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## Individual Endurance Training Prescription with Heart Rate Variability

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**Running title:** HRV-guided endurance training

## ABSTRACT

**Introduction:** Measures of heart rate variability (HRV) have shown potential to be of use in training prescription. **Purpose:** The aim of this study was to investigate the effectiveness of using HRV in endurance training prescription. **Methods:** Forty recreational endurance runners were divided into the HRV-guided experimental training group (EXP) and traditional, predefined training group (TRAD). After a 4-week preparation training period, TRAD trained according to a predefined training program including 2-3 moderate (MOD) and high intensity training (HIT) sessions per week during an 8-week intensive training period (INT). The timing of MOD and HIT sessions in EXP was based on HRV, measured every morning. MOD/HIT session was programmed, if HRV was within an individually determined smallest worthwhile change (SWC). Otherwise, low intensity training was performed. Maximal oxygen consumption ( $VO_{2max}$ ) and 3000 m running performance (RS3000m) were measured before and after both training periods. **Results:** The number of MOD and HIT sessions were significantly lower ( $P = 0.021$ ,  $ES = 0.98$ ) in EXP ( $13.2 \pm 6.0$  sessions) compared with TRAD ( $17.7 \pm 2.5$  sessions). No other differences in training were found between the groups. RS3000m improved in EXP ( $2.1 \pm 2.0\%$ ,  $P = 0.004$ ), but not in TRAD ( $1.1 \pm 2.7\%$ ,  $P = 0.118$ ) during INT. A small between-group difference ( $ES = 0.42$ ) was found in the change of RS3000m.  $VO_{2max}$  improved in both groups (EXP:  $3.7 \pm 4.6\%$ ,  $P = 0.027$ ; TRAD:  $5.0 \pm 5.2\%$ ,  $P = 0.002$ ). **Conclusion:** The results of the present study suggest the potential of resting HRV to prescribe endurance training by individualizing the timing of vigorous training sessions.

**Key Words:** Running Training, Training Adaptation, Autonomic nervous system, Vagal activity, Training Programming

## INTRODUCTION

Large individual variation in training adaptation has been observed after standardized endurance training. It is typical that some individuals show great improvements (even to 40 %) in maximal oxygen uptake ( $VO_{2max}$ ) or endurance performance after standardized endurance training, while some individuals show no changes or *sometimes* even a decrement in endurance performance (5, 7, 36). In our previous study (34), a slightly smaller variation in improvement of endurance performance was observed after 8 weeks of both high intensity (HIT) (0 – 10.2%) and low intensity training (LIT) (-2.8 – 4.1%), when training volume and frequency were individualized according to individuals' previous training history. However, some non-responders (change in endurance performance  $\leq 0\%$ ) were observed, which proposes that a more precisely and comprehensively individualized training program would be beneficial for achieving greater improvements and smaller variation in the adaptation to training.

Cardiac autonomic regulation is an important determinant of endurance training adaptation. Baseline vagal mediated resting heart rate variability (HRV) has been shown to be related to greater improvements in  $VO_{2max}$  and endurance performance after endurance training in different populations (2, 12, 13, 33, 34). In addition, increased resting HRV during a training period has been related to improvements of endurance performance or  $VO_{2max}$  (6, 7, 10, 12, 22).

It has been proposed that training prescription according to the status of cardiac vagal activity may be a beneficial method to improve endurance training adaptation. Kiviniemi et al. (18, 19) expressed promising results while using HRV in daily training prescription. Individuals who prescribed HIT sessions according to HRV, showed greater improvements in  $VO_{2max}$  among

moderately fit men (19) and in endurance performance among healthy (18, 19) compared with individuals who trained according to a traditional, predefined training program. Women benefitted from HRV guidance by achieving the same significant improvement in endurance performance with a lower amount of HIT compared with predefined training (18, 19). In studies of Kiviniemi et al. (18, 19) training prescription was based on daily, single HRV measurements. However, Plews et al. (24) suggested that it is more valuable to use longer trends of HRV, e.g. a week rolling average compared with assessing its value on a single day. In addition, Plews et al. (25) proposed to use individual's own HRV profile, the individual smallest worthwhile change (SWC), which reflects normal values of HRV, in interpreting HRV values and training prescription.

While determinants of endurance performance are widely accepted, the optimal training volume and intensity distribution is still indefinite (31). The majority of endurance training studies presents a high proportion of high volume, LIT among endurance athletes, but also a polarized training model with a higher amount of HIT has proposed to be an effective training model especially in high level athletes (21, 30). Furthermore, increasing training intensity would be more effective compared with increasing training volume also in sedentary adults (28). Recent studies have shown that changing the periodization of LIT and HIT without changing the training intensity distribution may have a positive effect on performance improvement (26, 27). Traditionally, periodized endurance training includes usually single HIT sessions, e.g. two times per week, simultaneously with low- and moderate-intensity training trying to develop many fitness components at the same time. On the contrary, block training includes shorter training periods (1-4 weeks), when the aim is to develop a few selected fitness components (17).

Recently, it has been suggested that block periodization of HIT may provide superior training adaptation compared with traditionally organized HIT (26, 27). However, the timing of HIT blocks has been typically determined subjectively without objective information about athlete's training status. A good recovery status may be needed before an intense training block for avoiding imbalance between training load and recovery.

Endurance training programs are typically predetermined based on literature, general recommendations and experience of coaches regardless of objective information about athlete's training and recovery status. In addition, adaptation to endurance training is individual and the same training program would not be optimal for everyone in spite of similar training background. Furthermore, more individualized, objective training prescription may improve training adaptation. The aim of this study was to investigate the effectiveness of using HRV averaged over 7 days in endurance training prescription on endurance training adaptation compared with traditional, predefined endurance training in recreational endurance runners. It was hypothesized that HRV-guided training would result in greater adaptations to training (18, 19).

## **METHODS**

**Subjects.** Forty recreational endurance runners (20 women, 20 men) were recruited by advertising in the local newspaper and social media to participate in the study. The minimal sample size was determined based on the data of Vesterinen et al. (35) and Stöggl & Sperlich (30) (expected change in maximal running speed  $3 \pm 3\%$  and  $5 \pm 3\%$ ). A priori power analysis suggested that 16 subjects were required for both groups to achieve 80% power and a

significance level of 5%. The subjects did not have any diseases or use regular (e.g. daily) medication for any kind of chronic or long-term diseases. They had at least 2 years of regular endurance running training background. Age,  $VO_{2max}$ , regular training background and weekly running kilometers during the previous two months were for women  $34 \pm 8$  years,  $49 \pm 4$  mL·kg<sup>-1</sup> min<sup>-1</sup>,  $13 \pm 8$  years and  $34 \pm 22$  km; and for men  $35 \pm 7$  years,  $56 \pm 5$  mL·kg<sup>-1</sup> min<sup>-1</sup>,  $15 \pm 8$  years and  $39 \pm 19$  km. After being fully informed about the study design and the possible risks, all subjects provided a written informed consent document. The study was approved by the Ethics Committee of the local University.

**Study Design.** The study protocol included two training periods; a 4-week preparation period (PREP) and an 8-week intensive training period (INT). All measurements were performed before and after both training periods on weeks 0, 5 and 14. For INT, the subjects were matched into pairs according their baseline background (sex, age, training background), endurance performance characteristics ( $VO_{2max}$ , 3000-m running time) and HRV. Thereafter, within each pair, the runners were randomized into the HRV-guided experimental training group (EXP) and traditional, predefined training group (TRAD).

**Maximal running tests.** The subjects were asked not to do any vigorous physical activity two days prior to the running tests. The subjects performed an incremental treadmill test, starting at 7 km·h<sup>-1</sup> for women and at 8 km·h<sup>-1</sup> for men, and followed by an increase of 1 km·h<sup>-1</sup> every third minute until volitional exhaustion. The incline was kept at 0.5 degrees during the whole test. HR was recorded continuously using a heart rate monitor (Suunto t6, Suunto Ltd, Vantaa, Finland). Oxygen consumption was measured breath-by-breath throughout the test using a



portable spiroergometer (Oxycon Mobile, Viasys Health Care, Würzburg, Germany). After each 3-min stage the treadmill was stopped for about 15-20-s for fingertip blood samples (20  $\mu$ L) and blood lactate (La) analysis. Blood lactate was determined using Biosen S\_line Lab+ lactate analyzer (EKF Diagnostic, Magdeburg, Germany). The highest 60-s VO<sub>2</sub> value during the treadmill test was considered as maximal oxygen uptake (VO<sub>2max</sub>). The determination of lactate thresholds was based on a rise and change in the inclination of the blood lactate curve during the test (11). Lactate threshold 1 (LT1) was set at 0.3 mmol·L<sup>-1</sup> above the lowest lactate value. Lactate threshold 2 (LT2) was set at the intersection point between 1) a linear model between LT1 and the next lactate point and 2) a linear model for the lactate points with La increase of at least 0.8 mmol·L<sup>-1</sup>.

For determining maximal endurance performance, the subjects performed the 3000-m running test on a 200-m indoor track before and after both training periods. Time and the mean running speed of the 3000-m (RS<sub>3000m</sub>) were calculated. At least two easy training days were prescribed between the treadmill test and 3000-m running test.

**Training.** During PREP, all subjects were asked to maintain the same training volume as before the study. The period followed a periodization model of three hard training weeks followed by an easy training week with progressively increasing intensity throughout the period (Table 1). Endurance training was mainly running but the subjects were encouraged to do at least one easy session per week in some other training mode than running (i.e. cycling or cross-country skiing). In addition, muscle endurance circuit training was instructed to be performed once a week.

**Predefined training.** For INT, all subjects were instructed to maintain the same training volume as during PREP. The TRAD-group trained according to a predefined training program, which included approximately 50% of weekly training sessions performed at low intensities (LIT, below LT1) and the other 50% at moderate (MOD)/high intensities (HIT), with the week periodization 3:1 as during PREP (Table 1). The main training sessions at moderate and high intensities were similar to training sessions during PREP in both groups.

**HRV guided training.** All subjects in EXP were instructed to measure their R-R interval data at home every morning after awakening and emptying their urinary bladder. Omegawave Pro Mobile System, with a two-lead chest belt (Omegawave Ltd., Helsinki, Finland) was used to record R-R intervals. Four minutes of recording was performed in supine position and the subjects were allowed to breathe spontaneously. R-R interval data was analyzed in Omegawave cloud service and vagal related, the square root of the mean squared differences of successive R-R intervals (RMSSD), was selected to be used in training prescription due to its greater reliability than other HRV spectral indices (1). Further, a 7-day rolling average of RMSSD (RMSSD<sub>7day</sub>) was calculated because it has been proposed to be more sensitive to track changes in training status compared with single-day values (24).

The basic idea of using HRV in endurance training prescription was to decrease training intensity when cardiac vagal activity differed meaningfully from the regular level based on the findings of Plews et al. (24, 25). Thus, the smallest worthwhile change (SWC) of RMSSD<sub>7day</sub> for each subject in EXP was determined, as  $\text{mean} \pm 0.5 * \text{SD}$ , from RMSSD values of four weeks over PREP based on observations by Plews et al. (24, 25) and Kiviniemi et al. (18, 19) (Fig. 1).

When  $RMSSD_{7day}$  was within the SWC, only MOD and HIT sessions were performed. If  $RMSSD_{7day}$  fell outside the SWC, the subjects trained only at low intensities or rested. When  $RMSSD_{7day}$  returned to the mean level of the SWC, the subjects started to perform MOD and HIT sessions and continued until  $RMSSD_{7day}$  fell outside the SWC. The subjects remained the same number of training sessions and rest days on every week compared the preparation period regardless of HRV. The SWC was updated after the first four weeks of INT based on the values over the previous four weeks due to previous findings about a relationship between an increment of resting cardiac autonomic activity and improved endurance performance (6, 7, 22).

**Training monitoring.** The subjects controlled their training intensity by measuring their HR and RS during all exercises using Garmin FR 610 heart rate monitor with GPS (Garmin Ltd, Schaffhausen, Switzerland). In addition, the subjects rated their perceived exertion (RPE) and recovery feelings using the scale of 0 – 10 after each training session (3) and reported possible other stress factors e.g. sicknesses, injuries, work/school stress in their training diary via a cloud service. HR data was used for determining the times at the three different training intensity zones; low (below LT 1), moderate (between LT 1 and 2) and high (above LT 2) intensities. Weekly main training sessions were supervised by experienced members of the research group.

**Statistical analysis.** The results are expressed as means  $\pm$  standard deviations (SD). The Gaussian distribution of the data was assessed with the Shapiro–Wilk goodness-of-fit test. The adaptation to training was analyzed using repeated measures of ANOVA followed by Bonferroni as a post hoc test. Differences in the training adaptation between EXP and TRAD were analyzed by Student's t-test for independent samples and between sexes by the Kruskal-Wallis test. In

addition, the magnitudes of changes after training and differences between groups were expressed as standardized effect sizes (ES), calculated from pooled means and standard deviations (15). Threshold values for Cohen's ES statistics were <0.2 (trivial), 0.2 – 0.5 (small) 0.5 – 0.8 (moderate) and >0.8 (large) (8). Pearson's product-moment correlation coefficient was used to determine the relationships between the amount of MOD/HIT sessions and the training adaptation (change of RS3000m and  $VO_{2max}$ ). Statistical significance was accepted as  $P \leq 0.05$ . Statistical analyses were carried out using SPSS Statistics 20 software (IBM, Armonk, New York, USA).

## RESULTS

A total of 31 subjects (13 in EXP, 18 in TRAD) completed the whole study. Nine subjects dropped out due to injuries ( $n = 2$ ), sicknesses ( $n = 2$ ) and insufficient compliance with the training program (i.e. < 90% of all training sessions in EXP and more than 2 main training sessions missing in TRAD during INT,  $n = 5$ ).

No differences were observed between the groups in training during PREP (Table 2). Training volume remained similar between PREP and INT. In addition, proportions of times in different training zones remained similar. The number of MOD and HIT sessions over INT was significantly lower ( $P = 0.021$ , ES = 0.98) in EXP ( $13.2 \pm 6.0$  sessions) compared with TRAD ( $17.7 \pm 2.5$  sessions). Individual ranges in the number of MOD/ HIT sessions were from 5 to 24 sessions in EXP and from 11 to 21 sessions in TRAD.

RS<sub>3000m</sub> improved by  $2.7 \pm 2.5\%$  ( $P < 0.001$ ) and VO<sub>2max</sub> by  $2.9 \pm 4.4\%$  ( $P = 0.003$ ) over PREP. Time in the 3000-m running test improved in EXP ( $-14.3 \pm 14.1$  s,  $P = 0.005$ ), but not in TRAD ( $-7.8 \pm 19.8$  s,  $P = 0.111$ ) during INT. A small between-group difference was observed in the change of RS<sub>3000m</sub> (Table 3, Fig. 2). VO<sub>2max</sub> and RS<sub>LT2</sub> improved in both groups (a small between-group difference), while RS<sub>LT1</sub> improved only in EXP (a moderate between-group difference). No differences were observed in the changes of the endurance performance variables between sexes.

Individual ranges in the change of RS<sub>3000m</sub> were from -1 to 6% in EXP and from -4 to 8% in TRAD. One subject in EXP and five subjects in TRAD showed decrements in RS<sub>3000m</sub>, while other subjects improved or maintained their running performance over INT. Figure 3 presents three examples of HRV based individualization in training prescription. Subject A responded well to high amount of MOD/HIT training. The training program included three MOD/HIT blocks (total of 34 days) during INT. Subject B performed also three MOD/HIT periods but those were much shorter (total of 15 days). However, the response to the high amount of low intensity training was good. Subject C performed two 7-day periods of MOD/HIT at the beginning of INT. After that HRV was below the SWC due to work stress and the training was solely low intensity training. Subject C was the only subject who showed a decrement in the 3000-m running performance in EXP during INT. No significant correlations were found between the number of MOD/HIT sessions and the change of RS<sub>3000m</sub> ( $r = 0.42$ ,  $P = 0.17$ ) or VO<sub>2max</sub> ( $r = 0.26$ ,  $P = 0.43$ ).

## DISCUSSION

The aim of the present study was to compare training adaptation induced by HRV-guided and predefined endurance training. The main finding was that 3000-m running performance improved only in the HRV-guided training group over the 8-week intensive training period, by performing less moderate and high intensity training sessions compared with predefined training.

**Changes in endurance performance.** Vagal activity of the autonomic nervous system has widely been observed to be related to individual adaptation to endurance training e.g. (6, 7, 10, 12, 22). To our best knowledge, only a few previous studies have examined the use of HRV in endurance training prescription (4, 18, 19). In the study of Kiviniemi et al. (19), the HIT session was programmed, if high frequency power (HFP), measured on every morning, was increased or remained the same compared with the reference value of HFP (average of 10 days – SD). Otherwise, LIT or rest was programmed. The HRV-guided group showed 7% improvement in  $VO_{2max}$  and 6% improvement in maximal running performance, while the predefined group improved by 4% in running performance and maintained  $VO_{2max}$  after four weeks of training. The change in running performance was greater in the HRV-group (19). The present study expressed similar findings. Maximal running performance and  $RS_{LT1}$  improved in EXP but not in TRAD, whereas  $VO_{2max}$  and  $RS_{LT2}$  improved in both groups. The group difference in the change of running maximal performance (2.1% in EXP vs 1.1% in TRAD) was rated as small in qualitative and as non-significant in the t-test analyses. However, in practice the difference of 1% in sport performance can make the difference between winning and losing (9). The finding may suggest that it may be possible to identify more optimal timing to receive vigorous training stimulus according to HRV compared with subjectively, predefined training.

It is worth considering that the slightly greater improvement in 3000-m running performance was achieved with a lower frequency of MOD and HIT sessions in EXP compared with TRAD. Furthermore, training focused more on LIT in EXP, which may explain the greater improvement in  $RS_{LTI}$  compared with TRAD. The previous finding is in a line with the results of Kiviniemi et al. (18) among moderately trained women. The authors did not observe any differences in the training adaptation between the HRV-guided and predefined groups but the HRV-group performed less HIT sessions (1.8 vs 2.8 sessions per week) during 8 weeks of training. In addition, they proposed that a different HRV-guided program is needed for women because they are more susceptible for longer recovery of HRV (18). In the present study, no differences were observed between sexes in the training adaptation. Kiviniemi et al. (18) proposed that the gender differences in HRV responses to HIT could be explained by a lower relative fitness level in women compared with men. In the present study, the relative fitness level was even a bit higher in women (29), which can explain the contradictory findings in gender differences between the present study and the study by Kiviniemi et al. (18). However, clarification of possible sex differences needs more investigations with larger sample sizes.

**Individual variation in the adaptation.** Large individual differences in training adaptation after standardized endurance training are common (5, 7, 36). In the present study, EXP showed a slightly smaller range (-1- 6%) in the change of  $RS_{3000m}$  compared with the predefined training group (-4 to 8%), while the individual range in the amount of HIT sessions was larger in EXP (5 to 24 sessions) compared with TRAD (11 to 21 sessions). This finding suggests that HRV based timing of HIT may be beneficial for diminishing variation in the adaptation. However, one subject in EXP failed to improve running performance during INT (Fig 3C). The subject trained

only at low intensities during the last five weeks of INT because his RMSSD values were below the SWC. Reduced HRV was mainly induced by work stress and it caused challenges to the function of the HRV based training prescription method. Regardless, it might be assumed that neither the predefined HIT training in that kind of stress state would result in optimal training outcomes and LIT is recommended for enhancing the recovery process. On the other hand, the insignificant correlation between the training adaptation and the number of MOD/HIT sessions showed that the adaptation to training was independent of the amount of vigorous sessions. Some individuals responded well to the high amount of MOD and HIT (Fig 3A), while other individuals (Fig 3B) achieved good responses with the smaller dose of MOD/HIT sessions. This can be partly explained by our previous finding (34), which showed that some individuals respond better to LIT and some individuals to HIT. It seems also that individuals' recovery of HRV and further capacity to cope vigorous training are different. Subject A (Fig. 3) performed three HIT blocks during INT. The longest one continued 21 days and included 15 MOD/HIT sessions. During the blocks, recovery feeling decreased and HRV changed relatively slowly from the regular level, while some individuals' HIT blocks were remarkable shorter. Thus, individualized training program is needed for diminishing variation in the adaptation and increasing effectiveness of training.

**Methodological issues to use HRV in training prescription.** In the present study, the HRV based method to prescribe training was different compared with the method by Kiviniemi et al. (18, 19). We used the vagal mediated, time domain index, RMSSD, instead the HFP spectral density because it has been proposed that RMSSD has greater reliability compared with HRV spectral indices (1). Furthermore, in the present study, 7-day rolling average was used because it



provides a better representation of training adaptation by diminishing the large day-to-day variation in HRV compared with single-day values (24), which were used in the studies of Kiviniemi et al. (18, 19). An averaged value of HRV and SWC together result that one single training session does not typically change HRV more than SWC. Thus, the present method prescribes the timing of MOD/HIT blocks rather than single MOD/HIT sessions. It is closer to practical endurance athletes' training, which includes vigorous training periods, such as training camps not only single training sessions. In addition, block periodization of HIT has been proposed to provide superior training adaptation compared with traditionally organized HIT (26, 27). However, exhaustive HIT block training has mainly been used among high level athletes. Individually determined duration and timing of HIT block according to HRV may be a more approachable training model also for untrained individuals. It may be easier to avoid the imbalance between training load and recovery, when training prescription is based on the status of cardiac vagal activity. However, further studies are needed in different populations.

Instead of using a strict limit for HRV value to determine the intensity of training, which was used in the studies of Kiviniemi et al. (18, 19), we used the individual smallest worthwhile change (SWC), which reflects regular values of HRV (24, 25). When HRV value falls either below or above the SWC, it is reflecting a sign of an abnormal situation. When HRV is below the SWC, it is indicating increased sympathetic activity, which has been observed to occur after vigorous training periods reflecting insufficient recovery state (16, 23). When HRV is above the SWC, it is indicating increased vagal activity, called parasympathetic hyperactivity, which could also be a sign of functional overreaching (20) or overtraining (14, 32). The imbalance of cardiac autonomic regulation may indicate an unfavorable situation to adapt to HIT sessions. It is also

worth considering that HRV response to training is individual and it can vary in different situations. For example, it can be seen in Fig 3A that HRV decreased during the first and third MOD/HIT blocks but during the second block it oppositely increased above the SWC. As it is unknown, whether HRV should be expected to increase or decrease in the case of overreaching and overtraining, it is recommended that the HRV based training prescription method includes upper and lower limits for normal area of HRV.

Regardless of the encouraging results to use the present HRV method for training prescription, there are some uncertain issues to solve in future studies. Firstly, baseline HRV recordings for determining the SWC should not be performed under extensive stress factors, like work stress, sicknesses etc. Otherwise, the SWC does not represent a normal situation. The second issue is related to the magnitude of the SWC. In the present study, it was determined as  $\text{mean} \pm 0.5 * \text{SD}$  based on the previous findings by Plews et al. (25) and Hopkins et al. (15). The SWC should be wide enough for allowing an individual to train enough at high intensities to achieve adequate disturbances in homeostasis so that further training adaptation can be attained. On the other hand, it should give enough recovery time after HRV falls outside the SWC. That is the reason why LIT was performed until HRV returned to the mean level of the SWC, not only to the area of SWC. Performance changes and recovery feelings during INT did not reveal any signs of overtraining in the present study. Future studies should examine whether a shorter recovery time results in greater adaptations. In that case, LIT should continue until HRV is close to the mean level (e.g. within area of  $\text{mean} \pm 0.1 * \text{SD}$ ). In addition, an uncertain issue is the updating of SWC. Previous studies have expressed that resting HRV can increase as a positive result of training, especially in previously untrained and moderately trained subjects (6, 7, 10, 12,

22). Therefore, the SWC was decided to be updated after the first four weeks of INT. Although the change in the SWC was relatively small in most subjects in the present study, it is recommended to update the SWC after certain time spans, especially during longitudinal training periods.

**Limitations.** HRV measurements performed at home may not be as highly standardized as those performed in laboratory conditions. However, it is impractical to perform the measurements in the laboratory on every morning during the training period. In addition, it is possible to avoid psychophysiological effects of laboratory conditions on HRV by performing the measurements at home. In addition, the present study is limited by its relatively small number of the subjects. Unfortunately, the relatively big number of the drop-outs due to sicknesses and injuries reduced statistical power, especially in comparisons between sexes. It does not allow adequate statistical power to investigate possible sex differences with parametric analyses. Furthermore, future studies should aim to examine the usefulness of HRV in endurance training prescription among different populations from sedentary individuals to high level endurance athletes.

## CONCLUSIONS

The present study expressed that the 3000-m running performance improved only in the HRV-guided training group over the 8-week intensive training period, by performing less moderate and high intensity training sessions compared with the predefined training. In addition, individual range in the training adaptation was smaller in the HRV-guided group compared with the traditional, predefined training group. The findings may suggest that the timing of moderate

and high intensity training sessions according to HRV is more optimal compared subjectively predefined training. Therefore, HRV shows a potential tool in endurance training prescription by optimizing the timing of vigorous training sessions, although there is a need to solve some methodological issues related to the use of HRV in training prescription in future studies.

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#### **CONFLICT OF INTEREST**

The authors have no conflict of interest do disclose. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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## FIGURE LEGENDS:

FIGURE 1—Example of programming moderate and high intensity sessions in the HRV-guided experimental training group.

The grey area indicates the smallest worthwhile change of RMSSD. The black area indicates timing of moderate and high intensity training. The dashed line area indicates timing of low intensity training. The arrows represent timing of the running tests.

FIGURE 2—Changes (%) in running performance of 3000 m after the 8-week HRV-guided training (EXP) and predefined training (TRAD).

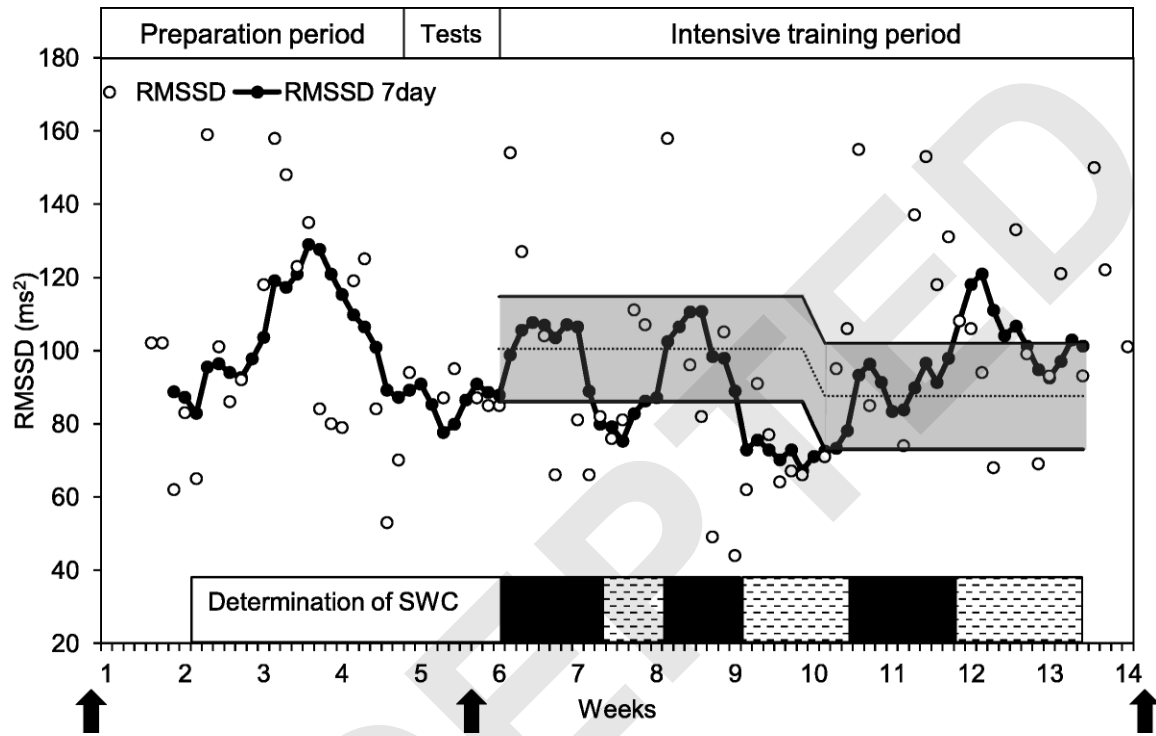
Box plots represent median values (solid line), 50<sup>th</sup> percentile values (box outline), and minimal / maximal values (whiskers).

\*\*  $P < 0.01$ , significant difference from week 5, ES = effect size in the difference between the groups.

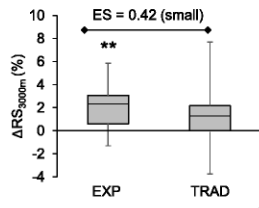
FIGURE 3—Daily changes in the square root of the mean squared differences of successive R-R intervals (RMSSD), 7-day rolling average of RMSSD and recovery feeling for subject A (good response to the high amount of high intensity training), subject B (good response to the high amount of low intensity training and subject C (poor response to the high amount of low intensity training).

The grey area indicates the smallest worthwhile change (SWC) of RMSSD. The black area indicates timing of moderate and high intensity training. The dashed line area indicates timing of low intensity training. The arrows represent timing of the running tests.

Figure 1



**Figure 2**



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Figure 3

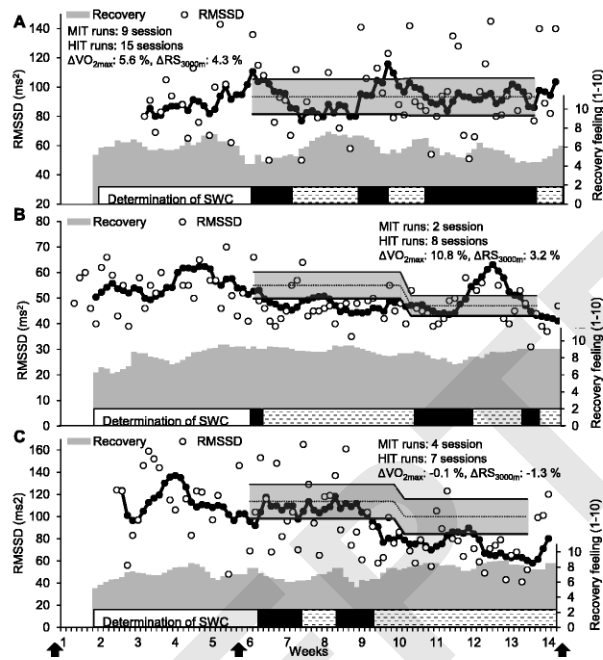


TABLE 1. Week template of the predefined training program for both groups over weeks 0 – 5 and for predefined group (TRAD) over weeks 6 – 14.

Weeks	Week periodization	Test runs	High intensity training Constant run	Intervals	Moderate run	Low intensity runs (intensity < LT1)
0	Test	3000 m run VO <sub>2max</sub> test				
1	Int				30' at 80-85%	3-6 x 6-12 km
2	Int			4x4' at 90-95% / rec 3'	40' at 80-85%	2-5 x 6-12 km
3	Int		30' at 85-90%	4x4' at 90-95% / rec 3'	40' at 80-85%	2-5 x 6-12 km
4	Rec					3-5 x 6-12 km
5	Test	VO <sub>2max</sub> test				3-5 x 6-12 km
6	Int	3000 m run	30' at 85-90%		40' at 80-85%	2-4 x 6-12 km
7	Int		30' at 85-90%	4x4' at 90-95% / rec 3'	40' at 80-85%	2-4 x 6-12 km
8	Int		30' at 85-90%	4x4' at 90-95% / rec 3'	40' at 80-85%	2-4 x 6-12 km
9	Rec					3-5 x 6-12 km
10	Int		30' at 85-90%	4x4' at 90-95% / rec 3'	40' at 80-85%	2-4 x 6-12 km
11	Int		30' at 85-90%	4x4' at 90-95% / rec 3'	40' at 80-85%	2-4 x 6-12 km
12	Int		30' at 85-90%	4x4' at 90-95% / rec 3'	40' at 80-85%	2-4 x 6-12 km
13	Rec			4x4' at 90-95% / rec 3'		3-4 x 6-12 km
14	Test	3000 m run VO <sub>2max</sub> test				2-4 x 6-12 km

Training intensities are expressed as a percentage of maximal heart rate.

All moderate and high intensity sessions started with a 15-20 min warm-up and were followed by a 15 min cool down. Moderate and high intensity runs were instructed to perform after rest or easy training day. If the number of all training sessions per week was  $\leq 4$ , only two moderate/high intensity runs were instructed to perform per week.

Int, Intensive training week; Rec, recovery week; Test, testing week; rec, recovery between intervals (intensity < lactate threshold 1); LT 1, lactate threshold 1.

TABLE 2. Training characteristics of HRV-guided experimental (EXP) and predefined (TRAD) training groups over the preparation (PREP, weeks 1-4) and intensive (INT, weeks 6-13) training periods are means  $\pm$  SD.

	EXP ( <i>n</i> = 13)		TRAD ( <i>n</i> = 18)	
	PREP	INT	PREP	INT
Training (h·wk <sup>-1</sup> )	7.1 $\pm$ 3.0	6.5 $\pm$ 2.8	7.0 $\pm$ 2.7	6.3 $\pm$ 2.5
Running (km·wk <sup>-1</sup> )	43 $\pm$ 18	42 $\pm$ 22	40 $\pm$ 23	41 $\pm$ 20
Training (times·wk <sup>-1</sup> )	6.0 $\pm$ 1.7	6.1 $\pm$ 1.8	5.9 $\pm$ 1.8	5.6 $\pm$ 1.6
Low-intensity (%)	89 $\pm$ 8	83 $\pm$ 27	88 $\pm$ 9	84 $\pm$ 12
Moderate-intensity (%)	10 $\pm$ 7	14 $\pm$ 25	10 $\pm$ 8	13 $\pm$ 10
High-intensity (%)	2 $\pm$ 3	3 $\pm$ 5	1 $\pm$ 2	3 $\pm$ 4

Low-intensity training, intensity below lactate threshold 1; Moderate-intensity, intensity between lactate thresholds 1 and 2; High-intensity, intensity above lactate threshold 2.

TABLE 3. Endurance performance variables in EXP and TRAD before (week 5) and after (week 14) the 8-week intensive training period. Values are means  $\pm$  SD.

	$VO_{2max}$ ( $mL \cdot kg^{-1} \cdot min^{-1}$ )	$RS_{3000m}$ ( $km \cdot h^{-1}$ )	$RS_{LT2}$ ( $km \cdot h^{-1}$ )	$RS_{LT1}$ ( $km \cdot h^{-1}$ )
EXP (n = 13)				
week 5	54.4 $\pm$ 6.2	15.4 $\pm$ 1.6	13.4 $\pm$ 1.4	11.0 $\pm$ 1.2
week 14	56.4 $\pm$ 7.0	15.7 $\pm$ 1.5	13.8 $\pm$ 1.3	11.3 $\pm$ 1.2
% change	3.7 $\pm$ 4.6*	2.1 $\pm$ 2.0**	2.6 $\pm$ 3.3*	2.8 $\pm$ 3.7*
ES (rating)	0.40 (small)	0.54 (mod)	0.38 (small)	0.37 (small)
TRAD (n = 18)				
week 5	53.0 $\pm$ 5.8	15.0 $\pm$ 1.6	12.8 $\pm$ 1.6	10.6 $\pm$ 1.4
week 14	55.5 $\pm$ 5.8	15.2 $\pm$ 1.5	13.1 $\pm$ 1.5	10.7 $\pm$ 1.5
% change	5.0 $\pm$ 5.2**	1.1 $\pm$ 2.7 <sup>ns</sup>	1.9 $\pm$ 2.2**	1.0 $\pm$ 2.9 <sup>ns</sup>
ES (rating)	0.49 (small)	0.14 (trivial)	0.46 (small)	0.17 (trivial)
Between group differences in responses to training				
	0.26 (small)	0.42 (small)	0.25 (small)	0.54 (mod)

\*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$  (significant difference from mid); ES = effect size; EXP, HRV-guided experimental training group; TRAD, predefined training group;  $VO_{2max}$ , maximal oxygen consumption;  $RS_{3000m}$ , running speed in 3000m running test;  $RS_{LT2}$ , running speed at lactate threshold 2;  $RS_{LT1}$ , running speed at lactate threshold 1.