Daily Exercise Prescription on the Basis of HR Variability among Men and Women

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ABSTRACT

KIVINIEMI, A. M., A. J. HAUTALA, H. KINNUNEN, J. NISSILÄ, P. VIRTANEN, J. KARJALAINEN, and M. P. TULPPO. Daily Exercise Prescription on the Basis of HR Variability among Men and Women. *Med. Sci. Sports Exerc.*, Vol. 42, No. 7, pp. 1355–1363, 2010. **Purpose**: To test the utility of HR variability (HRV) in daily exercise prescription in moderately active (approximately two exercises per week) men and women. **Methods**: A total of 21 men and 32 women were divided into standard training (ST: males = 7 and females = 7), HRV-guided training (HRV-I: males = 7 and females = 7; HRV-II: females = 10), and control (males = 7 and females = 8) groups. The 8-wk aerobic training period included 40-min exercises at moderate and vigorous intensities (70% and 85% of maximal HR). The ST group was instructed to perform two or more sessions at moderate and three or more sessions at vigorous intensity weekly. HRV-I and HRV-II groups trained on the basis of changes in HRV, measured every morning. In the HRV-I group, an increase or no change in HRV resulted in vigorous-intensity training on that day. Moderate-intensity exercise or rest was prescribed if HRV had decreased. The HRV-II group performed a vigorous-intensity exercise only when HRV had increased. Peak oxygen consumption ($\dot{V}O_{2peak}$) and maximal workload ($Load_{max}$) were measured by a maximal bicycle ergometer test before and after the intervention. **Results**: The changes in $\dot{V}O_{2peak}$ did not differ between the training groups either in men or in women. In men, the change in $Load_{max}$ was higher in the HRV-I group than in the ST group (30 ± 8 vs 18 ± 10 W, P = 0.033). In women, no differences were found in the changes in $Load_{max}$ between the training groups (18 ± 10, 15 ± 11, and 18 ± 5 W for ST, HRV-I, and HRV-II, respectively). The HRV-II group performed fewer vigorous-intensity exercises than the ST and HRV-I groups (1.8 ± 0.3 vs 2.8 ± 0.6 and 3.3 ± 0.2 times per week, respectively, P < 0.01 for both). **Conclusions**: HRV measurements are beneficial in exercise training prescription in moderately active men and women. Women benefit from HRV guidance by achieving significant improvement in fitness with a lower training load. **Key Words:** EXERCISE TRAINING, VAGAL ACTIVITY, TRAINING PRESCRIPTION, AUTONOMIC NERVOUS SYSTEM

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The responsiveness of cardiorespiratory fitness to aerobic training is individual (4,18,39). In maximal oxygen consumption, as large a range as from a slightly negative response to up to 40% improvement has been observed. Whereas genetic factors explain part of the interindividual differences in responses to exercise training (4), cardiac autonomic regulation has also been shown to be an important factor in this respect (18,21). Higher vagally mediated HR variability (HRV) has been associated with larger improvements in cardiorespiratory fitness (18,21).

An individualized training program is the most practical tool for optimizing responses to exercise training. According to a large body of previous studies on the association between both chronic and acute exercise training and autonomic regulation of the heart (14,17,23,33), we generated and tested a training program on the basis of daily HRV measurements among male recreational runners (26). In this training scheme, vigorous-intensity exercises are prescribed on days when HRV is either increased or unchanged compared with previous days. We observed that a 4-wk HRV-guided aerobic training resulted in larger improvements in cardiorespiratory fitness, especially in maximal running performance (6% vs 3%), than a predetermined program with the same training load. However, the applicability of daily HRV measurements in the optimization of training responses is unknown in women and in less active populations. Gender differences reproductive hormone production, thermoregulation, and hemoglobin concentration may have important contributions in the responses to acute exercise and recovery and in the adaptation to exercise training that should probably be taken in to account when applying HRV in training prescription among women (7,8,20,24,34,38).

The primary purpose of the present study was to assess the effectiveness of aerobic training on the basis of previously described HRV guidance on cardiorespiratory fitness

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among moderately active (approximately two exercises per week) women and men. We hypothesized that a different HRV-based training prescription should be applied to women than to men to obtain a desirable benefit from daily HRV measurements. Our secondary aim was to assess gender differences in acute HRV responses after periods of vigorous-intensity training. We hypothesized that HRV may be perturbed longer after vigorous-intensity exercises in women than in men, which should be considered when applying HRV in daily exercise prescription.

METHODS

Subjects and study protocol. A total of 24 healthy men and 36 healthy women were recruited by advertising in the local newspaper. The subjects were interviewed with a standardized scheme to ascertain their medical history and level of physical activity. All smokers, subjects with a body mass index (BMI) $\geq$ 30 kg·m^{-2}, subjects who had done regular physical exercise training more than twice a week or had not done regular physical exercise during the past 3 months, competing athletes, and subjects with diabetes mellitus, asthma, or cardiovascular disorders were excluded. The subjects were randomized into a standard training group (ST: males = 8 and females = 8), an HRV-guided training group (HRV-I: males = 8 and females = 8), and a control group (males = 8 and females = 8). Moreover, 12 women were included in a group that trained on the basis of an HRV-guided program tailored for women (HRV-II). Group size was determined on the basis of *a priori* statistical power calculations to give at least 80% power to differences in the expected changes in maximal workload ($Load_{max}$) between ST and HRV groups (15 ± 10 vs 30 ± 10 W for men and 10 ± 7 vs 20 ± 7 W for women, respectively, for ST and HRV groups). The study was performed according to the Declaration of Helsinki; the ethical committee of the Northern Ostrobothnia Hospital District, Oulu, Finland, approved the protocol; and all the subjects gave their written informed consent.

The laboratory measurements were performed in the Department of Exercise and Medical Physiology at Verve (Oulu, Finland). The subjects were not allowed to eat or drink coffee for 3 h before the tests. Physical exercise or use of alcohol was prohibited during the test day and on the preceding day. Before each maximal exercise test, a resting ECG (standard 12-lead ECG) was recorded to confirm the subject's cardiac health status. The tests were performed before and after the training period at the same time of day for each subject.

Maximal exercise test. The subjects performed a ramped maximal exercise test on a bicycle ergometer (Monark Ergomedic 839 E; Monark Exercise AB, Vansbro, Sweden), starting at 25 W and followed by an increase of 1 W·5 s^{-1} until voluntary exhaustion. Ventilation ($\dot{V}_E$) and gas exchange (M909 ergospirometer; Medikro, Kuopio, Finland) were measured and reported as the mean value per minute. The highest 1-min mean value of oxygen consumption was expressed as the peak oxygen consumption ($\dot{V}O_{2peak}$) because a plateau of $\dot{V}O_2$ was not observed during the test in all cases, although other criteria for maximal $\dot{V}O_2$ given in the literature (i.e., RER > 1.1 and HR_{peak} within 10 beats of the age-appropriate reference value) were fulfilled (22). $Load_{max}$ was calculated as average workload during the last 2 min of the test and used as a measure of maximal performance. Age- and gender-specified classification on the basis of $\dot{V}O_{2peak}$ was determined to obtain relative aerobic fitness (36).

Training. The controlled 8-wk training period consisted of aerobic exercise sessions (40 min) at either a moderate- or a vigorous-intensity level according to the recommendations of the American College of Sports Medicine (1). HR for moderate-intensity exercise was 70% of HR_{peak} − 5 bpm as a lower limit and 70% of HR_{peak} as an upper limit. Vigorous-intensity exercise included 5-min warm-up and cool-down periods at moderate intensity and 30 min at HR between 85% of HR_{peak} − 5 bpm as a lower limit and 85% of HR_{peak} as an upper limit. The ST group was instructed to perform at least two moderate-intensity and three vigorous-intensity exercises weekly. The subjects in the HRV-I and HRV-II groups exercised at a moderate- or a vigorous-intensity exercise or rested on the basis of their daily HRV measurements at home. The subjects were allowed to choose the training mode and the time of day for training that were most convenient for their daily routines. All the subjects were familiarized with the use of an HR monitor during the training and the daily RR (R wave to R wave) interval recordings (Polar RS800; Polar Electro Oy, Kempele, Finland). The training and RR interval data were stored in the HR monitor and were extracted at the laboratory for further analysis.

Exercise programs on the basis of daily HRV. All the subjects in the training groups were instructed to measure their RR intervals at home every morning after awakening and emptying their urinary bladder. They were allowed to breathe spontaneously. An HR monitor (Polar RS800; Polar Electro Oy) was used to record RR intervals with a timing resolution of 1 ms. It has been shown with Polar HR monitors that inaccuracy of RR interval measurement, in the absence of true RR variation, can result in SD1 values between 0.57 and 1.07 ms (noise). When $SD1\_measured^2 = SD1\_true^2 + SD1\_noise^2$ and SD1_true is 3.00 and 25.00 ms, the effect of noise in the measured SD1 value is 0.19 and 0.02 ms, respectively (25). The measurement started with 2 min of sitting followed by 3 min of standing. In addition, the subjects in the training groups on the basis of HRV (HRV-I and HRV-II) used a tailored noncommercial HR monitor (modified AXN300; Polar Electro Oy) for real-time analysis of SD1 from a Poincaré plot taken while standing for 3 min, which is the prescribed exercise for that day. HRV measurement while standing was chosen to avoid possible saturation of HRV, expressed as unchanged or even decreased HRV despite increased cardiac vagal outflow, which is susceptible at low HR levels (27). The SD1 parameter was updated after two acceptable RR intervals. The RR interval, when transformed to instantaneous HR, was accepted for calculation if it was not more than 12 bpm higher and not more than 18 bpm smaller than the immediately preceding interval. In addition, the RR interval was not accepted for SD1 calculation if it differed for more than 500 ms from the previously accepted RR interval.

The basic idea was to decrease the training stimulus when SD1 was attenuated. The baseline values of HRV were measured daily during the five nonexercise days (after the maximal exercise test) before exercise training intervention. A moderate-intensity exercise was prescribed on the sixth day, and a vigorous-intensity exercise was prescribed on the seventh day. Thereafter, training was based on the daily value of SD1 compared with reference values obtained from previous measurements that first included seven measurements and were extended up to 10 when more data became available. Thereafter, a 10-d window that moved day by day was used as the reference value. SD and mean were calculated for SD1 from the previous measurements. SD1 was defined as decreased if the daily value was lower than SD subtracted from the mean. SD1 values between SD subtracted from the mean and the mean itself were defined as unchanged, unless there was a decreasing trend in SD1 (0.5 ms if SD1 < 20 ms and 1.0 ms if SD1 ≥ 20 ms) for two successive days, which was considered a decreased SD1. These limits exceed the effect of noise that is related to the timing accuracy of HR monitor. SD1 was defined as increased if it was above the mean and higher than that on the previous day.

In the HRV-I group, if there was no significant decrease in SD1 on the eighth day and thereafter, a vigorous-intensity exercise was prescribed. A moderate-intensity exercise was prescribed regardless of SD1 after two successive vigorous-intensity training days. A maximum of nine successive training days were allowed before a day of rest was prescribed, regardless of the daily SD1. Significantly decreased SD1 led to training at moderate intensity, and rest was prescribed if SD1 remained significantly decreased on the following day. A maximum of two successive resting days were allowed, and a moderate-intensity exercise was prescribed regardless of the daily HRV on the following day (26).

The HRV-II group trained on the basis of SD1 definitions similar to those of the HRV-I group, with the exception of having a vigorous-intensity exercise only when HRV was higher than the mean of previous measurements and was increased from the previous day. In addition, a moderate-intensity exercise was prescribed if SD1 was defined as unchanged. The whole procedure was determined in advance and integrated into the tailored HR monitor, which automatically provided a daily training program for each subject after HRV measurements.

Analysis of HRV. SD1 from Poincaré plot was retrospectively analyzed from daily RR interval recordings at home using separate HRV analysis software (Heart Signal Co, Oulu, Finland) (40). The data were edited by deleting artifacts (<10% for all measurements). The mean HR and SD1 from the first and last seven measurements were used to assess the effects of training on cardiac vagal activity.

Effects of vigorous-intensity exercises on daily HRV. We assessed the effects of the vigorous-intensity training on daily SD1 separately for men and women in the ST group. We detected a series of three consecutive days with rest or a moderate-intensity exercise on the first day, a vigorous-intensity exercise on the second day, and rest or a moderate-intensity exercise on the third day. SD1, measured on corresponding mornings after each day of rest or exercise, was averaged case-wise (10 ± 4 series for women and 9 ± 4 series for men, n = 7 for both) and represented the mean response to the vigorous-intensity exercise within each case. Similarly, we detected a series of four consecutive days that included two subsequent days of vigorous-intensity exercises (5 ± 2 series for women and 4 ± 2 series for men).

Training load and fatigue sensation. Training load was assessed by calculating training impulse (TRIMP) using the following formula: TRIMP = ABC, in which A is exercise time (min), B is HR (proportionally of HR reserve), and C is $e^{1.92B}$ for men and $e^{1.67B}$ for women (31). The subjects filled out a questionnaire in which a subjective feeling of fatigue was estimated after each training session (33), and training mode was marked. The sensation of fatigue was plotted on a visual scale between 0 and 10, with 0 corresponding to a lack of fatigue and 10 corresponding to a maximal feeling of fatigue.

Statistical methods. The Gaussian distribution of the data was assessed with the Shapiro–Wilk goodness-of-fit test. The effects of a vigorous-intensity training on daily HR were analyzed by one-way ANOVA for repeated measures, separately for men and women, using Bonferroni *post hoc*

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TABLE 1. Characteristics of the test subjects divided into ST training, training by different HRV-based prescription (HRV-I and HRV-II), and control groups.

	Men			Women			
	ST (n = 7)	HRV-I (n = 7)	Control (n = 7)	ST (n = 7)	HRV-I (n = 7)	HRV-II (n = 10)	Control (n = 8)
Age (yr)	37 ± 3	35 ± 4	34 ± 4	34 ± 4	33 ± 4	35 ± 4	34 ± 4
Min–max	33–39	30–39	30–40	28–40	29–40	30–40	29–39
Height (m)	1.79 ± 0.06	1.79 ± 0.04	1.81 ± 0.04	1.68 ± 0.07	1.64 ± 0.03	1.65 ± 0.05	1.66 ± 0.08
Weight (kg)	81 ± 14	82 ± 9	81 ± 7	67 ± 6	64 ± 5	64 ± 9	65 ± 12
BMI (kg·m^{-2})	25 ± 3	26 ± 2	25 ± 2	24 ± 2	24 ± 1	24 ± 3	23 ± 3
Min–max	22–29	22–29	23–28	21–27	22–26	19–28	20–29

Values are means ± SD.

TABLE 2. Realized training in ST and training according to different HRV-based prescriptions (HRV-I and HRV-II).

	Men		Women		
	ST (*n* = 7)	HRV-I (*n* = 7)	ST (*n* = 7)	HRV-I (*n* = 7)	HRV-II (*n* = 10)
Exercises per week	5.3 ± 0.6	5.8 ± 0.2*	5.0 ± 0.8	5.8 ± 0.3*	5.0 ± 0.3**
Vigorous-intensity exercises per week	3.1 ± 0.5	3.1 ± 0.3	2.8 ± 0.6	3.3 ± 0.2	1.8 ± 0.3*,**
Moderate-intensity exercises per week	2.1 ± 0.1	2.7 ± 0.2*	2.2 ± 0.2	2.5 ± 0.3*	3.3 ± 0.3*,**
Mean TRIMP per week	492 ± 91	515 ± 49	343 ± 107	390 ± 42	314 ± 46**
Subjective feeling of fatigue	5.2 ± 0.8	5.2 ± 1.4	4.0 ± 1.6	4.2 ± 1.8	3.6 ± 1.2
Training mode (%)					
Walking or running	58 ± 22	48 ± 15	70 ± 16	65 ± 14	61 ± 27
Cycling	11 ± 8	15 ± 10	6 ± 6	16 ± 16	14 ± 16
Other	31 ± 26	37 ± 30	25 ± 19	19 ± 16	25 ± 25

Values are means ± SD.
* $P < 0.05$ compared with the ST group.
** $P < 0.05$ compared with the HRV-I group.

test. Because SD1 had a non-Gaussian distribution in this setting, Friedman test was applied, followed by Wilcoxon test as a *post hoc* test. The effects of training were analyzed by two-factor ANOVA with time and interventions, followed by a *post hoc* analysis using paired *t*-test between pre- and posttraining values within each group. In this statistical setting, all variables had normal Gaussian distribution. ANCOVA with Bonferroni *post hoc* test was used to compare differences in the changes in $\dot{V}O_{2peak}$, $Load_{max}$, HR, and SD1 between the groups, using the baseline value as a covariate. The changes in all these variables were normally distributed. Differences in training realization among the ST, HRV-I, and HRV-II groups were analyzed by ANOVA, followed by Bonferroni as a *post hoc* test. The Kruskal–Wallis test, followed by Mann–Whitney *U*-test as a *post hoc* test, was used for variables having a non-Gaussian distribution (total exercises per week, moderate-intensity exercises per week, mean TRIMP per week and training modes for men, moderate-intensity exercises per week, mean TRIMP per week and training modes for women). The data were analyzed using SPSS software (SPSS 14.0; SPSS Inc, Chicago, IL). A *P* value < 0.05 was considered statistically significant.

RESULTS

The final series consisted of 7 subjects for each group among men and 7 for the ST and HRV-I groups, 10 for the HRV-II group, and 8 for the control group among women (Table 1). Four subjects terminated the study because of illness or injury and three subjects were excluded because of insufficient compliance with the training. The cardiorespiratory fitness class was 4.4 ± 1.3 for women and 5.5 ± 1.1 for men ($P = 0.007$) before the intervention. The training realization is presented in Table 2.

Daily HRV after vigorous-intensity exercises. We found no significant changes in mean HR in men or women after either a single vigorous-intensity exercise (P = 0.969 and P = 0.142 for main effects, respectively) or two consecutive vigorous-intensity exercises (P = 0.448 and P = 0.214 for main effects, respectively; Figs. 1A and C). No significant changes in SD1 were observed in men after a single or two successive vigorous-intensity exercises (P = 0.565 and P = 0.815 for main effects, respectively; Figs. 1B and D). In women, SD1 was decreased on the day after a single vigorous-intensity exercise (P = 0.018) and was increased after a day of rest or a moderate-intensity exercise (P = 0.047; Fig. 1B). Two consecutive vigorous-intensity exercises further decreased the SD1 values (P = 0.028 between

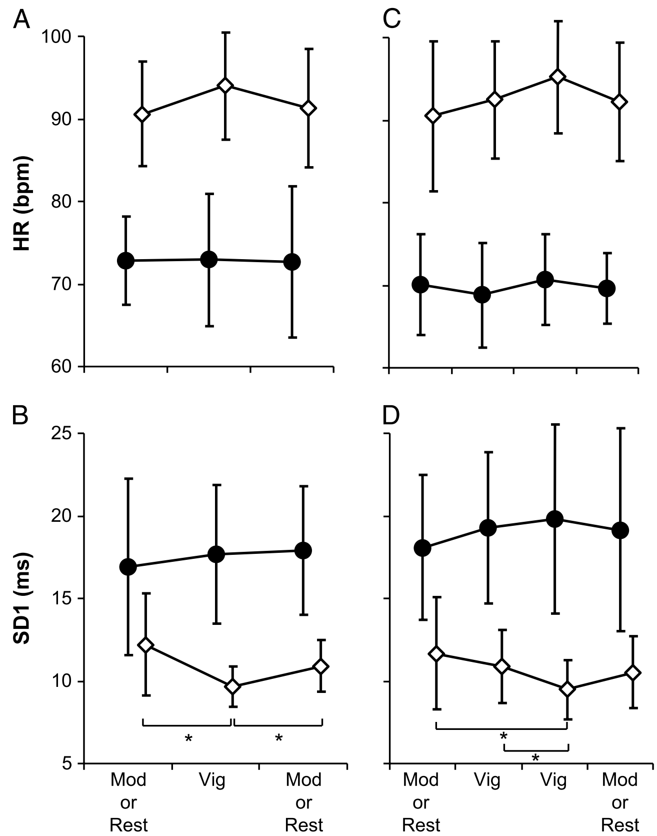

FIGURE 1—Poincaré plots of day-to-day responses of HR (A and C) and SD1 (B and D) to a single (A and B) and two consecutive vigorous-intensity (Vig) exercises (C and D) among men and women who trained in the standard training group. The HR and SD1 values correspond to the measurement taken on the morning after a resting day, after a moderate-intensity exercise (Mod), or a vigorous-intensity exercise. In men, SD1 was unaffected by exercises at vigorous intensity. Women showed significant decreases in SD1, which increased after a moderate-intensity training or resting day after a day of single vigorous-intensity exercise, but not in the case of two consecutive vigorous-intensity exercises. The values are means ± SD. *P < 0.05.

TABLE 3. $\dot{V}O_{2peak}$, $Load_{max}$, and HR and SD1 as Poincaré plots, analyzed from the home recordings as the 7-d mean, before and after the training period in the men divided into ST, HRV-I, and control groups.

	ST (n = 7)		HRV-I (n = 7)		Control (n = 7)	
	Pre	Post	Pre	Post	Pre	Post
$\dot{V}O_{2peak}$						
$L \cdot min^{-1}$	3.96 ± 0.52	4.14 ± 0.53**	4.04 ± 0.35	4.33 ± 0.31**	3.96 ± 0.50	4.05 ± 0.55
$mL \cdot kg^{-1} \cdot min^{-1}$	50 ± 7	53 ± 7*	50 ± 6	54 ± 6**	49 ± 6	50 ± 6
$Load_{max}$ (W)	275 ± 28	293 ± 35**	270 ± 29	300 ± 25**	277 ± 37	274 ± 36
HR (bpm)	73 ± 7	73 ± 6	84 ± 15	78 ± 11	—	—
SD1 (ms)	19.2 ± 5.1	19.2 ± 4.4	13.7 ± 6.7	16.9 ± 8.7*	—	—

Values are means ± SD.
* $P < 0.05$, compared with pretraining values.
** $P < 0.01$, compared with pretraining values.

the baseline and second vigorous-intensity exercise and P = 0.018 between the first and second vigorous-intensity exercises), and no significant recovery was observed thereafter (P = 0.091 between the second vigorous-intensity exercise and after day of rest or a moderate-intensity exercise; Fig. 1D). No differences between women and men were found in training mean HR and subjective feeling of fatigue during vigorous-intensity exercises. TRIMP for vigorous-intensity exercises seemed to be lower in women compared with that in men (86 ± 11 vs 113 ± 7, P = 0.002).

Training responses in men. $Load_{max}$ and $\dot{V}O_{2peak}$ increased in men in both the ST and HRV-I groups (Table 3; $P < 0.05$ for all). The change in $\dot{V}O_{2peak}$ did not differ between the ST and HRV-I groups (Fig. 2A; P = 0.156), but the change in $Load_{max}$ was higher in the HRV-I group than in the ST group (Fig. 2B; P = 0.033). SD1 increased in the HRV-I group (P = 0.018; Table 3) but not in the ST group. No changes were observed in HR in either group, and the changes in HR (P = 0.465) and SD1 (P = 0.051) did not differ between the training groups.

The HRV-I group performed more exercises (P = 0.010) and, specifically, moderate-intensity exercises than the ST group (P = 0.002; Table 2). The frequency of vigorous-intensity exercises, TRIMP, subjective feeling of fatigue, and training modes did not differ between the training groups (P = 0.522, P = 0.570, P = 0.897, and P = 0.317–0.520, respectively).

Training responses in women. $Load_{max}$ and $\dot{V}O_{2peak}$ increased in women in all the training groups ($P < 0.05$; Table 4). No differences were found in the changes in $\dot{V}O_{2peak}$ and $Load_{max}$ between the training groups (Figs. 2C and D). HR and SD1 showed significant time effects ($P < 0.001$ for both) without a time–group interaction (P = 0.622 and P = 0.239, respectively). The changes in HR (P = 0.585) and SD1 (P = 0.306) did not differ between the training groups.

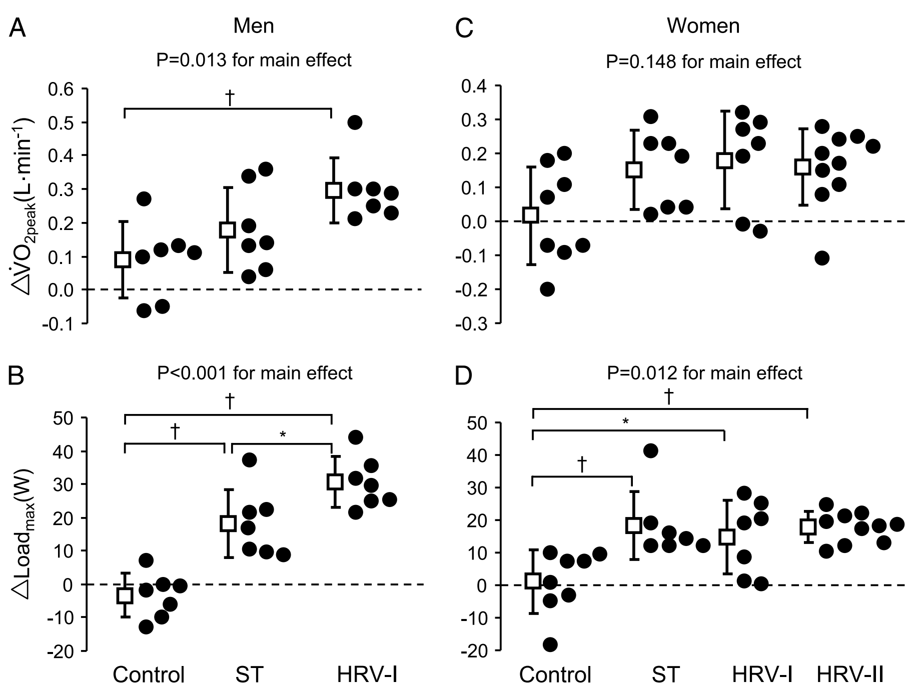

FIGURE 2—Changes in peak oxygen consumption ($\dot{V}O_{2peak}$; A and B) and maximal workload ($Load_{max}$; C and D) during the training intervention in men (A, C) and women (B, D) divided into HRV-guided training (HRV-I and HRV-II), standard training (ST), and control groups. Among men, a better response to endurance training in $Load_{max}$ was observed in the HRV-I group than in the ST group in terms of $Load_{max}$. No significant differences between the training groups were found in women. The results were the same when comparing relative changes in these variables. Values are means ± SD. *$P < 0.05$, †$P < 0.01$.

TABLE 4. $\dot{V}O_{2peak}$, $Load_{max}$, and HR and SD1 as Poincaré plots, analyzed from the home recordings as the 7-d mean, before and after the training period in the women divided into ST, HRV-I and HRV-II, and control groups.

	ST, (*n* = 7)		HRV-I, (*n* = 7)		HRV-II, (*n* = 10)		Control, (*n* = 8)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
$\dot{V}O_{2peak}$								
$L \cdot min^{-1}$	2.33 ± 0.46	2.48 ± 0.48*	2.28 ± 0.43	2.46 ± 0.38*	2.34 ± 0.45	2.50 ± 0.39**	2.56 ± 0.36	2.57 ± 0.38
$mL \cdot kg^{-1} \cdot min^{-1}$	35 ± 5	37 ± 4*	36 ± 4	39 ± 3**	37 ± 5	40 ± 5**	40 ± 6	40 ± 5
$Load_{max}$ (W)	179 ± 32	198 ± 35**	174 ± 28	189 ± 25**	177 ± 26	194 ± 23**	201 ± 22	202 ± 22
HR (bpm)	95 ± 9	87 ± 7	93 ± 12	88 ± 13	90 ± 13	84 ± 10	—	—
SD1 (ms)	10.3 ± 2.6	11.9 ± 2.0	11.6 ± 4.5	15.8 ± 7.3	11.3 ± 2.3	15.7 ± 4.0	—	—

Values are means ± SD.
* $P < 0.05$, compared with pretraining values.
** $P < 0.01$, compared with pretraining values.

The HRV-II group had an exercise frequency similar to that of the ST group ($P = 1.000$) but lower than that of the HRV-I group ($P = 0.021$; Table 2). The HRV-II group did less vigorous-intensity exercises than the ST and HRV-I groups ($P < 0.001$ for both) but more moderate-intensity exercises than the ST and HRV-I groups ($P = 0.001$ for both). TRIMP was lower in the HRV-II group than in the HRV-I group ($P = 0.006$) but similar to the ST group ($P = 0.845$). No differences were found in fatigue sensation between the training groups and training modes ($P = 0.650$ and $P = 0.549$–0.868 for main effects, respectively).

DISCUSSION

The present study showed that HRV-based exercise prescription that was found beneficial for men did not provide similar benefits in training responses of cardiorespiratory fitness among moderately active women. This may be related to differences in the recovery of cardiac vagal activity, as measured by HRV techniques, which was perturbed longer after vigorous-intensity exercises in women compared with that in men. When this is taken into consideration in HRV-based training prescription by timing vigorous-intensity exercises more carefully on days when HRV is increased, women benefit more from HRV guidance than from standard training prescription on the basis of weekly training goals by achieving significant improvement in cardiovascular fitness with a lower frequency of vigorous-intensity exercises.

Owing to the wide interindividual variation in responsiveness to exercise training (4,18,39), individualized training programs are required to improve training responses in those with poor response to standardized training. In our recent study, we introduced an exercise training program on the basis of daily HRV measurements (26). The rationale for HRV-guided training prescription is based on 1) a higher baseline level of vagally mediated HRV being associated with greater improvements in cardiorespiratory fitness, indicating that high cardiac vagal activity is related to a favorable physiological condition for exercise training (18,21); 2) HRV providing important information on the periodization of exercise training (14,23,33); and 3) recovery from a single bout of exercise (6,13,17,32).

We assessed the effects of a vigorous-intensity training, meant to be the main component in training adaptations, on daily HRV. This was performed among subjects in the standard training groups with periods of one to two vigorous-intensity exercises that were preceded and followed by rest or by a moderate-intensity exercise, thus having no HRV guidance determining their daily training sessions. First, we found that vigorous-intensity exercises on a single day or on two consecutive days did not perturb SD1 on the following mornings in men, indicating that the vigorous-intensity exercises of the present training intervention were probably not the main component causing variation in daily SD1. It is plausible to expect that vagally mediated HRV indexes are attenuated during the acute phase of recovery after vigorous-intensity exercises (13,32). This suggests that cardiac vagal activity measured by SD1 may have been decreased after exercise, but it was recovered on the morning after the day of exercise in men. In women, we found decreased SD1 after a single vigorous-intensity exercise, which was recovered after the day of rest or a moderate-intensity exercise. Secondly, we observed further decreases in SD1 during two successive vigorous-intensity exercises without significant recovery after the day of rest or a moderate-intensity exercise after vigorous-intensity exercises. We suggest that these vigorous-intensity exercises performed at ~85% of HR_{peak} perturb cardiac vagal activity longer in women than in men. Previous studies have mainly shown no gender differences in HR and HRV during the acute phase of postexercise recovery, whereas there are inconsistent results regarding postexercise hemodynamics (5,7,11,30). Gender differences in the long-term (up to 48 h) recovery of cardiac autonomic regulation after endurance-type exercise have not been reported previously. Mourot et al. (32) showed that a high-frequency oscillation of RR intervals, quantifying vagal modulation of HR similar to SD1, recovers to the baseline within 24 h after constant (~45 min at ~91% of maximal HR) and intermittent (45 min at ~87% of maximal HR) submaximal exercises measured both at supine rest and during an upright position among trained men. Furlan et al. (13) also observed that the absolute high-frequency spectral power of RR interval oscillations was recovered 24 h after intermittent exercise to exhaustion (30 min), although the normalized value was still decreased. In these studies, the relative workload was higher compared with the present study. Still, cardiac vagal activity returned to baseline within 24 h after exercise in men.

The gender differences in HRV responses to a vigorous-intensity training could be explained by lower absolute and relative fitness level in women compared with that in men, which was observed despite the similar training status. In contrast, although no differences were observed between women and men in the mean HR and subjective feeling of fatigue during vigorous-intensity exercises, TRIMP during vigorous-intensity exercises was lower in women than in men, which can partly compensate the difference in relative fitness regarding the HRV responses to a vigorous-intensity training. Therefore, other factors such as circulating reproductive hormone levels and higher probability for excessive heat stress after an acute exercise among women may be involved (8,24). Interestingly, Carter et al. (7) have observed greater acute postexercise hypotension in women. This was because of the larger decrease in cardiac output and lesser increase in total peripheral resistance compared with men during recovery. It is not known how long these differences persist after exercise. In addition, women also exhibit less α-adrenergic control of vasoconstriction (16). It is possible that these differences are sustained during longer-term recovery, resulting greater cardiac vagal withdrawal during orthostatic stress compared with men day after a vigorous-intensity exercise.

The present results confirm that an HRV-based daily exercise prescription is beneficial in men in training responses in cardiorespiratory fitness. In conjunction with our previous study, differences in training responses were observed mainly in the maximal performance during a bicycle ergometer test because no significant differences were found in the changes in $\dot{V}O_{2peak}$. Although the results followed the same pattern in less active men as in highly active men in our previous study (26), there is an important difference in the training regimens of these studies. In the present study, standard training was based on weekly goals instead of a daily fixed training program. This allowed the participants in the standard training group to adjust subjectively their training program according to their weekly routines, which is closer to real-life conditions. This underlines that HRV-guided training may provide benefits over subjectively decided training periodization among moderately active men. Moreover, although the frequency of training sessions was higher in the HRV-guided training group, this was attributable to the higher incidence of moderate-intensity exercises, thus, still resulting in a similar total training load. However, it is possible that not only the periodization but also the frequency of a moderate-intensity exercise will have an important function in training adaptations, as observed in elite endurance athletes (35).

In women, we found that an HRV-based daily training prescription, observed to be beneficial in men (HRV-I), did not result in higher improvements in cardiorespiratory fitness than standard training. Importantly, we observed that cardiac vagal activity was decreased longer after vigorous-intensity exercises in women than in men. Therefore, a different method of HRV-based training prescription should be applied to women. The rationale for HRV guidance in men was based more on the detection of decreased HRV, resulting in the lowering of the training stimulus or in rest. For women, we developed another HRV-guided training regimen (HRV-II) where the timing of vigorous-intensity exercises was more important. In this HRV-guided training prescription, a vigorous-intensity exercise was prescribed only when SD1 was found to be at least the same as the 10-d average and increasing from the previous day. In the HRV-I, vigorous-intensity training could be prescribed even if SD1 is less than the 10-d average. This allowed women to have more of a "buffer" against a forthcoming decrease in HRV induced by a vigorous-intensity exercise. This training scheme resulted in a significant decrease in the frequency of a vigorous-intensity exercise, allowing a longer recovery period without excluding the possibility of consecutive vigorous-intensity exercises when HRV was favorable. We observed that HRV-guided training, tailored for women, resulted in similar improvements in cardiorespiratory fitness as training based on standard weekly based prescription and HRV-based training beneficial for men, by performing less vigorous-intensity training. Because women had lower absolute and relative fitness in the present study than men, it remains partly unclear whether different training regimen was needed because of the lower fitness level or gender. Together with our previous study, among highly active men (26), the present results suggest that HRV-guided training is beneficial regardless of relative fitness in men. Taken together, HRV-guided training tailored for women showed the best dose–response ratio among those prescribed for women in the present study, and future studies will show if similar HRV guidance is beneficial also among highly active women.

Recent studies have shown an evident dose–response relationship between training load and response in cardiorespiratory fitness among women (9,37). Interestingly, we did not observe such a dose–response relationship between training load and the changes in cardiorespiratory fitness in women, although there were marked differences in training characteristics. Our findings do not refute the dose–response relationship in exercise training observed previously among women but rather underlines that daily periodization on the basis of HRV has an important contribution to training responses, regardless of training load.

Implications. Current recommendations for exercise training do not suggest that aerobic exercise should be prescribed differently for women and men (1). This is based on previous studies showing that gender is not a major determinant of responsiveness of cardiorespiratory fitness to aerobic exercise training at the population level because heterogeneity in training responses occurs in both sexes (4). However, because of the gender differences in both acute and chronic metabolic responses to exercise training, gender should be taken into consideration in an individualized training program (8). The present study suggests that HRV may serve as an objective tool for tailoring an aerobic

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training program not only in men but also in women. Future studies will show if HRV-guided exercise prescription is a valid tool to optimize responses to resistance and supramaximal training among moderately active subjects as well as among athletes. From the clinical perspective, our present study is limited to training responses in cardiorespiratory fitness, which is an important predictor of cardiovascular morbidities (12). Because heterogeneity in responsiveness to exercise training is a broader phenomenon that involves other clinically important factors, such as blood pressure, HR response to exercise and recovery, and glucose and lipid metabolism (2,3,19), the possible benefits of HRV-based training prescription in this respect remain unclear.

Limitations. Measurements performed at home may not be as highly standardized as those performed in laboratory conditions. Our aim was to test the applicability of HRV in training prescription in a real-life scenario that is more convenient for the participants. By these means, we also avoided possible confounding psychophysiological effects of laboratory conditions on cardiovascular measurements (15). However, uncontrolled factors such as the nighttime sleep or other psychological and physiological stressors may contribute to daily HRV, and their significance in HRV-based training prescription remains unclear. In addition, the subjects were allowed to decide the time of day for exercise, which resulted in variation in the period from exercise to measurement the following morning (12–24 h). Therefore, we cannot provide a more specific time frame for HRV recovery after vigorous-intensity exercises. Training mode was self-selected, which can confound the training responses measured during bicycle ergometer test according to training specificity. However, we did not observe any differences in training mode between the training groups. Instead of using the high-frequency power of RR interval oscillations in training prescription, as we did in our previous study, we used SD1 calculations that were implemented on an HR monitor. This involves simpler algorithms and is an existing feature in current HR monitors. SD1 has shown a high correlation to other beat-to-beat HRV indexes, such as high-frequency power of RR interval oscillations, and therefore, it likely did not affect the present results (40). Decreasing trend for SD1 was defined on the basis of absolute values, although relative values might be more appropriate. However, a different definition for decreasing trend in SD1 was used when SD1 was <20 ms than when SD1 was ≥20 ms, partly reducing this disadvantage. Finally, we did not adjust training for the menstrual cycle. Although estrogen-induced increases in cardiac vagal outflow, as assessed by HRV, have been observed in women (28,29), no differences in vagal control of the heart have been observed between the different phases of the menstrual cycle (10,28).

CONCLUSIONS

Cardiorespiratory fitness can be effectively improved during endurance training by using daily HRV for exercise prescription and may have benefits over subjectively decided training periodization in moderately active men. Because women are more susceptible to longer recovery of HRV after a vigorous-intensity training, a different HRV-guided training program, where vigorous-intensity training is performed on days with increased HRV, is required for women. By these means, women benefit from HRV guidance by achieving similar improvements in cardiovascular fitness by performing less vigorous-intensity exercises.

The authors have no conflict of interest to disclose.

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