magnitude of decline in physical activity levels is much greater in physically active men. These results suggest that the combined effects of the declines in these training factors may have contributed significantly to the decrease in VO$_{2\text{max}}$ with age in the endurance-trained men. In this context, it has been reported that maximal aerobic capacity can be maintained over 10- to 20-yr periods in middle-aged men who are able to sustain their high levels of aerobic exercise training (17, 21). It should be noted that our results do not conflict with these earlier studies. Rather, our results suggest that on average the rate of decline in VO$_{2\text{max}}$ is not associated with the aerobic exercise status when viewed over the normal adult lifespan.

The present study has at least two important limitations. First, we cannot discount the possibility that genetic or other constitutional factors may have influenced the present cross-sectional study findings. However, as emphasized in our previous studies (5, 23), it has been demonstrated that, when cross-sectional and longitudinal analyses are combined in the same subject population, the estimation of the average rate of decline in VO$_{2\text{max}}$ with age is similar with the two approaches (12, 15, 22). Nevertheless, longitudinal studies will be necessary to provide more definitive insight into this issue. Second, a strength of the present study is the use of meta-analysis allowing us to systematically inte-
grate a large number of studies. However, we should emphasize that a limitation of meta-analysis is the lack of experimental control due primarily to the heterogeneity of the methods used among the individual studies making up the database. A well-controlled laboratory-based study is needed to complement the findings of the present study.

In summary, the present cross-sectional meta-analytic findings do not support the hypothesis that the rate of decline in $V_\text{O}_{2\text{max}}$ with advancing age is related to habitual aerobic exercise status in men. As such, these results suggest that sedentary men who are healthy and who undergo successful aging demonstrate similar rates of decline in $V_\text{O}_{2\text{max}}$ as highly physically active men.

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REFERENCES