The Effect of Age on the $\dot{V}O_{2max}$ Response to High-Intensity Interval Training

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ABSTRACT

STØREN, Ø., J. HELGERUD, M. SÆBØ, E. M. STØA, S. BRATLAND-SANDA, R. J. UNHJEM, J. HOFF, and E. WANG. The Effect of Age on the $\dot{V}O_{2max}$ Response to High-Intensity Interval Training. *Med. Sci. Sports Exerc.*, Vol. 49, No. 1, pp. 78–85, 2017. **Purpose**: High-intensity interval training (HIIT) is documented to yield effective improvements in the cardiovascular system and be an excellent strategy for healthy aging. However, it is not determined how age may affect the training response of key components of aerobic endurance. **Methods**: We recruited 72 males (mean ± SD, weight = 84.9 ± 12.9 kg, height = 180.4 ± 5.8 cm) and 22 females (weight = 76.0 ± 17.2 kg, height = 171.2 ± 6.7 cm) from 20 to 70+ yr with a training status typical for their age group and divided them into six decade cohorts. The participants followed supervised training with a targeted intensity of 90%–95% of maximal HR (HR_{max}) three times a week for 8 wk. **Results**: After HIIT, all age groups increased (P < 0.001–P = 0.004) maximal oxygen consumption ($\dot{V}O_{2max}$) with 0.39 ± 0.20 (20–29 yr), 0.28 ± 0.21 (30–39 yr), 0.36 ± 0.08 (40–49 yr), 0.34 ± 0.27 (50–59 yr), 0.33 ± 0.23 (60–69 yr), and 0.34 ± 0.14 (70+ yr) $L \cdot min^{-1}$, respectively. These 9%–13% improvements were not significantly different between the age groups. In contrast to age, the percentage improvements after HIIT were inversely associated with baseline training status (r = 0.66, P < 0.001). HR_{max} was not altered within the respective age cohorts, but the two oldest cohorts exhibited a tendency (P = 0.07) to increase HR_{max} in contrast to a training-induced decrease in the younger cohorts. **Conclusion**: In healthy individuals with an aerobic capacity typical for what is observed in the population, the training response is likely not affected by age in a short-term training intervention but may rather be affected by the initial training status. These findings imply that individuals across age all have a great potential for cardiovascular improvements, and that HIIT may be used as an excellent strategy for healthy aging. **Key Words:** AGING, $\dot{V}O_{2max}$, HEART RATE, TRAINING STATUS, ENDURANCE TRAINING, HIIT

Maximal oxygen consumption ($\dot{V}O_{2max}$) is one of the strongest predictors for cardiovascular health and mortality (8,27) and is observed to decrease with ~1% per year until old age where the decline may accelerate (12,16). As a consequence, individuals suffer an elevated risk of cardiovascular disease and premature death with increasing age. Recognizing that the age-related decline in $\dot{V}O_{2max}$ indeed has multifactorial causes (9); some of it may be explained by reductions in the physical activity level as this also is shown to decrease with age (7). Thus, counteracting inactivity with effective aerobic endurance training to attenuate some of the $\dot{V}O_{2max}$ decline may be an excellent strategy for healthy aging.

There is strong evidence that supervised aerobic exercise training can improve $\dot{V}O_{2max}$ in healthy middle-age and older adults (35,37). However, a sufficient training intensity (≥60% of pretraining $\dot{V}O_{2max}$), frequency (more than three times a week), and duration (≥16 wk) may be required (10). Indeed, higher aerobic intensity has been heralded as a key factor to induce large improvements in $\dot{V}O_{2max}$ (15,19). Whole-body high-intensity interval training (HIIT), performed with a targeted intensity of 85%–95% of maximal HR (HR_{max}), has been shown to induce large improvements in $\dot{V}O_{2max}$ across initial training status in a vast number of studies with healthy young individuals (18,19,38), healthy old individuals (30,40), and several patient populations (13,20,21,32,36,42). In fact, longer intervals, typically 3–5 min, combined with

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Submitted for publication April 2016.
Accepted for publication August 2016.

0195-9131/17/4901-0078/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000001070

high-intensity continuous training are argued to induce marked $\dot{V}O_{2max}$ improvements in most relatively young adults (3). The improvements are large and typically yield a response of 0.3%–0.7% per training session in a 2- to 3-month training intervention (19,30,32,40), suggesting that even shorter (<16 wk) exercise training programs also are effective for $\dot{V}O_{2max}$ enhancement. The commonly observed age-related decline in $\dot{V}O_{2max}$ may thus be counteracted with HIIT. This has been demonstrated in a study with >70-yr-old adults, where a 13% improvement was observed after 10 wk of training (30). In addition to reducing the risk of cardiovascular events and premature death, the $\dot{V}O_{2max}$ improvements are also associated with improved endurance performance (6,39) and will likely lead to an improved physical independence and quality of life at old age (16). Importantly, it is the aerobic system that should be targeted after high-intensity endurance training, especially the heart, because a close relationship between cardiac output and $\dot{V}O_{2max}$ improvements has been demonstrated (11,25,33).

Recently, it was shown that training-induced $\dot{V}O_{2max}$ responses after HIIT were large but blunted compared with young individuals (40). From a similar baseline, the $\dot{V}O_{2max}$ training response in young individuals was approximately twofold compared with that of the old. By experimental design, the young and old subjects in the study of Wang et al. (40) were matched for baseline $\dot{V}O_{2max}$, implying that the 60-yr-old men were moderately active and that the young men had a training status typical for their age, but with both groups having a great potential for $\dot{V}O_{2max}$ improvements. This observation indicate that a smaller training-induced plasticity may be expected with age and is in accordance with previous observations showing that even if training status is taken into account, there are still differences between age groups (16). It has been argued that $\dot{V}O_{2max}$ improvements may be predominantly due to an increased cardiac output (19,33,40). In turn, the cardiac output improvements are predominantly explained by an increased stroke volume of the heart (19,40). Although HR_{max} is largely contributing to the attenuation in cardiac output with age, training appears not to influence the HR_{max} decline (16). Old adults are also demonstrated not to change HR_{max} after short-term HIIT (40). Interestingly, by contrast, young subjects are often shown to exhibit a small HR_{max} decline as a consequence of endurance training (40,43). Although these training-induced alterations in HR_{max} are small, they may have important implications for appropriate training intensity administration. This is important in the high end of the intensity scale, where effective training of the heart is a fine balance between too high-lactate accumulation from anaerobic metabolism and the intention of stressing the oxygen taxing organs maximally. Noteworthy are also possible training-induced differences in HR_{max} between old and young individuals, as they may provide important indications of how plasticity of both autonomic and nonautonomic factors of the heart may change with age.

HIIT is documented to be an excellent strategy for improving $\dot{V}O_{2max}$. Although training-induced improvements previously have been reported in specific groups of old, it is unclear if these improvements are representative for what is typically observed in the population. To our knowledge, no previous study has systematically investigated the training response to HIIT in age groups ranging from 20 to 70+ yr of age. This may provide an important insight into expected effects if HIIT is used to improve $\dot{V}O_{2max}$ in the average population in the worldwide war against inactivity. HIIT may not only be of vital importance for the individual but may also be a cost-effective socioeconomic enterprise for public health. Thus, in the current study, our aim was to examine supervised HIIT-induced $\dot{V}O_{2max}$ responses in six decade cohorts from 20- to 70+-yr-old males and females. Our hypothesis was that all of the cohorts would exhibit significant improvements in $\dot{V}O_{2max}$, but that improvements would be significantly smaller with advancing age.

METHODS

Subjects. A total of 94 healthy male (n = 72) and female (n = 22) volunteers with an age ranging from 20 to 83 yr (48.6 ± 18.1 yr) participated in this study. Subjects' characteristics are given in Table 1. The participants were matched for pretest $\dot{V}O_{2max}$ relative to age mean $\dot{V}O_{2max}$ (22) to represent what is observed in the population and typically meant that they engaged in weekly activities with low to moderate aerobic intensity from 0 to 2 $h \cdot wk^{-1}$. The subjects were divided in six decade age cohorts of 20–29, 30–39, 40–49, 50–59, 60–69, and 70+ yr, respectively. The subjects were recruited from advertisement, and by invitation to workplaces or other arenas in the local communities where we expected to find participants of the right age. The exclusion criteria were history of cardiorespiratory or musculoskeletal diseases or use of medications that could affect the responsiveness of aerobic endurance training. The subjects were also excluded if they had experienced any kind of disease or injuries lasting more than a week, during the last month before the intervention. The limit for inclusion to the data material was a compliance of 80% of all training sessions. Informed consent was obtained from all subjects, and the study was approved by the ethical committee of the University College of Southeast Norway and the institutional review board of Telemark University College. The study was performed in accordance with the declaration of Helsinki. All invited subjects who met the inclusion criteria for participation and compliance, and with a $\dot{V}O_{2max}$ representative for their age group, were included in the data material, resulting in differences in the number of participants in each age group.

Study timeline. The subjects performed pretesting 1–2 d before the 8-wk HIIT training intervention and posttesting 2–5 d after the last training session. Testing protocols were identical and conducted at the Telemark University College and the Norwegian University of Science and Technology. Subjects were instructed to not exercise, or only perform light exercise the last 24 h before the test days, and not to eat

TABLE 1. Subject characteristics.

Age Groups	All (n = 94)	20–29 (n = 26)	30–39 (n = 9)	40–49 (n = 8)	50–59 (n = 15)	60–69 (n = 29)	70+ (n = 7)
Females (%)	23	14	38	29	27	28	14
Cycling (%)	44	55	44	62	53	30	14
Age (yr)	48.6 ± 18.2****	24.5 ± 2.9*	34.6 ± 3.2*	47.7 ± 1.4*	55.6 ± 3.2*	64.5 ± 3.0*	74.4 ± 4.4*
Height (cm)	178 ± 7	179 ± 8	180 ± 6	181 ± 6	178 ± 8	178 ± 7	178 ± 6
Body mass (kg)	83.3 ± 14.9	78.3 ± 12.9	88.8 ± 21.1**	89.0 ± 17.2**	80.5 ± 13.1	86.7 ± 14.8	81.9 ± 13.4
BMI ($kg \cdot m^{-2}$)	26.1 ± 4.0	24.4 ± 3.2	27.5 ± 6.3	27.3 ± 5.7	25.4 ± 3.2	27.4 ± 3.8	25.8 ± 2.9
$\dot{V}O_{2max}$ pre							
$L \cdot min^{-1}$	3.36 ± 0.97*****	3.99 ± 0.81*******	3.99 ± 1.16***	3.42 ± 0.95	3.26 ± 0.81	2.80 ± 0.72******	2.74 ± 0.91**
$mL \cdot kg^{-1} \cdot min^{-1}$	41.4 ± 12.8*****	51.3 ± 8.3***	46.7 ± 15.8***	40.1 ± 14.1*****	41.3 ± 10.8**,***	33.3 ± 10.5**	33.3 ± 8.9**
$mL \cdot kg^{-0.75} \cdot min^{-1}$	123.9 ± 36.9*****	152.1 ± 24.0*******	141.3 ± 44.8***	121.5 ± 40.0	122.8 ± 31.3**	100.7 ± 29.6**	99.9 ± 27.6**
$\dot{V}O_{2max}$ post							
$L \cdot min^{-1}$	3.70 ± 0.96*****	4.38 ± 0.76*******	4.26 ± 1.06***	3.78 ± 0.97	3.61 ± 0.87	3.13 ± 0.68******	3.06 ± 0.91**
$mL \cdot kg^{-1} \cdot min^{-1}$	45.5 ± 12.6*****	56.5 ± 7.4***	49.9 ± 14.5***	43.9 ± 14.1*****	45.4 ± 10.3**,***	37.2 ± 9.7**	36.0 ± 8.3**
$mL \cdot kg^{-0.75} \cdot min^{-1}$	136.3 ± 36.1*****	167.4 ± 21.3*******	151.1 ± 40.3***	133.4 ± 40.0	135.4 ± 30.3**	112.4 ± 27.1**	108.2 ± 26.2**
HR_{max} (bpm)	176.3 ± 21.8*****	198.0 ± 8.0***	182.1 ± 12.7***	182.1 ± 7.8***	172.7 ± 11.7**	162.1 ± 20.2**	149.7 ± 22.2**
RER	1.10 ± 0.08	1.17 ± 0.09	1.07 ± 0.05	1.11 ± 0.07	1.10 ± 0.06	1.06 ± 0.06	1.05 ± 0.07**

Values are presented as mean ± SD. BMI, body mass index.
*$P < 0.05$ different from all other age groups.
**$P < 0.05$ different from the 20- to 29-yr age group.
***$P < 0.05$ different from the 60- to 69-yr and the 70+-yr age groups.
****$P < 0.01$ increasing with increasing age.
*****$P < 0.01$ decreasing with increasing age.
******$P < 0.01$ different from the 20- to 29-yr age group.
*******$P < 0.01$ different from the 60- to 69-yr and the 70+-yr age groups.

within 2–4 h before the tests, and only to drink water for the last 2 h.

Testing. Before the training intervention, subjects performed a whole-body $\dot{V}O_{2max}$ test using a cycle ergometer (Lode Excalibur Sport, Lode, Groningen, Netherlands; Ergomedic 839, Monark Exercise, Sweden) applying a cadence of ~1 Hz, or a treadmill (Woodway PPS 55 Sport, Waukesha, Germany) starting at 5% inclination. At inclusion, to minimize the dropout rate from the study, the participants chose one of the two whole-body testing and training modes, based on what they thought would be most motivating and/or involve the least orthopedic restriction to carry out. Pulmonary oxygen uptake was measured with the ergospirometry test systems SensorMedics Vmax Spectra (Sensor Medics, Yorba Linda, CA) and Metamax II (Cortex, Leipzig, Germany). The two different systems had been validated against each other for the range of measures that included all of the participants, and the same metabolic system was used for the same individuals at pre- and posttest. HR was continuously measured throughout the test (Polar RS 100, Polar Electro Oy, Finland). After 10 min of warm-up, the incremental $\dot{V}O_{2max}$ test started at an intensity corresponding to ~70%–80% of HR_{max}. The work was then progressively increased every minute with 1 $km \cdot h^{-1}$/3% (treadmill) and 25 W (bicycle), respectively. The length of the test ranged between 4 and 10 min, until exhaustion. Subjects that cycled were encouraged to take standing position toward the end of the testing protocol, and verbal encouragement was given from the tester. Together with voluntary exhaustion, the following criteria were used to determine whether $\dot{V}O_{2max}$ was reached: a plateau in $\dot{V}O_2$ despite increase in workload, RER ≥ 1.10, within 5 bpm of the subject's HR_{max} (if HR_{max} was known) (41). $\dot{V}O_{2max}$ was recorded as the highest 30-s average during the test. HR_{max} was measured at the same time and calculated as the highest observed HR + 5 bpm. Because $\dot{V}O_{2max}$ comparisons between individuals, groups or males and females with different body mass will overestimate subjects with a large body mass in terms of absolute values ($L \cdot min^{-1}$) and overestimate subjects with a small body mass in terms of relative values ($mL \cdot kg^{-1} \cdot min^{-1}$), it has been suggested to rather express $\dot{V}O_{2max}$ comparisons relative to body mass raised to the power of 0.75 (5). Thus, in the current study, $mL \cdot kg^{-0.75} \cdot min^{-1}$ was used as an additional term to take possible body weight differences between genders and age cohorts into account.

Training intervention. The training was conducted three times a week for 8 wk, and all the training sessions were supervised, with the HR continuously monitored, to ensure that the targeted aerobic intensity was met. The training sessions started with a 10-min warm-up and ended with a 5-min cooldown at an intensity corresponding to 70% of HR_{max}. After the warm-up, the participants performed 4 × 4 min work intervals of HIIT with an intensity corresponding to 90%–95% of HR_{max}. The intensive work periods were separated by 3-min active recovery periods at 70% of HR_{max}. The absolute intensity was thus adjusted throughout the training period to correspond to the same relative intensity. The targeted intensity during the HIIT intervals had to be met in every training session. Using the treadmill, the training was performed at an inclination ≥5%, and using the cycling ergometer, cycling was performed with a cadence of 60–80 rpm. Participants were instructed to carry out their regular physical activities as usual.

Statistics. Statistics were performed using the Statistical Package for Social Sciences (SPSS) version 19 (Chicago, IL). Figures were made by GraphPad Prism 5. $\dot{V}O_{2max}$ values were evaluated for normal distribution by using a QQ-plot and were found to be normally distributed. HIIT-induced improvements are presented as mean percentage changes. Two-way repeated-measures ANOVAs (age × time) were used to identify differences between groups pre- to posttraining and were followed up with a Tukey *post hoc* analysis. Unpaired *t*-tests were used to determine between group differences at baseline and potential across groups gender differences. Paired *t*-tests were used to detect within-group differences after training. Pearson's bivariate correlation test was used to investigate correlations between variables. A linear regression was used to assess standard error of estimate (SEE) in correlations. The level of significance was set as $P < 0.05$ for all variables, and data are presented as mean ± SD unless stated otherwise.

RESULTS

Mean compliance with the 8-wk HIIT intervention was 92% ± 4%, with no significant differences between age-groups or gender. No adverse effects of the HIIT training were reported among the participants. Neither body mass nor BMI changed in any of the groups after the training period. As expected, ANOVA analyzes displayed both a reduced $\dot{V}O_{2max}$ ($P < 0.001$) and a reduced HR_{max} ($P < 0.001$) with increasing age at baseline.

All age groups improved their $\dot{V}O_{2max}$ ($P < 0.001$–0.004) and work performance (W) ($P < 0.01$–$P = 0.04$) after the training period. HIIT intervention results are presented in Table 2 and Figures 1A, 1B, and 1C. No significant differences in training response in $\dot{V}O_{2max}$ were observed between the different age groups regardless if the expressions of $\dot{V}O_{2max}$ were given in absolute values ($P = 0.56$–1.00), relative to body weight ($P = 0.19$–1.00), or allometrically scaled ($P = 0.20$–1.00). The same applied for training responses in work performance (W) ($P = 0.32$–1.00).

As for the different age groups, there were no differences in the HIIT responses between males and females. When combing all the age cohorts the males exhibited a $\dot{V}O_{2max}$ improvement of 0.35 ± 0.22 L·min^{-1} ($P < 0.001$), which represented a 10.8% ± 8.1% increase. The females improved $\dot{V}O_{2max}$ by 0.29 ± 0.20 L·min^{-1}, which represented a 13.8% ± 10.0% increase. Expressed relative to body weight, the results confirmed the similar $\dot{V}O_{2max}$ improvements with the males exhibiting a 4.1 ± 2.5-mL·kg^{-1}·min^{-1} increase ($P < 0.001$) and the females exhibiting a 4.2 ± 2.5-mL·kg^{-1}·min^{-1} increase ($P < 0.001$). No differences in HIIT-induced $\dot{V}O_{2max}$ improvement were evident between the genders ($P = 0.30$). Also, work performance enhancements were similar for males and females, revealing that males increased external work by 24.5% ± 34.4% ($P < 0.001$) and females increased external work by 23.8% ± 43.7% ($P < 0.001$). There was no significant difference between genders ($P = 0.98$). The participants using the treadmill as a training and testing modality ($n = 52$) improved $\dot{V}O_{2max}$ by 0.35 ± 0.22 L·min^{-1} ($P < 0.001$). Participants using the cycling as training and testing modality ($n = 42$) improved $\dot{V}O_{2max}$ by 0.31 ± 0.21 L·min^{-1} ($P < 0.001$). There was no significant difference between the two modalities ($P = 0.50$). HIIT-induced improvements in work performance were in accordance with the $\dot{V}O_{2max}$ increase, showing participants that trained at the treadmill to increase external work by 35.1 ± 36.2 W ($P < 0.001$). In a practical terms, the training-induced improvement after HIIT typically resulted in an increase of ~1 km·h^{-1} if speed was adjusted when running (e.g., 12 km·h^{-1} (pre)–13 km·h^{-1} (post)) and an increase of ~4% if inclination was adjusted when walking (e.g., 10% (pre)–14% (post)). The participants that performed cycling improved external work by 37.8 ± 21.5 W ($P < 0.001$) after HIIT. Again, in work improvement, there was no significant difference between the two modalities ($P = 0.67$). HR_{max} was not altered as a consequence of HIIT in any of the age-groups. However, if the two oldest age cohorts were combined (60–70+ yr) and contrasted to a cluster of the younger cohorts (20–59 yr), a tendency ($P = 0.07$) to a difference in HR_{max} response was observed after training (Fig. 2). Although all subjects improved their aerobic capacity, the percentage improvement was dependent on the participants' initial training status. Subjects that were more sedentary had the greatest $\dot{V}O_{2max}$ training response (Fig. 3).

DISCUSSION

HIIT has been shown to effectively improve $\dot{V}O_{2max}$ and, thus, be an advantageous strategy for reducing the risk for cardiovascular disease and premature death, especially with advancing age. However, it is unclear how age may affect the magnitude of the training response to HIIT and the quantification of the expected benefits. We therefore sought to investigate training responses in 94 males and females from 20 to 70+ yr, with a $\dot{V}O_{2max}$ corresponding to what is

TABLE 2. Physiological responses (Δ) to 8 wk of HIIT.

Age Groups	All (n = 94)	20–29 (n = 26)	30–39 (n = 9)	40–49 (n = 8)	50–59 (n = 15)	60–69 (n = 29)	70+ (n = 7)
$\Delta\dot{V}O_{2max}$							
L·min^{-1}	0.34 ± 0.22**	0.39 ± 0.20**	0.28 ± 0.21**	0.36 ± 0.08**	0.34 ± 0.27**	0.33 ± 0.23**	0.34 ± 0.14**
mL·kg^{-1}·min^{-1}	4.2 ± 2.5**	5.2 ± 2.5**	3.3 ± 2.2**	3.8 ± 1.1**	4.2 ± 2.7**	3.9 ± 2.7**	2.7 ± 1.8**
mL·kg$^{-0.75}$·min^{-1}	12.4 ± 7.4**	15.3 ± 7.3*	9.8 ± 6.8**	11.9 ± 8.0**	12.6 ± 8.1**	11.7 ± 8.0**	8.3 ± 5.0**
Pct.	11.6 ± 8.6**	10.8 ± 6.8*	8.8 ± 7.3*	10.8 ± 5.0**	11.5 ± 9.1**	13.0 ± 10.9**	9.2 ± 5.6**
ΔHR_{max} (bpm)	−1.3 ± 7.9	−2.6 ± 3.9	−1.4 ± 3.4	−1.9 ± 7.7	−2.1 ± 5.9	0.3 ± 5.5	0.6 ± 2.8
ΔRER	0.01 ± 0.06	−0.02 ± 0.08	0.01 ± 0.05	−0.03 ± 0.04	0.00 ± 0.04	0.00 ± 0.04	0.03 ± 0.02
ΔWork performance							
Watts	36.3 ± 30.5**	40.2 ± 21.4**	19.5 ± 22.7**	27.4 ± 15.1**	39.8 ± 39.8**	38.1 ± 38.0**	35.8 ± 20.8**
Pct.	24.3 ± 36.6**	17.2 ± 36.6**	7.2 ± 7.2**	13.8 ± 9.8**	19.8 ± 24.2**	37.1 ± 53.5**	39.3 ± 58.5**
ΔBody weight (kg)	−0.4 ± 2.7	−0.4 ± 2.3	−0.6 ± 0.9	0.2 ± 1.9	−0.4 ± 3.4	−0.5 ± 1.8	0.1 ± 1.5

Values are presented as mean ± SD.
** $P < 0.01$ different from pretest.

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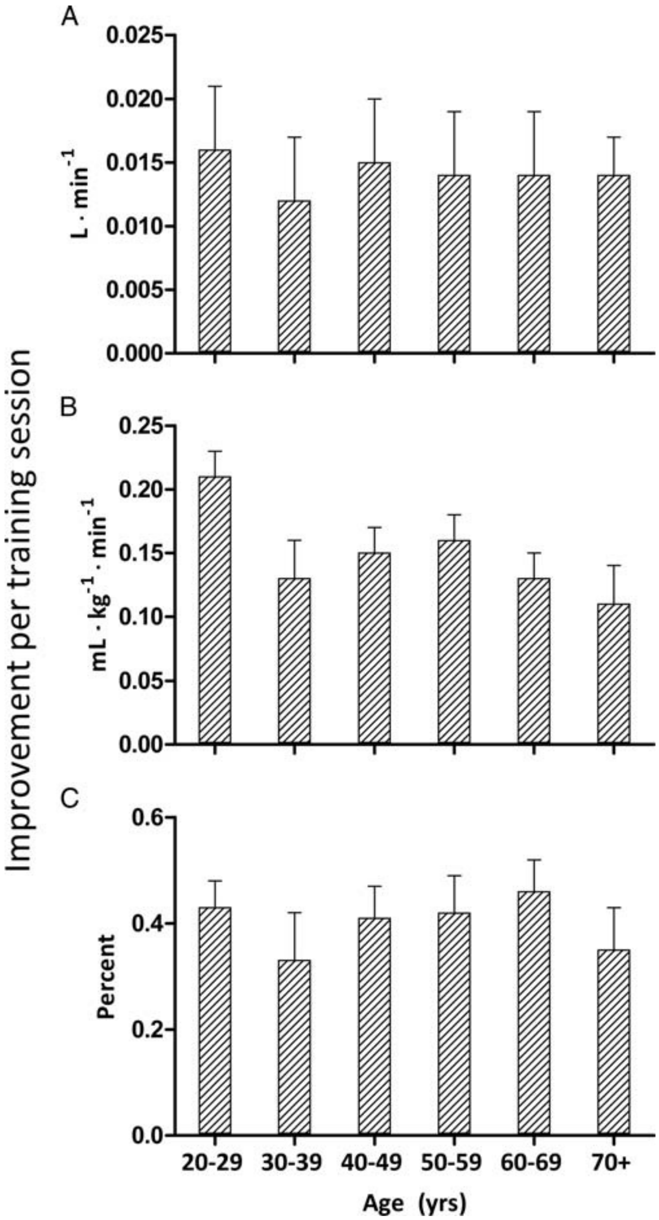

FIGURE 1—Improvement per training session after 8 wk of HIIT. Data are presented as mean ± SE for each age group. Improvement in maximal oxygen consumption ($\dot{V}O_{2max}$) per training session in liters per minute (A), milliliters per kilogram of bodyweight per minute (B), and percent (C).

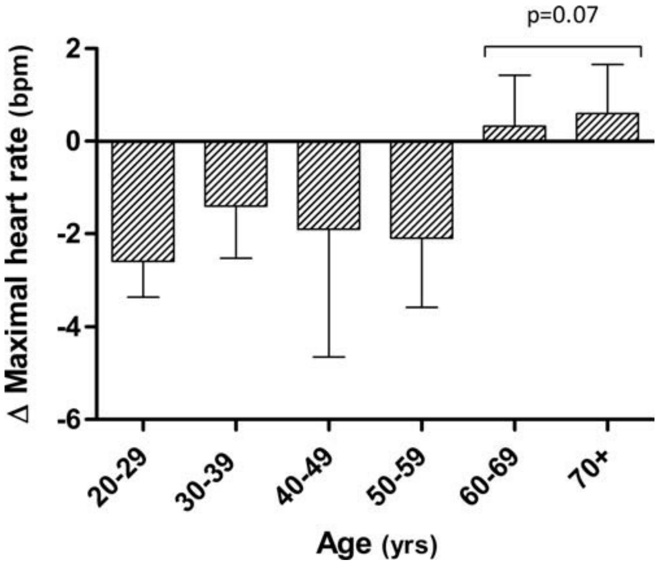

FIGURE 2—Pre- to posttest differences (Δ) in maximal HR after 8 wk of HIIT. Data are presented as mean ± SE for each age group. P = 0.07, tendency of increased maximal HR in the two oldest age cohorts (60–70+ yr) compared with a combination of the younger age cohorts (20–59 yr).

typically observed in the population. The main findings were as follows: 1) All age groups exhibited similar absolute and relative $\dot{V}O_{2max}$ improvements and yielded 9%–13% improvements after the 8-wk HIIT intervention. 2) In contrast to age, initial training status was associated with the $\dot{V}O_{2max}$ response, meaning that the most sedentary subjects exhibited the largest improvement. 3) HR_{max} tended to decrease after HIIT in the young, in contrast to old, where it exhibited a tendency to increase, implying that autonomic and nonautonomic training responses in the heart may be different with age. Our results imply that a short-term HIIT intervention results in similar effective and large $\dot{V}O_{2max}$ improvements with age, and that the most sedentary individuals may exhibit the largest gain in cardiovascular health and risk-reduction of premature death.

$\dot{V}O_{2max}$ response, age, and training status. HIIT-induced $\dot{V}O_{2max}$ responses were not different between the age groups in the current study, but all of the groups exhibited a $\dot{V}O_{2max}$ increase from pre- to posttest. Previously, only a limited number of studies have investigated physiological adaptations from HIIT with an aerobic intensity as high as 90%–95% of HR_{max} in healthy individuals older than 60 yr (30,40). The results from the current study are in accordance with the study of Osterås et al. (30) (13% $\dot{V}O_{2max}$ improvement), showing that even moderately old individuals, with a $\dot{V}O_{2max}$ typical for what is observed in the population, have a great potential for improving $\dot{V}O_{2max}$. In fact, the $\dot{V}O_{2max}$

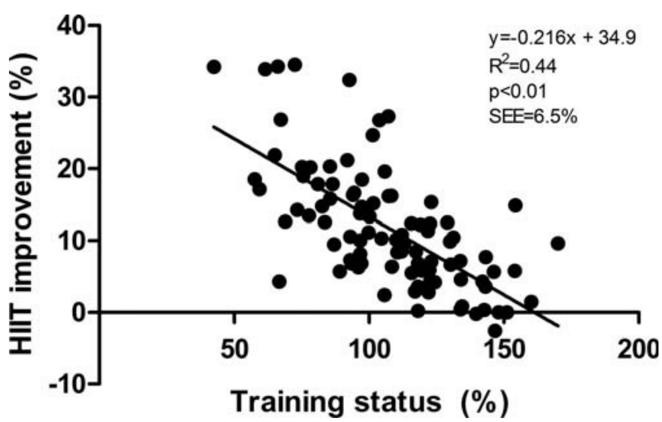

FIGURE 3—Maximal oxygen consumption improvement related to training status. Values are baseline maximal oxygen consumption ($\dot{V}O_{2max}$) training status (x-axis) and percentage $\dot{V}O_{2max}$ improvement after 8 wk of HIIT (y-axis). n = 94. Baseline training status is expressed relative (%) to age mean $\dot{V}O_{2max}$ (e.g., a training status of 150% implies a $\dot{V}O_{2max}$ 50% higher than the age mean $\dot{V}O_{2max}$). The regression is significant (P < 0.01) and is derived from percentage values.

improvements in the two oldest age cohorts in our study correspond to a $\dot{V}O_{2max}$ decline that is commonly observed with ~10 yr of aging (12,16). Thus, a training intervention of relatively short duration may yield important benefits, and the magnitude of the beneficial effects seems not to be reduced up to 80 yr of age. The $\dot{V}O_{2max}$ improvements (9%–13%) in the old subjects in the current study are somewhat larger than the 6% increase that was observed in the 60-yr-old participants in the study of Wang et al. (40) where an identical HIIT intervention was applied. However, this should be expected considering the effect of initial training status. Although the subjects in the current study had a $\dot{V}O_{2max}$ representative for what is typically observed in the population (22), the subjects in the study of Wang et al. (40) were moderately active and participated in activities such as running, orienteering, and cross-country skiing. In combination, our study and the study of Wang et al. (40) are in line with regard to the notion of a reduction in $\dot{V}O_{2max}$ increases with improvements in training status.

Aerobic training intensity has been argued to be a key factor for $\dot{V}O_{2max}$ improvements (19,32,36,42), and it is likely that the 90%–95% of HR_{max} intensity applied in our study played a key role in the large improvement. Thus, it is somehow surprising that a recent meta-analysis that investigated the magnitude of $\dot{V}O_{2max}$ alterations after endurance training in sedentary old adults reported that exercising at intensities higher than 75%–80% of HR reserve (HRR) (i.e., between 80% and 90% of HR_{max}) did not lead to greater enhancement of $\dot{V}O_{2max}$ improvements compared with exercising at 66%–73% of HRR (23). However, the meta-analysis of Huang et al. (23) included only a limited number of studies (2,4,24,34) that applied an intensity between 75% and 80% of HRR and no studies with an intensity corresponding to 90%–95% of HR_{max}. This may explain the discrepancies between our study and the meta-analysis of Huang et al. (23). Indeed, compared with another study with a similar duration (4), applying a fairly high (75% of HRR) yet lower intensity than ours, the participants in our study had an almost twofold $\dot{V}O_{2max}$ improvement (12% vs. 7%). The ~70-yr-old subjects in the Bellman and Gaesser (4) study were also more sedentary (24 $mL \cdot kg^{-1} \cdot min^{-1}$) than ours, implying that they both physiologically and mathematically should have a higher potential for percentage improvement. In combination, these results indicate that a training intensity higher than 90% of HR_{max} may be important for the largest training-induced improvements in $\dot{V}O_{2max}$ with age.

Although individuals may reach a slightly higher $\dot{V}O_{2max}$ during running compared with cycling (1), the aerobic intensity during the intervals in the current study was high, but not maximal. The difference between cycling and running was also reduced because cyclists were able to carry out training in a weight-bearing standing position. Thus, despite that cycling, walking, and running were all used as training modalities, all the participants across age and gender were able to reach the intended intensity training zone for effectively taxing the oxygen transporting organs, yielding a similar training stimulus for $\dot{V}O_{2max}$ improvements. However, the cycle test may have resulted in somewhat lower absolute measurements both before and after training, and this may have contributed to a slight underestimation of $\dot{V}O_{2max}$ for the respective age cohorts.

A low baseline $\dot{V}O_{2max}$ has been suggested to imply a higher risk of illness or injury during high-intensive exercise and potentially have harmful cardiovascular effects (29,31). However, there was no adverse incident due to the training regime in the present study. HIIT has previously also been applied as a strategy for improved cardiovascular health in several groups of patients with various medical conditions. Interestingly, the magnitude of $\dot{V}O_{2max}$ improvements in our study is also in accordance with studies that have used an identical HIIT protocol on a wide range of patients with a variety of medical conditions. Some of these studies involve patients with coronary artery disease (21,32), peripheral arterial disease (21,26,36), heart failure (42), chronic stroke (14), schizophrenia (17), and substance use disorder (13), respectively. Taken together, all these report that HIIT should be recommended for cardiovascular health. Notably, many of the patients in these studies have a similar age as the two oldest cohorts in the present study. Despite experiencing the various medical conditions, most of the patients share the characteristic that they are untrained, and, consequently, respond similarly to a strong and effective cardiovascular stimulus. Thus, it is not surprising that they exhibit $\dot{V}O_{2max}$ improvements of 9%–18%, also similar to what is presented in the current study, after an HIIT intervention. However, the HIIT study with heart failure patients (42) contrasts the other studies because it reported a $\dot{V}O_{2max}$ improvement of 46% (13.0–19.0 $mL \cdot kg^{-1} \cdot min^{-1}$) after a 12-wk HIIT intervention. The longer training intervention and the extremely poor training status for these patients may explain the large percentage improvement.

Maximal HR and age. As expected, our results confirmed an HR_{max} decline with age, evident as a 6% decline per decade of increased age. The most marked difference was observed from the 60- to 69-yr-old cohort to the 70+-yr-old cohort (9%). Although the apparently inevitable age-related decline in HR_{max} is likely a major contributor to the $\dot{V}O_{2max}$ reduction, it is noteworthy that the decline in $\dot{V}O_{2max}$ per decade was higher (8.5%) in our study. This is in line with previous observations (6,16) that have showed up to a twofold decline in $\dot{V}O_{2max}$ compared with HR_{max}. Indeed, both maximal stroke volume and maximal arteriovenous oxygen difference are also suggested to be important contributors, in addition to HR_{max}, to the decline in $\dot{V}O_{2max}$ with age (28). Among the proposed mechanisms for the age-related decline in HR_{max} are attenuated electrophysiology of the sinoatrial node, ß-adrenergic function, and intrinsic HR (39).

As a consequence of HIIT, HR_{max} remained unaltered within the respective age cohorts in the current study. However, there was a tendency (P = 0.07) to a difference in training-induced HR_{max} response when the two oldest cohorts were contrasted to the youngest cohorts, with the young and old exhibiting a lower and higher HR_{max}, respectively, after HIIT. Although this indication should be interpreted with caution, an HR_{max} decrease after endurance training is not uncommon in young subjects and has previously been reported in several studies (43).

A decline in the HR_{max} was also observed in young (~20 yr), but not old (~60 yr), subjects after an identical HIIT intervention (40). Although training-induced changes in HR_{max}, if documented, typically are small (1–8 bpm), they may be very important for correct training intensity administration, especially in the high end of the intensity scale.

Practical implications. The HIIT was supervised in the current study. Although the training is relatively easy to carry out, careful intensity administration involves an HR_{max} test and fairly strenuous exercise. Thus, it may be advantageous with guidance from an educated instructor, at least in the beginning of an HIIT program. Importantly, HIIT intervals are not to be performed with a maximal training intensity. The targeted 90%–95% of HR_{max} intensity typically means that the individuals are able to continue another 1–2 min after the termination of the 4-min intervals. The intention is to stress the cardiovascular system optimally and to minimize the involvement of the anaerobic system and too high-lactate accumulation. Of course, a certain lactate build up is inevitable, making it necessary with at least 3 min active recovery periods between the intervals to ensure sufficient lactate removal. If a treadmill is applied, the inclination should be set to ≥5% inclination and intensity adjustment may be performed by increasing either speed or inclination. For minimal stress on joints, the intervals may be performed by walking with adjustment of treadmill inclination only or cycling. Alternating between standing and sitting position during cycling can make it easier to maintain the right intensity during the high-intensity aerobic intervals. With age, individuals may experience various situations or orthopedic restrictions that could limit participation in certain training modalities (e.g., running/walking). However, if a sufficient taxation of oxygen transporting organs is attained during training, cardiovascular health benefits will be achieved. Not only could cycling or walking/running be used as in this study, but also other whole-body modalities such as, e.g., cross-country skiing or rowing may be applied. Thus, the tailored training regime for the individual should be based on both what is feasible and motivating, as long as large muscle groups are involved in the training.

Although the observations in the current study clearly suggest that the training response in individuals with an aerobic capacity typical of what is observed in the population is likely not affected by age, the results have some limitations. Of notice is the small number of participants in some of the age cohorts. Also, the unequal proportion of male and female participants across age may bias the assessment of relative $\dot{V}O_{2max}$ because the body composition between genders differs. Thus, the implications should be interpreted with caution with regard to these limitations.

CONCLUSION

Against our hypothesis, the current study revealed similar improvements in $\dot{V}O_{2max}$ in participants from 20 to 70+ yr of age and implies that the training response to short-term HIIT is not affected up to moderate age in individuals with a $\dot{V}O_{2max}$ representative for what is typically observed in the population. By contrast, our results showed that the magnitude of $\dot{V}O_{2max}$ improvement was affected by the initial training status. Our results advocate that HIIT can be used as an effective strategy to improve $\dot{V}O_{2max}$ in the aging population, and given the close association between $\dot{V}O_{2max}$ and physical health, this may be beneficial for the quality of life of the individual and serve as a cost-effective socioeconomic enterprise for public health.

No funding was received for this project. There are no conflicts of interests. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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