Adaptation to a standardized training program and changes in fitness in a large, heterogeneous population: the HERITAGE Family Study

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ABSTRACT

SKINNER, J. S., K. M. WILMORE, J. B. KRASNOFF, A. JASKÓLSKI, A. JASKÓLSKA, J. GAGNON, M. A. PROVINCE, A. S. LEON, D. C. RAO, J. H. WILMORE, and C. BOUCHARD. Adaptation to a standardized training program and changes in fitness in a large, heterogeneous population: The HERITAGE Family Study. *Med. Sci. Sports Exerc.*, Vol. 32, No. 1, pp. 157–161, 2000. **Purpose:** This paper describes the variations in response to a standardized, computer-controlled training program. **Methods:** Steady-state heart rate (HR) and oxygen intake ($\dot{V}O_2$) of 614 healthy, sedentary men and women aged 16–65 yr were measured during three cycle ergometer exercise tests. The HR associated with 55, 65, 70, and 75% of each subject's pretraining $\dot{V}O_2$max was used to prescribe exercise intensity. Subjects exercised three times a week, beginning at a HR associated with 55% $\dot{V}O_2$max for 30 min. Duration and intensity was gradually increased over 20 wk of training. The duration and HR of each training session were controlled by a computer. **Results:** Using the linear relationship between HR, $\dot{V}O_2$ and power output (PO), PO were predicted for each of 60 training sessions at the respective programmed HR. The average ratio of the actual training HR to programmed HR was 0.99. It was hypothesized that participants whose actual training PO exceeded their predicted PO would improve $\dot{V}O_2$max more than those whose actual PO was less than their predicted PO. Using the ratio of actual/predicted PO determined after the training was over, participants were arbitrarily assigned to three groups: 128 participants had low (LO) ratios (0.65–0.84), 408 had average (AV) ratios (0.85–1.14), and 78 had high (HI) ratios (1.15–1.34). Secondary analysis showed that the training program significantly increased mean $\dot{V}O_2$max of all three groups. Those who had a smaller increase in training PO (LO) had significantly less increase in $\dot{V}O_2$max than those with larger increases in PO (HI). **Conclusion:** People who exercise at a HR associated with the same %$\dot{V}O_2$max can vary substantially in their training PO, in their rate of increase in PO over a 20-wk training program, and in improvement of their $\dot{V}O_2$max. **Key Words:** HEART RATE, OXYGEN INTAKE, EXERCISE PRESCRIPTION, TRAINABILITY

It is a common observation that some people have less and some have more difficulty adapting to a training program and that some progress more slowly or more rapidly than others. As a result, there is considerable individual variation in the rate of adaptation to the same exercise training program. There is also a large variation in the physiological responses of participants to the same training program. For example, Prud'homme et al. (8) found a wide variation in improvement in $\dot{V}O_2$max in 10 pairs of monozygotic twins in a 20-wk endurance training program. Although the mean increase in $\dot{V}O_2$max was 12%, improvements ranged from 0 to 41%. There was reasonable agreement within twin pairs, however, suggesting that these extreme differences in response were genetically mediated. After a highly standardized training program lasting 20 wk, Lortie et al. (6) reported gains in $\dot{V}O_2$max ranging from 0% to almost 100%. Kohrt et al. (4) reported similar findings with men and women aged 60–71 yr who trained aerobically for 9–12 months. Although the mean improvement for the group was 24%, this ranged from 0 to 58%. Although there are individual differences in adaptation to training and in the responses to training, it is not clear whether those who adapt more easily to the training program also have greater improvements in $\dot{V}O_2$max. Although it might seem obvious that such would be the case, it is often not possible to adequately study this issue because the number of participants in most training studies is too small and the training program may not have been standardized.

It is well known and accepted that heart rate (HR) and oxygen intake ($\dot{V}O_2$) increase linearly with the exercise intensity and that they are linearly related to each other (1,7,9,11). This linear relationship was used to prescribe a

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standardized, 20-wk aerobic training program of progressively increasing intensity and duration for a large group of healthy, sedentary men and women aged 16–65 yr in the HERITAGE Family Study. This study has been described in detail in a previous publication (3). Exercise intensity was prescribed based on the HR associated with 55, 65, 70, and 75% of each subject's initial $\dot{V}O_2$max. Assuming that the relative intensity (%$\dot{V}O_2$max) at a given HR would not change with training, we predicted what the power outputs (PO) would be for each of the 60 training sessions at the prescribed HR. It was hypothesized that participants whose mean actual PO exceeded their mean predicted PO over the 60 sessions would improve their $\dot{V}O_2$max more (i.e., they would be more trainable) than those whose actual PO was less than that predicted. As an example, it may have been predicted that a participant would increase his average training PO from 100 W to 170 W while exercising at progressively higher HR. If he did, he would have a ratio of actual to predicted PO of 1.00. However, if he increased his training PO to 200 W at the same HR (a ratio of 1.18), then it was assumed that he had adapted better to the training program than if he had increased the training PO to only 140 W (a ratio of 0.82). Because there was such a wide range in age and initial fitness level in both men and women in this study and because there was a wide variation in ratio of actual to predicted training PO found after the training program was completed, a large data set was available for a secondary analysis to investigate whether participants with higher ratios improved their $\dot{V}O_2$max more than those with lower ratios.

METHODS

Subjects

The HERITAGE participants came from families that included the natural mother and father (aged 65 or less) and at least two offspring 16–40 yr of age. This paper describes the results from 614 men and women studied at the four clinical centers (Arizona State University [later moved to Indiana University], Laval University, University of Minnesota, and The University of Texas at Austin). Before participants were accepted into the study, they had to be healthy and sedentary, meet a set of inclusion criteria (3) and pass a medical examination with a physician that included a 12-lead electrocardiogram obtained during a maximal exercise test. The study protocol had been previously approved by the Human Subjects Committee at each of the four clinical centers. Informed consent was obtained from each subject.

Exercise Tests

Three exercise tests were performed before and after training on a SensorMedics Ergometrics 800S cycle ergometer (Yorba Linda, CA), which was connected to a SensorMedics 2900 metabolic measurement cart. The electrocardiogram was used to monitor HR before, during the last 15 s of each exercise stage, and after all exercise tests.

TABLE 1. Overview of the 20-wk training program.

Weeks	Frequency (sessions·wk^{-1})	Intensity (% $\dot{V}O_2$max)	Duration[a] (min·session)
2	3	55	30
2	3	55	35
2	3	65	35
2	3	65	40
2	3	70	40
2	3	70	45
2	3	75	45
6	3	75	50

[a] Does not include 5-min warm-up or 3-min cool-down.

During each exercise stage, gas exchange variables ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$, and RER) were recorded as a rolling average of three 20-s intervals. The exercise tests were conducted the same time of day, with at least 48 h between tests, and included the following:

Progressive, continuous cycle ergometer test to maximum. Participants exercised at a PO of 50 W for 3 min, followed by increases of 25 W every 2 min until volitional exhaustion. Because data from this test were used to calculate the PO used in subsequent tests, we wanted to have as many submaximal PO as possible before participants reached their maximum. Therefore, if the testing team felt that particular participants were not very fit, then they were arbitrarily given a starting PO of 40 W with increases of 10–20 W thereafter until volitional exhaustion. Criteria for $\dot{V}O_2$max were: RER $>$ 1.1, plateau in $\dot{V}O_2$ (change of less than 100 mL·min^{-1} in the last three consecutive 20-s points), and a HR within 10 beats of the maximal level predicted by age.

Submaximal, steady-state exercise test. During the first stage, participants exercised at an PO of 50 W for 10–12 min to have data on all subjects at the same absolute submaximal PO before and after training. After a 3-min pause, participants exercised for 10–12 min at 60% of their $\dot{V}O_2$max determined in the first test in order to have data of all subjects at the same relative submaximal PO. These first two stages were long because we needed to measure steady-state HR, $\dot{V}O_2$, and cardiac output during the last 4–6 min.

Submaximal, steady-state exercise test, followed by progressive test to maximum. The first two stages of this test were the same as during the second test, i.e., participants exercised for 10–12 min at an absolute PO (50 W) and at a relative PO equivalent to 60% $\dot{V}O_2$max. They then exercised for 3 min at a relative PO that was 80% of their $\dot{V}O_2$max determined with the first test, after which resistance was increased to the highest PO attained for at least 1 min in the first maximal test. If participants were still able to pedal after 2 min, PO was increased each 2 min thereafter until they reached volitional fatigue.

Training Program

To determine each person's training intensity, HR, PO, and $\dot{V}O_2$ obtained during the three baseline cycle ergometer tests were plotted to determine the average HR and PO associated with 55, 65, 70, and 75% of his/her $\dot{V}O_2$max before training. These HR and PO values were then used throughout the training program (see Table 1). Training sessions during the first two weeks began at a HR associated with 55% $\dot{V}O_2$max for 30 min. Either duration or intensity was then increased each 2 wk until the 14th wk of training when participants exercised at the HR associated with 75% of their initial $\dot{V}O_2$max for 50 min. This was then maintained for the next 6 wk.

Participants trained under supervision in the clinical centers on a Universal Aerobicycle (cycle ergometer) (Cedar Rapids, IA) for 60 sessions using the same standardized training protocol. They were required to complete the 60 sessions within 21 wk. They could not exercise more than one session per day, more than four sessions per week, or less than one session per week. As well, they could not get ahead by more than two sessions or fall behind more than two sessions. Participants who knew they might miss a few sessions were encouraged to train four times per week for two weeks to build up a reserve. Program adherence was monitored several times per week. Participants were contacted when they appeared to be falling behind and a plan was developed to bring them back on schedule as soon as possible.

Training was controlled by HR using the Universal Gym Mednet® (Cedar Rapids, IA) computerized system. An individualized training protocol (session number, HR, duration, and estimated PO) was programmed for each subject and stored in the computer. A magnetic card was then encoded for each participant. Each time participants came in, they began cycling on the Universal Aerobicycle® and put their encoded card through the card reader connected to the ergometer. The computer determined the training session number for that subject, as well as the programmed HR and duration. The approximate PO for that session was recorded in the program so that the Mednet® system could determine the rate of gradual increase in PO during the 5-min warm-up period to reach the programmed HR.

The computer received a HR signal via the ergometer from either a Polar transmitter (chest strap) (Polar USA, Inc., Montvale, NJ) or an ear-clip sensor. Participants trained for the programmed duration at a HR that was maintained within $\pm$ 5 beats·min^{-1} of the programmed HR by manipulating PO. For example, if participants became fatigued toward the end of a training session, HR tended to rise. When this occurred, the computer reduced PO to keep their HR near or at its programmed level. Time, HR, and PO over the previous 3 min were displayed for each subject so that the supervisor of the training session could see whether there were any problems (e.g., if the HR sensors were not functioning properly).

At the end of each training session, PO was gradually reduced during a 3-min cool-down recovery period. If requested, the computer then printed 1) a graph of HR and PO for each min of the session and 2) a table with session number, date, duration, average HR, average PO, and total work done, as well as the average total work done during the past three sessions. These printouts provided useful information about the progress of each participant and allowed the staff to determine whether there were any problems. Data from each training session were stored in the computer to be used in later analyses.

Based on the average HR obtained at several PO during the tests given before training, it was possible to plot a graph of programmed HR and the PO predicted at that HR for each participant for each 2-wk period throughout the 20-wk training program. The computerized training program was set up to maintain the programmed HR (i.e., the HR associated with the desired %$\dot{V}O_2$max) throughout the various stages of the training program. It was hypothesized that those whose actual PO at the programmed HR was greater than their predicted PO (ratio $>$ 1.0) were adapting better to the training, whereas those who did less than expected (ratio $<$ 1.0) were not adapting as well.

Statistical Analysis

Data were analyzed by an ANOVA using the general linear models to assess whether there were any differences (see Table 2 for variables studied). The Tukey Studentized range (HSD) test was used to identify the source of significant differences. Statistical significance was set at the 0.05 level.

RESULTS

The first question raised was whether the computer-controlled program actually did what it was supposed to do. Looking at the mean data for the 614 participants who completed all of the 20-wk training program and who had complete data on all variables of interest, it was found that the mean value of the actual HR during the 60-session training program was similar to the mean value of the programmed HR, as the ratio of actual/programmed HR was 0.99 $\pm$ 0.02. To determine whether this ratio was consistent over the entire training program, the 60 training sessions were split into five 12-session intervals. The ratio of actual/programmed HR for each of these five intervals was 0.99 $\pm$ 0.02. Thus, the computer kept the actual HR of the participants near their programmed value.

The next question was how well we were able to predict what the average PO would be throughout the training session. Because the mean ratio of actual/predicted PO remained constant (0.99 $\pm$ 0.20) for all 614 participants throughout each of the five consecutive sets of 12 training sessions, it appeared that the group as a whole responded to training as predicted.

When the individual variation in actual/predicted PO was studied, however, it was found that the ratio fell between 0.65 and 1.34. It was then decided to put these 614 participants into three arbitrarily defined groups based on their ratio of actual/predicted PO. Because about two-thirds of a normal distribution fell within one standard deviation of the mean, we looked for an interval of ratios around the mean that contained about two-thirds of the total group. The 408 participants (66%) with ratios from 0.85 to 1.14 were classified as average (AV). The 128 participants (21%) with ratios from 0.65 to 0.84 were classified as having a low (LO)

TABLE 2. Characteristics of 614 HERITAGE Family Study participants classified according to the ratio of actual/predicted training PO into low (LO), average (AV), and high (HI) responses to training; values are mean ± SD.

Group	LO	AV	HI
Actual/Predicted PO	0.65–0.84	0.85–1.14	1.15–1.34
Number of Participants	128	408	78
Variable			
Age (yr)	33.3 ± 13.4 (a)*	33.9 ± 13.4 (a)	37.8 ± 13.3 (b)
Height (cm)	170.6 ± 9.0 (a)	170.6 ± 9.5 (a)	166.4 ± 8.8 (b)
Weight (kg)			
Pretraining	79.0 ± 16.9 (a)	75.3 ± 17.0 (ab)	73.0 ± 15.6 (b)
Posttraining	78.8 ± 16.6 (a)	75.0 ± 16.7 (ab)	72.5 ± 15.3 (b)
$\dot{V}O_{2max}$ (mL·min^{-1})			
Pretraining	2505.3 ± 657.1 (a)	2425.3 ± 718.9 (a)	2016.1 ± 653.2 (b)
Posttraining	2810.2 ± 712.1 (a)	2830.0 ± 801.2 (a)	2440.6 ± 738.6 (b)
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})			
Pretraining	32.4 ± 8.1 (a)	32.7 ± 8.6 (a)	28.1 ± 8.2 (b)
Posttraining	36.4 ± 8.5 (ab)	38.3 ± 9.3 (a)	34.3 ± 9.6 (b)
HR at 50W (beats·min^{-1})			
Pretraining	111.9 ± 15.7 (a)	118.3 ± 16.8 (b)	131.9 ± 17.2 (c)
Posttraining	106.8 ± 14.6 (a)	107.1 ± 13.7 (a)	113.2 ± 12.8 (b)
Training HR (beats·min^{-1})			
Actual	142.2 ± 12.4 (a)	146.3 ± 13.5 (b)	144.3 ± 12.7 (ab)
Programmed	143.0 ± 13.0 (a)	148.4 ± 14.2 (b)	147.1 ± 13.9 (b)
Actual/programmed	1.00 ± 0.02 (a)	0.99 ± 0.02 (b)	0.98 ± 0.02 (b)
Training PO (total W·session^{-1})			
Actual	3818.0 ± 1226.1 (a)	4650.7 ± 1643.5 (b)	4125.3 ± 1563.2 (a)
Predicted	4989.9 ± 1498.8 (a)	4782.4 ± 1741.9 (a)	3363.0 ± 1300.3 (b)
Actual/predicted	0.76 ± 0.05 (a)	0.98 ± 0.08 (b)	1.23 ± 0.06 (c)

* Means with the same letter in parenthesis are not significantly different from each other.

response to training and the 78 participants (13%) with ratios from 1.15 to 1.34 were classified as having a high (HI) response. See Table 2 for the characteristics of the three groups.

As can be seen in Table 2, the ratios of actual/programmed HR for all three groups were similar (0.98–1.00) but significantly different. The HI group was older, shorter, weighed less, and was less fit than the other groups before training. All three groups increased their $\dot{V}O_2$max significantly as a result of the training program, but the LO group improved significantly less than did the other two groups. Because there was no mean change in body mass for any group (Table 2), this difference was significant when $\dot{V}O_2$max was expressed in absolute terms (mL·min^{-1}) or relative to body mass (mL·kg^{-1}·min^{-1}). Similarly, all three groups lowered their HR at 50 W but the reduction in LO was less than that of AV, which was less than that of HI.

DISCUSSION

A unique feature of this study is its use of a computerized cycle ergometer system to control the duration and intensity of exercise. The computer was programmed to control duration (minutes per session) and intensity (HR associated with a percentage of the initial $\dot{V}O_2$max) for each participant according to the number of sessions that had been completed. We believe that this is the first time that such a system has been used to regulate a training program for research purposes.

As seen in Table 2, most participants (66% in the AV group) responded to training as expected, i.e., their actual and programmed values for HR (ratio = 0.99 ± 0.02) and their actual and predicted values for PO (ratio = 0.98 ± 0.08) were similar throughout the 20-wk training program. The ratio of actual/programmed HR for the LO and HI groups were 1.00 ± 0.02 and 0.98 ± 0.02, respectively (i.e., participants in both groups exercised at the correct HR). Although the difference among the three groups is statistically significant, this may have arisen only because of the large sample sizes.

Because we arbitrarily assigned participants by their ratio of actual/predicted PO, these ratios were significantly different (0.76, 0.98, and 1.23 for the LO, AV, and HI groups, respectively). Although there were differences in these ratios, all three groups had a significant training effect, that is, an absolute increase in $\dot{V}O_2$max of 4–6 mL·kg^{-1}·min^{-1} and a drop in HR of 5–19 beats·min^{-1} at the absolute PO of 50 W. Thus, the training program was effective for all three groups. These results compare favorably with those from studies using similar training programs (2,4,5,7).

The absolute increases in $\dot{V}O_2$max with training were significantly different among the three arbitrarily assigned groups (4.0 < 5.6 and 6.2 mL·kg^{-1}·min^{-1} for LO, AV and HI, respectively). In relative terms (% improvement), however, the statistical differences were greater (12.9% < 17.6% < 21.9% for LO, AV and HI, respectively). This can be partially explained by the fact that the HI group had a significantly lower $\dot{V}O_2$max before training and a similar absolute change resulted in a greater relative change. It is also possible that the uneven number of subjects in each group affected these results.

As mentioned earlier, the HI group was older, shorter, lighter, and less fit. These differences from the other two groups can be partly explained by the fact that there were more women in this group. Of the 614 participants in the total sample, 325, or 53% were women. In the HI group, 58 of the 78 participants (74%) were women, compared with 58 of 128 (45%) in the LO group and 209 of 408 (51%) in the

AV group. This should not be interpreted to mean that women adapt better to training, however. More analyses with the total sample of participants are needed; these analyses should look specifically at the question of gender and adaptation to training, while controlling for other variables.

The average actual and predicted PO values for the HI group over the 60 sessions were about 80 W and 98 W, respectively. In other words, the predicted PO was only 18 W greater than the actual PO, but this was enough to give a mean ratio of 1.23 because the denominator was smaller than that of the other two groups. As expected, the AV group had similar values (actual PO = 111 W and predicted PO = 114 W) for a mean ratio of 0.98. Because the denominator of the LO group was greater (actual PO = 91 W), this group exercised 28 W below the predicted PO of 119 W and had a mean ratio of 0.76.

Using HR at a standard submaximal PO as a fitness criterion, there were significant reductions in HR and significant increases in fitness in all three groups after training. The absolute decrease in HR was $5.1 < 11.2 < 18.7$ beats·min^{-1} for LO, AV, and HI, respectively, i.e., the HI group improved more than AV, who improved more than LO. Even though the HI group started with a significantly higher HR at 50 W, the same pattern was seen for the relative drop in HR after training ($7.1 < 9.8 < 13.9$% for LO, AV, and HI, respectively).

The larger drop in HR at 50 W in the HI group might be explained by the fact that they began with a higher HR (132 beats·min^{-1}) than did the LO group (112 beats·min^{-1}) or the AV group (118 beats·min^{-1}) and the effect of training on the sympathetic nervous system could be more easily detected at the higher HR values. Wilmore et al. (12) studied a subsample of 26 men and 21 women from the HERITAGE Family study and found only a small, nonsignificant drop in resting HR. No drop in HR at 50 W was seen after training in 19 men from this subsample who were able to exercise to 200 W. On the other hand, the reduction in exercise HR became progressively greater with increasing PO. Because the parasympathetic nervous system has more influence on HR below 100 beats·min^{-1} and the sympathetic nervous system has more of an effect on HR greater than 100 beats·min^{-1} (10), their interpretation was that training caused more of a drop in sympathetic tone than an increase in parasympathetic tone.

We used the linear relationship between HR and $\dot{V}O_2$ to prescribe exercise in a large, heterogeneous sample of men and women of differing ages and initial levels of fitness. The computerized, standardized training program kept the actual HR of most participants very near to their programmed HR and was effective in increasing the mean $\dot{V}O_2$max of most participants. From the results of the study, it appears that those who adapted less well to the training, as evidenced by smaller increase in training PO, had smaller increases in $\dot{V}O_2$ than those who seemed to adapt better to the training. People who exercise at a HR associated with the same %$\dot{V}O_2$max can vary substantially in the amount of exercise that they can do, in the rate of increase in PO throughout a 20-wk training program, and in their improvement in $\dot{V}O_2$max.

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