

## Greater rate of decline in maximal aerobic capacity with age in endurance-trained than in sedentary men

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**Pimentel, Annemarie E., Christopher L. Gentile, Hirofumi Tanaka, Douglas R. Seals, and Phillip E. Gates.** Greater rate of decline in maximal aerobic capacity with age in endurance-trained than in sedentary men. *J Appl Physiol* 94: 2406–2413, 2003. First published January 17, 2003; 10.1152/jappphysiol.00774.2002.—To determine the relation between habitual endurance exercise status and the age-associated decline in maximal aerobic capacity [i.e., maximal O<sub>2</sub> consumption ( $\dot{V}O_{2\max}$ )] in men, we performed a well-controlled cross-sectional laboratory study on 153 healthy men aged 20–75 yr: 64 sedentary and 89 endurance trained.  $\dot{V}O_{2\max}$  (ml·kg<sup>-1</sup>·min<sup>-1</sup>), measured by maximal treadmill exercise, was inversely related to age in the endurance-trained ( $r = -0.80$ ) and sedentary ( $r = -0.74$ ) men but was higher in the endurance-trained men at any age. The rate of decline in  $\dot{V}O_{2\max}$  with age (ml·kg<sup>-1</sup>·min<sup>-1</sup>) was greater ( $P < 0.001$ ) in the endurance-trained than in the sedentary men. Whereas the relative rate of decline in  $\dot{V}O_{2\max}$  (percent decrease per decade from baseline levels in young adulthood) was similar in the two groups, the absolute rate of decline in  $\dot{V}O_{2\max}$  was  $-5.4$  and  $-3.9$  ml·kg<sup>-1</sup>·min<sup>-1</sup>·decade<sup>-1</sup> in the endurance-trained and sedentary men, respectively.  $\dot{V}O_{2\max}$  declined linearly across the age range in the sedentary men but was maintained in the endurance-trained men until ~50 yr of age. The accelerated decline in  $\dot{V}O_{2\max}$  after 50 yr of age in the endurance-trained men was related to a decline in training volume ( $r = 0.46$ ,  $P < 0.0001$ ) and was associated with an increase in 10-km running time ( $r = -0.84$ ,  $P < 0.0001$ ). We conclude that the rate of decline in maximal aerobic capacity during middle and older age is greater in endurance-trained men than in their sedentary peers and is associated with a marked decline in O<sub>2</sub> pulse.

maximal oxygen consumption; aging; functional capacity

MAXIMAL AEROBIC CAPACITY, as measured by maximal O<sub>2</sub> consumption ( $\dot{V}O_{2\max}$ ), declines progressively with adult aging (10, 12, 14, 15, 35, 47). Although  $\dot{V}O_{2\max}$  may not provide an optimal measure of functional capacity (27), the decline in  $\dot{V}O_{2\max}$  with age contributes importantly to the age-associated reduction in physical functional capacity (11, 22, 39). Because a

$\dot{V}O_{2\max}$  of 15–18 ml·kg<sup>-1</sup>·min<sup>-1</sup> must be maintained for independent function (11, 30), maintaining maximal aerobic capacity is an important component of successful aging. The age-related reduction in maximal aerobic capacity is also associated with increased prevalence of cardiovascular disease (2, 5, 18, 38), the number-one cause of death in the United States (1). Specifically, higher  $\dot{V}O_{2\max}$  values are associated with more favorable coronary heart disease risk profiles (18), as well as lower cardiovascular mortality and morbidity (2, 5, 38). Because reduced maximal aerobic capacity is linked to elevated cardiovascular disease risk and mortality, as well as reduced physical functional capacity, it is important to understand the modulatory influences of the decline in  $\dot{V}O_{2\max}$  with age.

$\dot{V}O_{2\max}$  has been studied extensively in endurance-trained and sedentary men (4, 13, 20, 29, 34, 36, 37, 43, 46, 48). Although it is quite clear that  $\dot{V}O_{2\max}$  is higher in endurance-trained than in sedentary men of similar age (41), whether or not the rate of decline differs between the two groups is still unclear. Rates of decline have been reported to be attenuated (4, 19, 20, 29, 36, 46), similar (37, 43, 48), or slightly greater (13) in endurance-trained than in sedentary men. Discrepant results among studies may be attributed to an incomplete age range (29, 46), small group numbers (43), inclusion of diseased populations (20, 43), different measurement procedures (19, 36, 46), poorly defined training status criteria (4, 29, 37, 43, 46), and/or absence of an appropriate sedentary control group (13, 19, 48). This is the first well-controlled study employing a wide age range, selective inclusion criteria, large group numbers, and standardized measurement procedures.

Recently, we used meta-analysis, as well as cross-sectional and longitudinal laboratory-based experimental approaches, to establish that  $\dot{V}O_{2\max}$  actually declines at a greater absolute rate (ml·kg<sup>-1</sup>·min<sup>-1</sup>·decade<sup>-1</sup>) in endurance-trained than in sedentary women (6, 8, 44), whereas the relative rates of decline (percent decrease from baseline in young adulthood) were not

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Table 1. Selected subject characteristics

Variable	Age, yr					r With Age	P
	20–29	30–39	40–49	50–59	>60		
<i>Sedentary men</i>							
n	17	13	7	12	15		
Age, yr	25 ± 1	34 ± 1	46 ± 1	55 ± 1	66 ± 1		
Height, cm	178 ± 2	174 ± 2	176 ± 2	176 ± 3	175 ± 1		NS
Body mass, kg	76 ± 3	79 ± 4	85 ± 6	80 ± 3	86 ± 3	0.27	<0.05
FFM, kg	61 ± 2	58 ± 2	61 ± 2	60 ± 2	59 ± 1		NS
Body fat, %	20 ± 2	25 ± 2	27 ± 3	25 ± 2	30 ± 2	0.43	<0.0001
BMI, kg/m <sup>2</sup>	23.9 ± 0.7	26.0 ± 1.0	27.3 ± 1.8	25.9 ± 1.0	27.9 ± 0.8	0.35	<0.005
<i>Endurance-trained men</i>							
n	14	18	20	18	19		
Age, yr	25 ± 1	33 ± 0	43 ± 1	54 ± 1	67 ± 1		
Height, cm	180 ± 2	180 ± 2	178 ± 2	175 ± 2	176 ± 1	–0.26	<0.05
Body mass, kg	73 ± 2	72 ± 2	74 ± 2	74 ± 2	75 ± 3		NS
FFM, kg	65 ± 2	65 ± 2	63 ± 1	61 ± 1	60 ± 2	–0.33	<0.005
Body fat, %	11 ± 1	10 ± 1	14 ± 1	17 ± 2	20 ± 1	0.43	<0.0001
BMI, kg/m <sup>2</sup>	22.7 ± 0.4	22.2 ± 0.4	23.5 ± 0.6	24.1 ± 0.6	24.2 ± 0.6	0.30	<0.005

Values are means ± SE; n, number of subjects. NS, not significant; BMI, body mass index; FFM, fat-free mass.

different. In contrast to these findings in women, however, our meta-analysis of the literature in men indicated no significant difference in the absolute rate of decline in  $\dot{V}O_{2\max}$  between endurance-trained and sedentary men (47).

Given the limitations of meta-analysis, the equivocal data in the literature on men, and our contradictory findings in women, we sought to confirm the findings of the meta-analysis in men with a well-controlled, cross-sectional, laboratory-based investigation. On the basis of the meta-analysis in men, we hypothesized that there would be no difference between sedentary and

endurance-trained men in absolute or relative rates of decline in  $\dot{V}O_{2\max}$  with advancing age.

**METHODS**

*Subjects.* We studied 153 men: 89 endurance-trained (age range 21–74 yr) and 64 sedentary (age range 20–75 yr). All subjects were healthy and free of overt cardiovascular disease as assessed by medical history. Irrespective of training status, men >40 yr of age were further evaluated by physical examination and by resting and maximal exercise electrocardiograms. None of the subjects were smokers or were taking medications that could affect circulatory function. To elimi-

Table 2. Responses to graded exercise

Variable	Age, yr					r With Age	P
	20–29	30–39	40–49	50–59	>60		
<i>Sedentary men</i>							
$\dot{V}O_{2\max}$							
l/min	3.3 ± 0.1	3.2 ± 0.2	3.1 ± 0.2	2.7 ± 0.1	2.4 ± 0.1	–0.63	<0.0001
ml · kg <sup>–1</sup> · min <sup>–1</sup>	43.4 ± 1.3	40.6 ± 2.1	36.6 ± 1.3	33.7 ± 1.5	28.1 ± 1.3	–0.74	<0.0001
ml · kg FFM <sup>–1</sup> · min <sup>–1</sup>	54.1 ± 1.3	54.4 ± 1.9	50.4 ± 1.5	44.5 ± 1.5	40.5 ± 1.3	–0.74	<0.0001
HR <sub>max</sub> , beats/min	193 ± 2	190 ± 3	184 ± 3	170 ± 2	159 ± 3	–0.82	<0.0001
RER <sub>max</sub>	1.17 ± 0.01	1.19 ± 0.01	1.20 ± 0.01	1.19 ± 0.02	1.20 ± 0.02		NS
RPE <sub>max</sub>	19.4 ± 0.2	19.2 ± 0.3	18.9 ± 0.4	19.4 ± 0.2	18.9 ± 0.3		NS
$\dot{V}E_{\max}$ , l/min	105.2 ± 6.5	125.1 ± 8.4	124.0 ± 9.1	107.1 ± 7.9	103.1 ± 2.9		NS
O <sub>2</sub> pulse <sub>max</sub> , ml · kg <sup>–1</sup> · beat <sup>–1</sup>	0.225 ± 0.007	0.213 ± 0.009	0.199 ± 0.005	0.199 ± 0.010	0.177 ± 0.007	–0.52	<0.0001
<i>Endurance-trained men</i>							
$\dot{V}O_{2\max}$							
l/min	4.5 ± 0.1	4.5 ± 0.1	4.3 ± 0.1	3.6 ± 0.1	2.9 ± 0.1	–0.76	<0.0001
ml · kg <sup>–1</sup> · min <sup>–1</sup>	60.9 ± 1.2	62.5 ± 1.3	58.7 ± 1.5	49.2 ± 2.1	39.2 ± 1.4	–0.80	<0.0001
ml · kg FFM <sup>–1</sup> · min <sup>–1</sup>	68.5 ± 1.6	69.2 ± 1.1	68.9 ± 1.4	59.4 ± 1.9	48.8 ± 1.6	–0.76	<0.0001
HR <sub>max</sub> , beats/min	187 ± 2	185 ± 3	178 ± 2	169 ± 3	160 ± 2	–0.70	<0.0001
RER <sub>max</sub>	1.17 ± 0.02	1.17 ± 0.02	1.13 ± 0.01	1.11 ± 0.01	1.15 ± 0.02	–0.24	<0.05
RPE <sub>max</sub>	19.3 ± 0.2	19.3 ± 0.2	19.2 ± 0.2	19.5 ± 0.2	18.9 ± 0.3		NS
$\dot{V}E_{\max}$ , l/min	140.6 ± 13.0	153.8 ± 7.7	160.5 ± 6.7	118.6 ± 9.2	96.1 ± 7.1	–0.54	<0.0001
O <sub>2</sub> pulse <sub>max</sub> , ml · kg <sup>–1</sup> · beat <sup>–1</sup>	0.327 ± 0.005	0.340 ± 0.010	0.329 ± 0.007	0.292 ± 0.013	0.244 ± 0.008	–0.66	<0.0001

Values are means ± SE.  $\dot{V}O_{2\max}$ , maximal O<sub>2</sub> uptake; HR<sub>max</sub>, maximal heart rate; RER<sub>max</sub>, maximal respiratory exchange ratio; RPE<sub>max</sub>, maximal rating of perceived exertion;  $\dot{V}E_{\max}$ , maximal pulmonary minute ventilation in BTPS units.

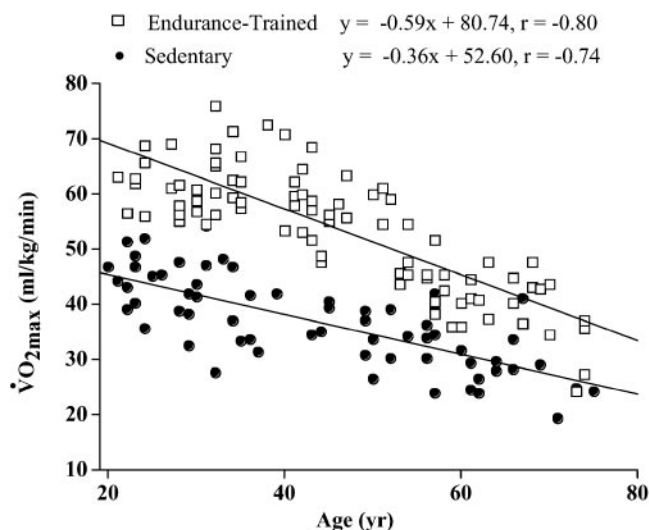


Fig. 1. Relation between maximal  $O_2$  uptake ( $\dot{V}O_{2\max}$ ) and age in endurance-trained and sedentary men. Absolute rate of decline in  $\dot{V}O_{2\max}$  with age was greater in endurance-trained than in sedentary men ( $P < 0.001$ ).

nate the confounding influence of severe obesity, only subjects with a body mass index  $< 35 \text{ kg/m}^2$  were included in the study. To ensure that the endurance-trained men were highly competitive runners, we recruited men who finished among the top 10 finishers from their age group in the Boulder Boulder road race (the second-largest 10-km road race in the United States). The men in the sedentary group were interviewed thoroughly to ensure that they performed no regular aerobic physical exercise. Before participation, verbal and written explanations of the procedures and potential risks were provided. In turn, the subjects gave their written informed consent to participate in the study. The study was approved by the Human Research Committee of the University of Colorado at Boulder.

**Measurements.**  $\dot{V}O_{2\max}$  was determined by a continuous incremental treadmill protocol by using on-line computer-assisted open-circuit spirometry, as described in detail previously (7, 42). Gas fractions were analyzed with a mass spectrometer (model MGA-1100, Perkin-Elmer, Pomona, CA) previously calibrated with standard gases of known concentrations. Expired air volume was measured with a turbine (model VMN-2, Interface Associates, Laguna Niguel, CA) or a pneumotachometer (Hans Rudolph, Kansas City, MO). There were no differences between these two systems when ventilation,  $O_2$  uptake, and  $CO_2$  production were analyzed simultaneously. Before each trial, these analyzers were calibrated with standard gases of known concentrations. Heart rates were continuously monitored with an electrocardiogram.

After a 6- to 10-min warm-up period, each subject ran or walked at a comfortable speed that corresponded to 70–80% of age-predicted maximal heart rate. Treadmill grade was increased 2.5% every 2 min until volitional exhaustion. At the end of each stage, the subjects were asked to rate their perception of effort by using a Borg scale (6–20). Each treadmill test lasted 8–12 min. Maximal heart rate was defined as the highest value recorded during the test. To ensure that each subject attained a valid  $\dot{V}O_{2\max}$ , at least three of the following four criteria were met by each subject: 1) a plateau in  $O_2$  uptake with increasing exercise intensity, 2) respiratory exchange ratio  $\geq 1.10$ , 3) achievement of age-predicted maximal heart rate ( $\pm 10$  beats/min), and 4) a rating of perceived exertion  $\geq 18$  units (9, 16).

Body mass was measured with a physician's balance scale (Detecto, Webb City, MO) to the nearest 0.1 kg. Percent body fat and fat-free mass (FFM) were estimated using dual-energy X-ray absorptiometry (DXA-IQ, Lunar Radiation, Madison, WI; software version 4.1), as previously described (45).

Information was obtained from each subject regarding his training records. Endurance-trained men reported average frequency (days/wk), duration (min/session), and volume (min/wk) of training over the past year. Subjects also reported a recent 10-km race time.

**Statistics.** One-way analysis of variance was used to determine differences in the dependent variables among age groups. Univariate correlations and regression analyses were performed to determine the relations among the dependent variables and the proportion of variance in  $\dot{V}O_{2\max}$  explained by selected predictor variables, respectively. Parallelism of regression lines was used to determine differences between slopes. Stepwise multiple-regression analyses were used to identify significant, independent determinants for the age-related decline in  $\dot{V}O_{2\max}$ . Values are means  $\pm$  SE. Statistical significance was set a priori at  $P < 0.05$ .

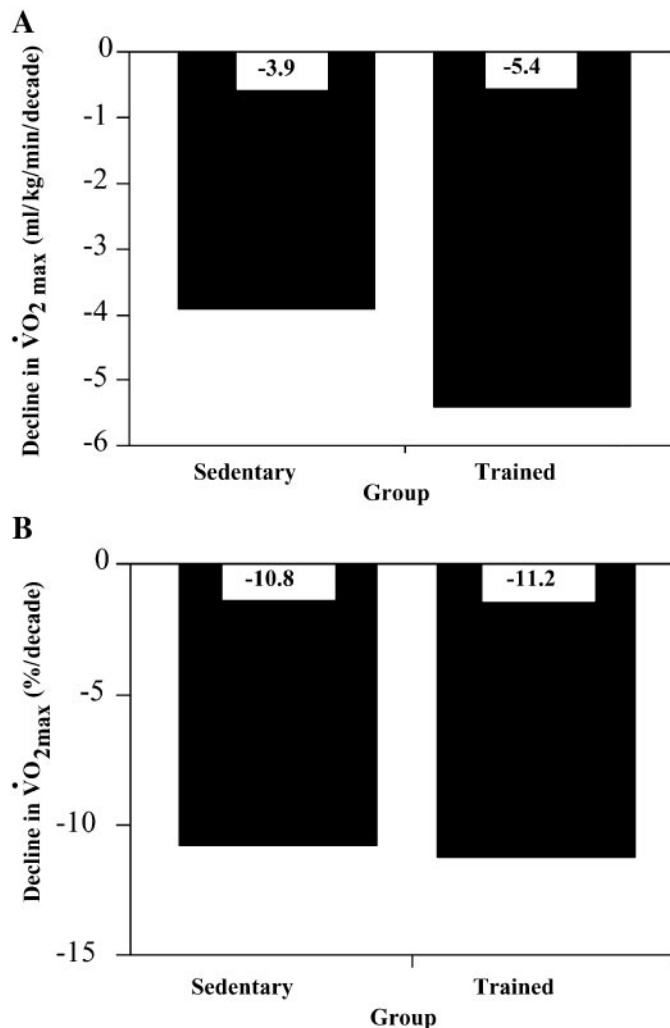


Fig. 2. Rates of decline in  $\dot{V}O_{2\max}$  with increasing age. A: absolute (i.e.,  $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\cdot\text{decade}^{-1}$ ) rates of decline were greater in endurance-trained than in sedentary men. B: relative ( $\%/decade$ ) rates of decline were similar between groups.

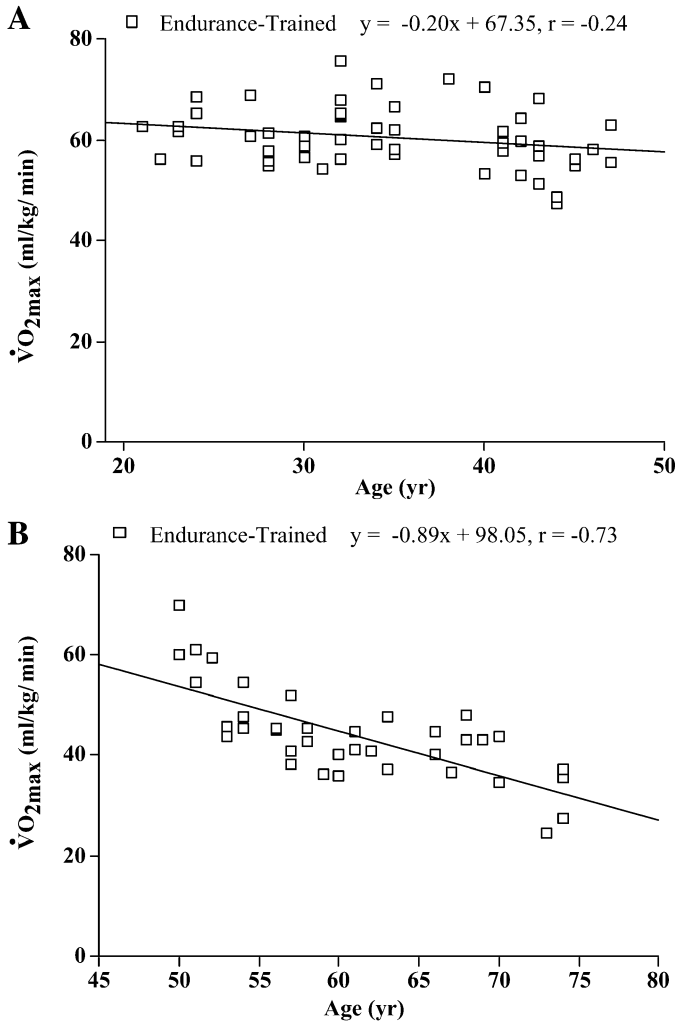


Fig. 3. Relation between  $\dot{V}O_{2\max}$  and age in endurance-trained men. A: before 50 yr of age,  $\dot{V}O_{2\max}$  declines moderately in endurance-trained men. B: after 50 yr of age,  $\dot{V}O_{2\max}$  declines at a greater rate.

**RESULTS**

*Subject characteristics.* Table 1 displays the mean values for the subject characteristics. FFM was negatively correlated with age in the endurance-trained men, whereas no relation was observed in the sedentary men. Conversely, body mass was unchanged in the endurance-trained men but increased with age in the sedentary men. Percent body fat increased throughout the age range in sedentary and endurance-trained men; the rate of increase did not differ between groups.

*Responses to maximal exercise.* All subjects attained  $\dot{V}O_{2\max}$  on the basis of the criteria described above.  $\dot{V}O_{2\max}$ , maximal heart rate, and maximal  $O_2$  pulse declined with age in both groups ( $P < 0.0001$ ; Table 2). Maximal pulmonary minute ventilation and respiratory exchange ratio declined with age in the endurance-trained men ( $P < 0.05$ ) only. Maximal ratings of perceived exertion did not differ with age in either group.

*Age-related changes in  $\dot{V}O_{2\max}$ .* On the basis of linear regression analysis,  $\dot{V}O_{2\max}$  ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) was in-

versely related to age in sedentary ( $r = -0.74$ ) and endurance-trained ( $r = -0.80$ ) men (Fig. 1). By testing for parallelism of the regression lines, we found that the slope of the change in  $\dot{V}O_{2\max}$  ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) with advancing age was greater in the endurance-trained than in the sedentary men ( $P < 0.001$ ). Specifically, the change in  $\dot{V}O_{2\max}$  was greater in the endurance-trained than in the sedentary men ( $-5.4$  vs.  $-3.9$   $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\cdot\text{decade}^{-1}$ ; Fig. 2A). Similar differences between endurance-trained and sedentary men existed when  $\dot{V}O_{2\max}$  was expressed in liters per minute and when normalized per kilogram of FFM. Conversely, the relative (%/decade) rate of change in  $\dot{V}O_{2\max}$  was similar in endurance-trained ( $-10.8\%$ ) and sedentary ( $-11.2\%$ ) men (Fig. 2B). Figure 3 portrays the greater slope of the  $\dot{V}O_{2\max}$  vs. age regression line in endurance-trained men after 50 yr of age compared with before 50 yr of age.

*Age-related changes in maximal heart rate.* Maximal heart rate was inversely related to age in both groups ( $P < 0.0001$ ; Fig. 4). The absolute rates of change were similar in endurance-trained and sedentary men ( $6.3$  vs.  $8.8$   $\text{beats}\cdot\text{min}^{-1}\cdot\text{decade}^{-1}$ ).

*Changes in training factors with age in the endurance-trained men.* Table 3 presents the exercise training data for the endurance-trained men ( $n = 67$ ). Frequency of training was negatively correlated with age ( $r = -0.25$ ,  $P < 0.05$ ). The 10-km race time increased ( $r = 0.76$ ,  $P < 0.0001$ ), whereas training volume decreased ( $r = -0.36$ ,  $P < 0.001$ ) with advancing age. Moreover,  $\dot{V}O_{2\max}$  was correlated with 10-km race time ( $r = -0.84$ ,  $P < 0.0001$ ) and training volume ( $r = 0.46$ ,  $P < 0.0001$ ).

*Correlates of the age-related decline in  $\dot{V}O_{2\max}$ .* Stepwise regression analysis was used to identify the significant predictor variables of the age-associated

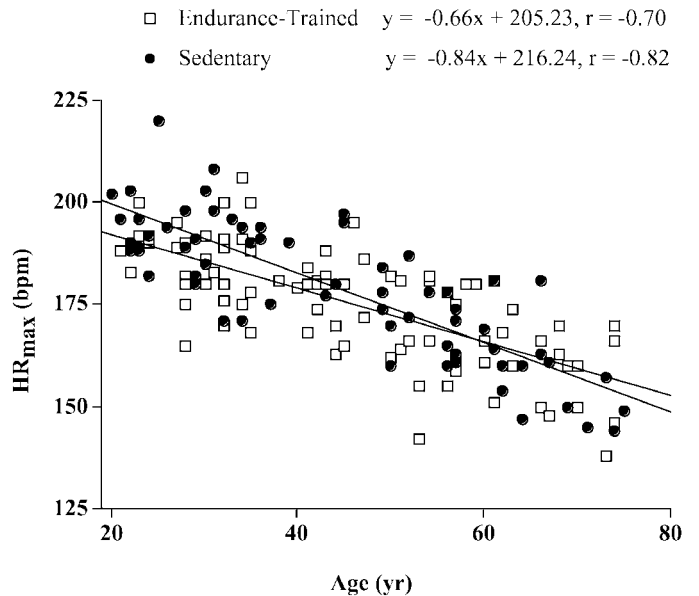


Fig. 4. Similar rates of decline in maximal heart rate ( $HR_{\max}$ ) with advancing age in endurance-trained and sedentary men. bpm, beats/min.



Table 3. Exercise training and performance data of endurance-trained men

Variable	Age, yr					<i>r</i> With Age	<i>P</i>
	20–29	30–39	40–49	50–59	>60		
Length of time training, yr	8.2 ± 1.9	11.9 ± 1.5	17.7 ± 1.5	19.8 ± 2.7	22.1 ± 6.2	0.48	<0.0001
Frequency, days/wk	6.1 ± 0.2	6.4 ± 0.2	5.8 ± 0.3	5.5 ± 0.2	5.6 ± 0.4	–0.25	<0.05
Training volume, min/week	522 ± 67	653 ± 60	578 ± 65	385 ± 60	352 ± 54	–0.36	<0.001
10-km time, min	36.1 ± 0.7	36.3 ± 1.0	38.1 ± 1.0	43.9 ± 1.2	53.1 ± 2.2	0.76	<0.0001

Values are means ± SE.

changes in  $\dot{V}O_{2\max}$  (Table 4). In endurance-trained and sedentary men, age was the primary predictor of  $\dot{V}O_{2\max}$ , describing 65 and 55% of the variance, respectively. For both groups, percent body fat was the secondary predictor of  $\dot{V}O_{2\max}$ , accounting for an additional 9 and 21% of the variance in the endurance-trained and sedentary men, respectively. When the groups were combined, percent body fat was the primary predictor of  $\dot{V}O_{2\max}$ , whereas age was the secondary predictor, accounting for 69 and 75% of the variance, respectively. In the endurance-trained men, reductions in the frequency ( $r = 0.31$ ,  $P < 0.005$ ) and volume ( $r = 0.46$ ,  $P < 0.001$ ) of average weekly training with age correlated with the corresponding decrease in  $\dot{V}O_{2\max}$ . The age-associated increase in 10-km running time was strongly related to the corresponding decrease in  $\dot{V}O_{2\max}$  ( $r = -0.84$ ,  $P < 0.0001$ ).

**Changes in  $O_2$  pulse with age.** Figure 5 illustrates the reduction in  $O_2$  pulse with age in endurance-trained and sedentary men. As with  $\dot{V}O_{2\max}$ , the slope of change in  $O_2$  pulse with age was greater in the endurance-trained than in the sedentary men ( $P < 0.001$ ). At any age, however,  $O_2$  pulse was higher in the endurance-trained than in the sedentary men.

## DISCUSSION

The primary findings of the present study are as follows. 1) The absolute, but not relative, rate of decline in  $\dot{V}O_{2\max}$  with increasing age was greater in endurance-trained than in sedentary men. 2) In the endurance-trained men,  $\dot{V}O_{2\max}$  declined minimally before 50 yr of age but at an enhanced rate thereafter; in the sedentary men, there was a linear relation between  $\dot{V}O_{2\max}$  and age. 3) The greater rate of decline in  $\dot{V}O_{2\max}$  with age in the endurance-trained men was not due to a greater rate of change in maximal heart rate or body composition but, rather, was associated with a decrease in weekly training volume.

The decline in  $\dot{V}O_{2\max}$  with age can be partially attributed to a reduction in maximal cardiac output, which is mediated in part by a reduction in maximal heart rate (10, 14, 15, 29). Hence, differences in the rate of reduction in maximal heart rate with age could lead to corresponding differences in the rate of decline in maximal aerobic capacity. In the present study, the reduction in maximal heart rate with age was strongly correlated with the age-related reduction in  $\dot{V}O_{2\max}$  among individual subjects. However, we found no difference in the age-related rate of decline in maximal heart rate between endurance-trained and sedentary

men, consistent with previous observations (32, 47). As such, age-related changes in maximal heart rate do not explain the accelerated rate of decline in  $\dot{V}O_{2\max}$  in our endurance-trained men.

Differential changes in body composition could also explain the greater rate of decline in  $\dot{V}O_{2\max}$  with age in the endurance-trained men. Because we expressed  $\dot{V}O_{2\max}$  relative to body weight ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ), increases in body mass would directly reduce  $\dot{V}O_{2\max}$ . In addition, increases in percent body fat and reductions in lean body mass may also be related to the diminished  $\dot{V}O_{2\max}$  (17, 26, 37). However, the age-related increases in percent body fat and body mass, as well as decreases in FFM, did not differ between our two groups, nor did the rates of decline in  $\dot{V}O_{2\max}$  differ between the groups when normalized for FFM. Therefore, we cannot attribute the greater rate of decline in  $\dot{V}O_{2\max}$  with age in endurance-trained men to differences in age-related changes in body composition or mass.

A reduction in peripheral  $O_2$  uptake with age could also explain the age-related reduction in  $\dot{V}O_{2\max}$ . McGuire et al. (24) reported that, in men followed over a 30-yr period, the decrease in  $\dot{V}O_{2\max}$  was associated with a reduction in peripheral  $O_2$  extraction, rather than a decrease in maximal cardiac output. In the same population, a 6-mo endurance exercise training program restored  $\dot{V}O_{2\max}$  via peripheral mechanisms (25, 40). In the present study, we found that  $O_2$  pulse, a commonly used index determined in part by peripheral  $O_2$  extraction, was attenuated with advancing age in sedentary and endurance-trained men.  $O_2$  pulse was, however, maintained at a higher absolute level in the endurance-trained men at any age. The reduction in peripheral  $O_2$  uptake with age can be attributed to reductions in muscle volume and oxidative capacity per muscle volume (3). Indeed, Neder et al. (28) reported a relation between the reductions in  $\dot{V}O_{2\max}$  and leg strength and leg muscle mass with age.

Table 4. Stepwise multiple regression analysis for predicting factors responsible for the age-related reduction in  $\dot{V}O_{2\max}$

Group	Predictor 1 ( $R^2$ )	Predictor 2 (cumulative $R^2$ )
Endurance trained	Age (0.65)	%Body fat (0.74)
Sedentary	Age (0.55)	%Body fat (0.76)
Combined	%Body fat (0.69)	Age (0.75)

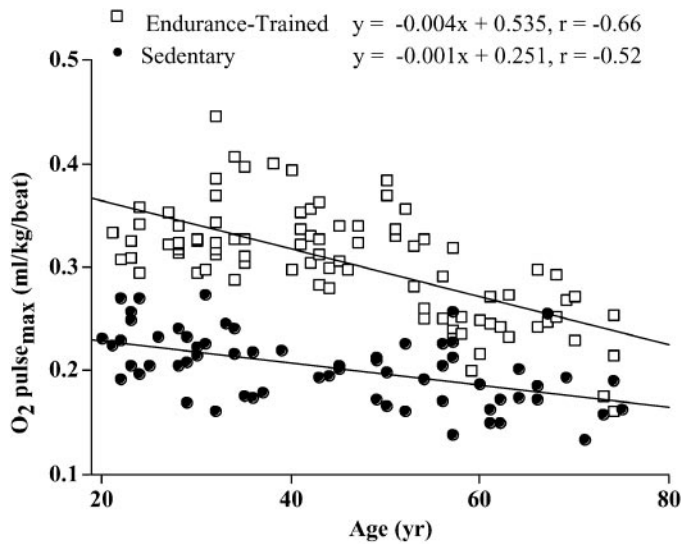


Fig. 5. Relation between maximal  $O_2$  pulse ( $O_2$  pulse<sub>max</sub>) and age in endurance-trained and sedentary men. Rate of decline in  $O_2$  pulse with age was greater in endurance-trained than in sedentary men ( $P < 0.001$ ).

Within individuals, habitual exercise behavior modulates  $\dot{V}O_{2\max}$  (17, 33). Consistent with our meta-analysis in men (47), we found that frequency of training decreased with advancing age and correlated with the decline in  $\dot{V}O_{2\max}$  in the endurance-trained men. These results suggest that the reduction in  $\dot{V}O_{2\max}$  with age in the endurance-trained men can be partially attributed to a decline in training volume. Our findings are consistent with longitudinal data showing preserved  $\dot{V}O_{2\max}$  when exercise training volume is maintained over periods of 10–20 yr (21, 23, 31). We should emphasize that a reduction in training intensity also may contribute to the accelerated decline in  $\dot{V}O_{2\max}$  after 50 yr of age. We are unable to elucidate, however, whether the decrease in training volume and intensity with age causes  $\dot{V}O_{2\max}$  to be reduced or, alternatively, with the age-related reduction in  $\dot{V}O_{2\max}$ , perception of exercise difficulty is increased and training volume and intensity are consequently decreased. The accelerated decline in  $\dot{V}O_{2\max}$  after 50 yr of age in our endurance-trained runners likely had a functionally significant impact on performance, in that 10-km race time increased with age and correlated with the decrease in  $\dot{V}O_{2\max}$ . Figure 6 illustrates the enhanced rate of increase in 10-km race time after 50 yr of age in the endurance-trained men.

We previously suggested that the greater rate of decline in  $\dot{V}O_{2\max}$  with age in endurance-trained than in sedentary women may be mediated in part by “a law of initial baseline” effect (8, 44). That is, because endurance-trained women had higher absolute levels of  $\dot{V}O_{2\max}$  than sedentary women during young adulthood, trained women experienced greater absolute rates of decline in  $\dot{V}O_{2\max}$  with advancing age. This is supported by the observation that the relative rate of decline in  $\dot{V}O_{2\max}$  (i.e., percent change from young adulthood) did not differ between sedentary and endur-

ance-trained women. In the present study, we also found that the absolute, but not the relative, rate of decline in  $\dot{V}O_{2\max}$  was greater in endurance-trained than in sedentary men. Therefore, the greater absolute rate of decline in  $\dot{V}O_{2\max}$  with age in the endurance-trained men may be mediated in part by their higher initial baseline levels.

A limitation of our study is its cross-sectional design. We realize that the rate of decline in  $\dot{V}O_{2\max}$  with age cannot be definitively determined using a cross-sectional study design. However, when Jackson et al. (17) employed cross-sectional and longitudinal analyses in a single study, the average rate of decline in  $\dot{V}O_{2\max}$  was similar with both types of analyses. Moreover, our cross-sectional and longitudinal studies in women provided similar results (6, 44). Still, we recognize that genetic and constitutional factors may have influenced our cross-sectional findings. Longitudinal studies are

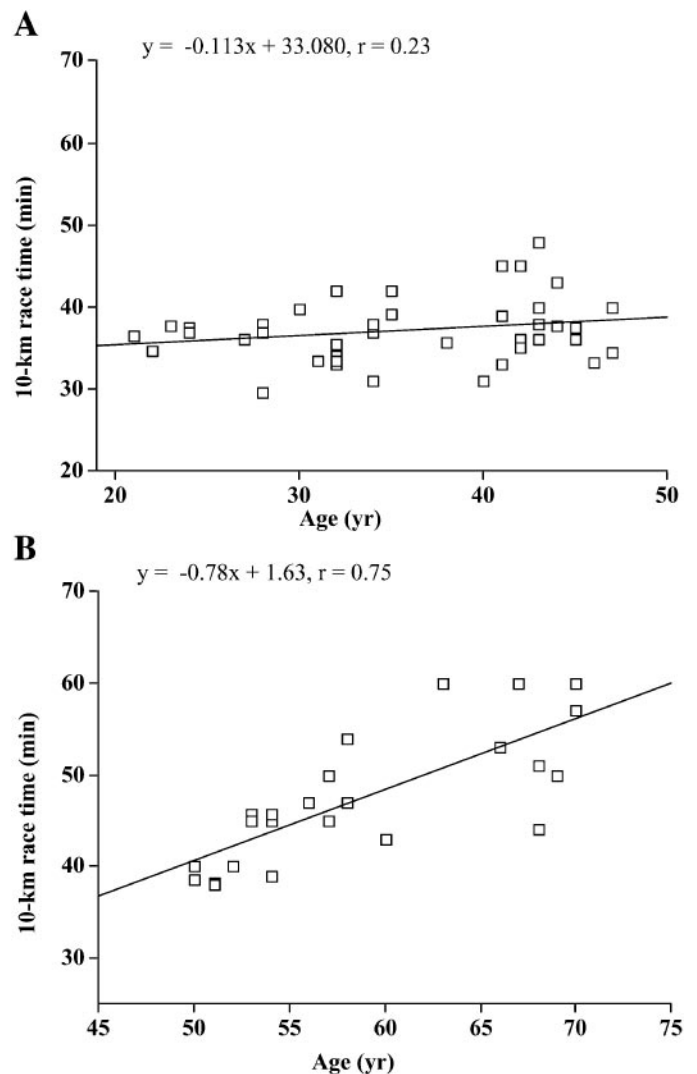


Fig. 6. Relation between 10-km race time and age in endurance-trained men. A: before 50 yr of age, 10-km race time increases minimally in endurance-trained men. B: after 50 yr of age, 10-km race time declines at a greater rate ( $P < 0.001$ ).

required to confirm the present cross-sectional observations.

Additionally, we acknowledge that self-reported physical activity is a crude measure of habitual exercise behavior. To ensure that our subjects were categorized appropriately, we thoroughly screened our sedentary and trained subjects. All our endurance-trained subjects were elite athletes who finished among the top 10 finishers in the second-largest 10-km road race in the United States, whereas our sedentary subjects abstained from regular aerobic physical activity. Furthermore, we understand that our measures of training volume also were relatively crude. However, despite this limitation, training volume strongly correlated with measures of  $\dot{V}O_{2\max}$  ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ;  $r = 0.46$ ,  $P < 0.001$ ) and 10-km race time ( $r = -0.84$ ,  $P < 0.001$ ).

In conclusion, despite their greater rate of decline in  $\dot{V}O_{2\max}$  ( $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) across age, endurance-trained men demonstrated a similar relative rate of decline (%/decade) and much higher mean levels of  $\dot{V}O_{2\max}$  at any age than their sedentary peers. The greater rate of decline in absolute  $\dot{V}O_{2\max}$  with age in the endurance-trained men may be mediated by their higher baseline levels of  $\dot{V}O_{2\max}$  than in sedentary men and a reduction in exercise training stimulus after 50 yr of age.

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