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TITLE PAGE

A SUBMAXIMAL RUNNING TEST WITH POST-EXERCISE CARDIAC AUTONOMIC AND NEUROMUSCULAR FUNCTION IN MONITORING ENDURANCE TRAINING ADAPTATION

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Running head: Monitoring Endurance Training Adaptation

ABSTRACT

The aim of this study was to investigate whether a submaximal running test (SRT) with post-exercise heart rate recovery, heart rate variability and countermovement jump measurements could be used to monitor endurance training adaptation. Thirty-five endurance trained men and women completed an 18-week endurance training program. Maximal endurance performance and maximal oxygen uptake were measured every eight weeks. In addition, SRT with post-exercise heart rate recovery, heart rate variability and countermovement jump measurements were performed every four weeks. SRT consisted of two 6-minute stages at 70% and 80% of HR_{max} and a 3-minute stage at 90% HR_{max}, followed by a 2-minute recovery stage for measuring post-exercise heart rate recovery, heart rate variability and countermovement jump test. The highest responders according to the change of maximal endurance performance showed significant improvement in running speeds during stages 2 and 3 in SRT, while no changes were observed in the lowest responders. The strongest correlation was found between the change of maximal endurance performance and running speed during stage 3, while no significant relationships were found between the change of maximal endurance performance and the changes of post exercise heart rate recovery, heart rate variability and countermovement jump. Running speed at 90% HR_{max} intensity was the most sensitive variable to monitor adaptation to endurance training. The present submaximal test showed potential to monitor endurance training adaptation. Furthermore, it may serve a practical tool for athletes and coaches to evaluate weekly the effectiveness of training program without interfering normal training habits.

Key Words: running, training, performance, heart rate recovery, heart rate variability, countermovement jump

INTRODUCTION

An optimal regulation of training load and recovery plays a major role in successful training. Failure in this regulation may lead to non-optimal adaptation to training, marked as decreased endurance performance, especially in the case of accumulated fatigue or overtraining (31, 40). Monitoring changes in performance during training may serve essential information for coaches and athletes in optimizing training load and recovery. Maximal laboratory tests are usually used in order to evaluate training adaptation. However, the tests are usually performed two to three times per year due to impracticality, expensiveness and exhaustiveness (25). Therefore, the maximal tests are not optimal methods for regular monitoring of training adaptation. The information should be found out non-invasively and quickly e.g. from standardized warm-up for providing a practical tool for athletes and coaches to monitor training adaptation.

Exercise HR is probably the most frequently used method to quantify the training intensity and internal training load in running. In addition, exercise HR at a certain submaximal level may reflect training induced changes in endurance performance. Decreased HR at submaximal exercise has been observed to be a sign of positive training adaptation (2, 3, 38). Lamberts et al. (25) developed a submaximal cycling test, which has been observed to be able to predict maximal cycling performance from submaximal power at standardized submaximal HR levels and post-exercise heart rate recovery (HRR) (24, 25). Recently, a cross-sectional study by Otter et al. (35) showed the potential of the same submaximal protocol to predict endurance performance also in rowing. Less is known about the usefulness of the submaximal protocol in monitoring changes in endurance running performance in longitudinal training studies. In our previous study, we observed that HR / running speed (RS) – index, calculated from all constant speed running exercises, serves a potential tool for daily monitoring of training adaptation (41). However, different durations and intensities of training sessions, may cause fluctuation in exercise HR, and thus, may disturb the relationship between HR and RS (1, 21). Recently, we observed that the changes in RS at 80 and 90 % of HR_{max} in a three-staged submaximal running test in field conditions were related with the change in maximal endurance performance during the 18-week endurance training program (43). However, environmental factors such as wind, temperature and terrain may impair the usefulness of the submaximal running test in monitoring of training adaptation in spite of the standardizing of exercise duration and intensity. Treadmill running is growing more popular and it serves more standardized conditions compared with running in outdoor field conditions.

In addition, cardiac autonomic activity is likely to have an important role in endurance training adaptation (2, 3, 15, 23, 24). Faster cardiorespiratory recovery after exercise has been shown to be related to a greater vagal activity and aerobic capacity (8, 13, 39, 43). In addition, the measurement of post-exercise HRR and heart rate variability (HRV) have been proposed to have potential for monitoring fatigue and predicting changes in endurance performance parameters (3, 20, 23, 24, 45), and would be easy and quickly to perform in practical training situation. However, previous studies are partly conflicting, and thus, more research is needed to investigate the ability of post-exercise HRR and HRV to monitor training adaptation.

Previous studies have also shown that neuromuscular factors are important determinants of endurance running performance (34, 36). Countermovement jump (CMJ) has been used in several sports to assess muscle power of the lower extremities often correlating with running performance(9, 16). In addition, it has been observed that reduced CMJ performance is related to neuromuscular fatigue (7, 12, 30), which could be essential information in monitoring endurance training adaptation. Measures of neuromuscular function with various jumping tests (e.g. CMJ, squat jump) have become popular in training monitoring, especially in team-sports, due to the simplicity and the minimal amount of additional training load (7, 12, 30). However, to our best knowledge there are no previously published studies about a possible relationship between changes in CMJ and endurance training adaptation.

The aim of this study was to investigate whether a submaximal running test (SRT) combined with the post-exercise HRR, HRV and CMJ measurements conducted in the laboratory conditions could be used in monitoring changes in endurance performance during an 18-week training period. We hypothesized that 1) increased running speeds at standardized submaximal HR levels and post-exercise cardiac vagal activity would be related to enhanced endurance performance (3, 38, 43, 45), and 2) decreased neuromuscular function would be related to negative endurance training adaptation (7, 9, 16).

METHODS

Experimental Approach to the Problem

The three-staged submaximal running test (SRT) was modified from the Lamberts and Lambert Submaximal Cycle Test (25). In addition to determining submaximal running speed at 70%, 80% and 90% of HR_{max} intensities, post-exercise HRR, HRV and CMJ measurements were performed. Recreational endurance runners performed SRT four times in laboratory conditions during the 18-week endurance training period. Changes in SRT were compared to changes in maximal endurance performance and maximal oxygen consumption in all subjects pooled and retrospectively divided quartiles according to the improvement of maximal endurance performance.

Subjects

Forty recreational endurance runners (20 women, 20 men), 22-50 years of age volunteered to participate in the study. The subjects were healthy and had been training at least three times per week during the previous 6 months. They did not have any diseases or use regular medication. Age, pre-training VO_{2max}, regular training background, weekly training times and weekly running kilometers (during the previous two months) were 35 ± 10 years, 47 ± 5 $mL \cdot kg^{-1} \cdot min^{-1}$, 14 ± 8 years, 5.6 ± 1.7 times, 38 ± 19 km for women and 35 ± 6 years, 53 ± 5 $mL \cdot kg^{-1} \cdot min^{-1}$, 14 ± 8 years, 4.4 ± 2.0 times, 27 ± 15 km for men. After being fully informed about the study design and the possible risks, all subjects completed an informed consent document. The study was approved by the Ethics Committee of the University of Jyväskylä, Finland and conducted according to the provisions of the most recent Declaration of Helsinki.

Study design

The subjects took part in an 18-week training program. The training program was divided into an 8-week low intensity endurance training period and an 8-week intensive training period with increased training volume or intensity. A maximal incremental treadmill running test was performed before and after both training periods (at weeks 0, 9 and 18) and submaximal running test (SRT) at weeks 0, 4, 9, 13 and 18. The maximal treadmill test and SRT were separated by at least two easy training days during the testing weeks. All testing was performed at about the same time of day (within 2 hours) with stable laboratory conditions.

Maximal incremental treadmill running test

The subjects were asked not to do any vigorous physical activity two days prior to the maximal treadmill running test. The subjects performed the running test for determination of maximal oxygen uptake (VO_{2max}), the peak treadmill running speed (RS_{peak}), LT2 and LT1 as described in the study of Vesterinen et al. (42). The test started at 7 $km \cdot h^{-1}$ for women 8 $km \cdot h^{-1}$ for men and followed by an increase of 1 $km \cdot h^{-1}$ 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). Blood samples (20 μL) were taken from the fingertip at the end of each stage to analyze blood lactate concentrations (La) (Biosen S_line Lab+ lactate analyzer, EKF Diagnostic, Magdeburg, Germany). Oxygen consumption was measured breath-by-breath throughout the test using a portable gas analyzer (Oxycon Mobile, Viasys Health Care, Würzburg, Germany). The highest 60-s VO_2 value during the treadmill test was considered as VO_{2max}. The maximal endurance performance was determined as the treadmill running speed (RS_{peak}) at exhaustion, which has been observed to be highly reliable with intraclass correlation coefficients of 0.99 ± 0.01 and the coefficient of variation of 1.2% measured in the incremental treadmill running test (10). If the subject could not complete the whole 3 min of the last speed, RS_{peak} was calculated as follows: speed of the last completed stage ($km \cdot h^{-1}$) + (running time (s) of the speed at exhaustion – 30 s) / (180-30 s) * 1 $km \cdot h^{-1}$. The determination of lactate thresholds was based on the rise and change in the inclination of the blood lactate curve during the test (11). LT1 was set at 0.3 $mmol \cdot L^{-1}$ above the lowest lactate value. LT2 was set at 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 $mmol \cdot L^{-1}$.

Submaximal running test (SRT)

The present submaximal running test (SRT) was modified from the Lamberts and Lambert Submaximal Cycle Test (25). SRT was designed to be as a standardized warm-up protocol. The 17-minutes SRT consisted of three stages (Fig 1). The speed of the treadmill was set by heart rate corresponding to 70%, 80% and 90% of a subject's maximum heart rate (HR_{max}) for 6, 6 and 3 minutes, respectively. The target HRs were calculated based on HR_{max} in the maximal incremental treadmill test at week 0. HR was recorded throughout the test using a HR monitor (Suunto t6, Suunto Ltd, Vantaa, Finland) but the data of the first minute of each stage was excluded from analyses due to the setting of running speed (RS) to reach the target HR. Therefore, average RS and HR were calculated over a five-minute period (1:00-6:00 and 7:00-12:00) for stage 1 and 2, and for a two-minute period (13:00-15:00) for stage 3. Mean power of all three stages has been observed to be highly repeatable with intraclass correlation coefficients of 0.91, 0.92 and 0.90 in rowing (35), and 0.91, 0.98 and 1.00 in cycling (25). RPE was recorded in the final minute of each stage. After completing the running test, the subjects were asked to stand without moving and talking for 2 minutes for determining post-exercise HRR and HRV. They were asked to breathe normally, without control of the respiratory rate. HRR was calculated by subtracting heart rate after 60 s recovery from HR at the end of third stage. A vagal-related HRV index, the natural logarithm of the square root of the mean squared differences of successive R-R intervals (lnRMSSD), was calculated over the second recovery minute (16:00-17:00) for achieving more stable HR compared the first recovery minute. Kaikkonen et al. (19) observed that the first 2-min recovery after exercise may give enough information on HRV recovery for evaluating training load. LnRMSSD has been suggested to provide the most reliable and practically applicable HRV variable for regular monitoring (39). R–R interval (RRI) data was analyzed using the Firstbeat Sports software (version 4.0.0.5, Firstbeat Technologies Ltd, Jyväskylä, Finland). RRIs were checked and edited by an artifact detection filter of the Firstbeat Sports (37) software and all falsely detected, missed, and premature heart beats were excluded before calculation of HRR and lnRMSSD.

Figure 1 about here

Countermovement jump (CMJ) test

CMJ test was performed 3 min after the end of SRT on a commercially available force plate (Accupower, Advanced Mechanical Technology, Watertown, USA) to measure CMJ height (CMJ_h) from the force time curve. The subjects performed three trials with hands held on the hips throughout the entire movement, separated by 60 s recovery between the trials. They were instructed to jump as high as possible. Countermovement depth was self-selected by the subject but no less than 90º. Force data were collected and analyzed by using custom-designed software (Research Institute for Olympic Sports, Jyväskylä, Finland), which used the equation $h = I^2 \cdot 2gm^{-2}$ to calculate jump height from impulse, where I is the impulse, g is the gravity, and m is the mass of subject. Jump height was determined as an average of the two best jumps.

Training

The subjects were asked to train at low-intensity (below or at lactate threshold 1, LT1) and maintain the same training frequency (mean: 5.2 ± 1.9 times per week) as before the study during the 8-week preparation period. Thereafter, running training volume and intensity was progressively increased during the following eight weeks. The training was periodized so that three weeks of intense training was followed by an easy training week. The subjects completed 1-3 moderate (30-40 min, intensity between LT1 and LT2) or high intensity interval (4x4 min with 4 min of recovery or 6x2 min with 2 min of recovery) or constant speed (20 min) training sessions with the intensity above LT2 during intense week. Endurance training consisted primarily of running but occasionally included also cycling, Nordic walking and/or cross-country skiing. Furthermore, the subjects were asked to complete 1 muscle endurance circuit training session per week. The subjects controlled their training intensity by measuring HR during all exercises with Garmin FR 610 heart rate monitor with GPS (Garmin Ltd, Schaffhausen, Switzerland). In addition, the moderate and high intensity training sessions were supervised by experienced members of the research group.

Statistical analysis

The results are expressed as means ± standard deviations (SD). Normality of the data was assessed by Shapiro–Wilk goodness-of-fit test and homogeneity of variance was assessed by Levene's variance test. The subjects were retrospectively divided into quartiles (the 1st quartile, Q1, the highest response (n = 9); the 2nd quartile, Q2, moderate response (n = 9); the 3rd quartile, Q3, low response (n = 9), the 4th quartile, Q4, the lowest response (n = 8)) of percentage change in RS_{peak} from week 0 to week 18. Differences between the quartiles were analyzed using a one-way analysis of variance (One-way ANOVA) and changes in maximal running test, SRT and CMJ_h (group-by-training interaction) were analyzed using repeated measures of ANOVA, followed by Bonferroni as a post hoc test. In addition, standardized effects sizes (ES) were calculated using the partial eta square with following threshold values: < 0.2 (trivial), 0.2 – 0.5 (small), 0.5 – 0.8 (moderate) and > 0.8 (large) (6). Pearson product moment correlation coefficient was used to determine relationships between absolute values of SRT and CMJ_h, and endurance performance variables at week 9. In addition, relationships were analyzed between changes in SRT, CMJ_h, and RS_{peak} for all the subjects and for women and men separately. In addition to measures of statistical significance, the following criteria were adopted to interpret the magnitude of the correlation between measurement variables: <0.1 (trivial), 0.1 – 0.3 (small), 0.3 – 0.5 (moderate), 0.5 – 0.7 (large), 0.7 – 0.9 (very large) and 0.9 – 1.0 (almost perfect) (18). Statistical significance was accepted as $p < 0.05$. Statistical analyses were carried out using SPSS software (IBM SPSS Statistics 20, IBM, New York, USA).

RESULTS

Training data

A total of 35 subjects completed the whole 18-week training program. Four subjects dropped out from the program due to injuries and one with lack of motivation. Training volume remained similar during both training periods (7.1 ± 2.6 h h·week^{-1} vs. 6.4 ± 2.0 h·week^{-1}), as well as training frequency (5.9 ± 2.1 sessions·week^{-1} vs. 6.0 ± 2.1 sessions·week^{-1}). Running volume increased from 33 ± 17 km·week^{-1} to 41 ± 16 km·week^{-1} ($p < 0.001$) in the second training period. In addition, the percentage amount of high intensity training increased from 1 ± 2% to 4 ± 3% ($p < 0.001$), when as amount of low (86 ± 9% vs. 84 ± 9%) and moderate intensity (13 ± 8% vs. 12 ± 9%) training remained unaltered between the training periods.

Submaximal running test

The speed of the treadmill was successfully set for the target HR levels (70%, 80% and 90% of HR_{max}) in SRT (Table 1), with no changes between the five testing sessions. Individual ranges in HR were 67 – 74% during the first, 79 – 82% during the second and 88 – 93% of HR_{max} during the third stage. RPE, post-exercise HRR and lnRMSSD remained constant during the whole training period but a constant increase was observed in RS of all stages during the second half of the training period ($p < 0.01$).

Table 1 about here

Predictors of endurance training

RS of all stages in SRT were well correlated with RS_{peak} (stage 1: r = 0.71, stage 2: r = 0.77, stage 3: r = 0.85, all $p < 0.001$, very large) and with VO_{2max} (stage 1: r = 0.68, large; stage 2: r = 0.74, very large; stage 3: r = 0.75, very large; all $p < 0.001$). Post exercise HRR and lnRMSSD correlated moderately with VO_{2max} (r = 0.44 and r = 0.39, both $p < 0.05$), but not with RS_{peak}. Similar correlations were observed in women and men, except HRR, which correlated with both VO_{2max} and RS_{peak} in women after SRT (r = 0.62 and r = 0.64, both $p < 0.01$, large), but not in men. A similar trend was found between HRR and VO_{2max} (r = 0.48, $p = 0.098$, moderate) in men. In addition, CMJ_h correlated with RS_{peak} (r = 0.57, $p < 0.001$, large), when all pooled, and the correlation separated for women and men were r = 0.44 ($p = 0.052$, moderate) and r = -0.23 ($p = 0.418$, small).

Training effects

VO_{2max} and RS_{peak} improved by 2.2 ± 6.2% ($p = 0.043$) and 3.2 ± 4.0% ($p < 0.001$) during the 18-week training period. VO_{2max} increased moderately in Q1 ($p = 0.004$), whereas small or trivial changes ($p > 0.05$) were observed in other quartiles (Table 2). Large improvement of RS_{peak} were observed in Q1, Q2 and Q3 (all $p < 0.001$), but not in Q4 ($p = 0.066$). The change in RS_{peak} was greater ($p < 0.001$) in Q1 compared with other quartiles. HR_{max} decreased (183 ± 10 vs. 180 ± 8; ES = 0.58, moderate; $p = 0.017$) in Q4, but remained unaltered in other quartiles. A large increase of RS 3 ($p < 0.001$) was observed in Q1, whereas small or moderate changes ($p < 0.01$) were observed in other quartiles. Moderate or small increases ($p < 0.05$) were observed in SRT RS 1 and RS 2 in all quartiles, except in Q4 ($p > 0.05$). Post exercise HRR, RMSSD and CMJ_h, showed trivial changes in all quartiles ($p > 0.05$), except CMJ_h in Q2 (moderate, $p < 0.05$).

Table 2 about here

Relationships between the changes of RS in SRT, and the changes of VO_{2max} and RS_{peak} after 18 weeks of training are shown in Fig 2. The changes in RS 2 and RS 3 showed large or moderate correlations with the change of both VO_{2max} and RS_{peak}. No significant relationships were found between the changes of VO_{2max} and RS_{peak}, and the changes of post exercise lnRMSSD (r = 0.06, r = -0.02, both trivial), HRR (r = 0.01, r = -0.09, both trivial) and CMJ_h (r = 0.21, small, r = 0.15, trivial). No sex differences were observed in the correlations.

Figure 2 about here

The changes of the variables in SRT in the highest (Q1) and the lowest (Q4) responders at weeks 4, 9, 13 and 18 are presented in Fig 3. A significant training effect (test of within-subjects effect) between the measurement weeks was observed in RS of all stages in Q1 ($p < 0.005$, all), but only in RS 3 ($p = 0.036$) in Q4. No changes were observed in either quartile in RPE, HRR, lnRMSSD and CMJ_h. Significant differences between Q1 and Q4 were observed in the change of RS 3 at week 13 ($p = 0.021$) and 18 ($p = 0.008$). In addition, the change of RS 2 tended to be greater in Q1 than Q4 at week 13 ($p = 0.076$) and 18 ($p = 0.136$).

Figure 3 about here

DISCUSSION

The first main finding of the present study showed the significant relationship between the changes in RS 2 and RS 3, and the changes in RS_{peak} and VO_{2max}. In addition, the RS change in SRT of the highest responders (Q1) differed significantly from the RS of the lowest responders (Q4) after the 13th training week, when the running volume and intensity were progressively increased. Secondly, contrary to our hypotheses, the changes in post-exercise cardiac vagal activity and neuromuscular function were not related to endurance training adaptation.

The speed of the treadmill was set successfully for the target heart rate levels of the stages in SRT by the exercise physiologist. Individual range of HR was the smallest during the third stage (90% of HR_{max}), which expresses that the intensity around LT2 seems to be reasonable for accurate regulation of HR. These findings are in line with the previous study related to submaximal running test (22). Unfortunately, no measurements of reliability were conducted in the present study. However, Otter et al. (35) observed almost perfect intra-class correlation coefficients in power of all three stages in rowing and Lamberts et al. (35) in cycling in the same kind of submaximal protocol than performed by running in the present study. High reliability has also been reported in running performance at 80% of HR_{max} intensity in a submaximal running test on treadmill (44). Heart rates (70%, 80%, 90%) and RPEs (2, 3, 5) of the stages showed that the SRT protocol was truly submaximal and did not cause remarkable training load. Thus, SRT seems to be a useful method for regular monitoring without interfering normal training.

Running speed during submaximal test in predicting endurance performance and monitoring training adaptation

The present results in the cross-sectional analysis showed the relationships between RS of all stages in SRT and maximal endurance performance (r = 0.71 – 0.85), and maximal aerobic capacity (r = 0.68 – 0.75). The strongest predictor for RS_{peak} and VO_{2max} was RS at 90% of HR_{max}, which is in line with our previous study (43) and the studies of Lamberts et al. (25) and Otter et al. (35). Recently, we observed the similar significant relationships between RS at 70-90% of HR_{max} in SRT performed in outdoor field conditions and maximal endurance performance (r = 0.74-0.83) and aerobic capacity (r = 0.58-0.75) (43). It seems that more standardized laboratory conditions in the present study did not enhance the relationships. Lamberts et al. (25) found the largest correlation between power corresponding the intensity of 90% of HR_{max} in the submaximal cycling test, and peak cycling performance (r = 0.94). Otter et al. (35) similarly observed that power at 90% of HR_{max} in a submaximal rowing test was the best predictor (r = -0.93) of 2000 m maximal rowing time. In addition, the previous studies reported high reliability of variables measured during the stages of 80% and 90% of HR_{max} (25, 35). Slightly smaller correlations between RS at submaximal intensities and maximal running performance in the present study may be explained by more challenging and rougher regulation of power (= running speed) compared to exercises with the ergometer, like cycling or rowing.

The previous findings support that power or RS at certain submaximal HR levels predicts endurance performance in the cross-sectional setup. However, less is known whether submaximal performance tracks sensitively enough the changes of endurance performance during longitudinal training studies. The present results showed that the changes in RS at 80% and RS 90% of HR_{max} intensities were related to the changes in both endurance performance and VO_{2max}. This is in line with the previous findings about the relationship between decreased exercise HR and improvements in endurance performance (2, 3, 38, 43). Regardless of the non-significant relationship between the change in RS at 70% of HR_{max} and the change in endurance performance, the first 6 min stage is needed for adequate warming-up for the subsequent stages and main training session. Recently, we observed the strongest relationships between changes in RS at 90% of HR_{max} intensity in SRT performed in field conditions and changes in both endurance performance (r = 0.79) and VO_{2max} (r=0.62) (43). In addition, RS at 90% HR_{max} was the most sensitive variable to separate the highest and the lowest responders during the training period (43). Unexpectedly, the correlations were lower in the present study in spite of the standardized laboratory conditions. It seems that the standardized laboratory condition may not be necessary for using SRT in monitoring training adaptation. The highest (Q1) and the lowest responders (Q4) were separated by the changes of RS 3 after 13 and 18 weeks of training. According to these findings, an intensity of 80-90% of HR_{max} is needed for monitoring training adaptation. A time point when it was possible to identify the highest and lowest responders for the first time was at week 13 based on the data of RS 3 in SRT and at week 18 based on the data of the maximal test. From the practical point of view, obtaining that kind of information about the adaptation 5 weeks earlier, would allow the possibility for athletes and coaches to change their training program earlier for achieving desirable training adaptation.

Regardless of relatively clear observations about the relationship between performance at certain submaximal HR and endurance performance in the present and in previous studies (2, 3, 38, 41, 43), decreased exercise HR and HR_{max} have been observed to be related also to negative training adaptation in the case of short-term overreaching or overtraining (17, 27). In the present study, only trivial changes were observed in HR_{max}, except among the lowest responders who showed moderate decreases in HR_{max}, which together with the poor improvement in endurance performance could be a sign of overreaching. However, RPE remained relatively unaltered at submaximal levels. In the case of overreaching or overtraining, RPE would increase at submaximal levels because one should work harder for achieving the same HR level due to higher relative intensity, if HR_{max} is reduced (26). Therefore, RPE together with the data of RS give reasonable information about training adaptation. Furthermore, no signs of fatigue or overreaching were observed in the injured subjects among dropouts who performed the repeated testing at least twice before the termination of the study. It seems that fatigue or overreaching was not a reason for the injuries or more frequent monitoring might be needed for identifying risks for injuries.

Post-exercise heart rate recovery and heart rate variability after submaximal exercise in predicting endurance performance and monitoring training adaptation

Faster cardiorespiratory recovery after exercise as measured by post-exercise HRR and HRV have been shown to be related to a greater VO_{2max} and/or endurance performance (8, 39, 43). In the cross-sectional analysis of the present study, HRR and HRV correlated with VO_{2max}, but not with endurance performance, except in women (r = 0.64). In our previous study, we observed the similar correlation between HRR after SRT in field conditions and VO_{2max} (r = 0.49) (43). When the correlations were analyzed separately by sexes, the stronger correlations between HRR and VO_{2max} were observed in women (r = 0.62) compared with men (r = 0.48). However, no sex differences were observed in the significances of the correlations, which is in line with previous studies (28, 29). A limitation of the present study was a relatively small number of subjects and a larger sample size would give more statistical power in comparison between sexes. The present results support that the higher post-exercise cardiovascular autonomic activity measured by HRR and HRV is related with the higher aerobic capacity, but not with endurance performance.

Changes in post-exercise HRR and HRV have been proposed as markers of changes in cardiac autonomic regulation and training adaptation. An increased HRR has been shown to be related with the improved VO_{2max} or endurance performance (8, 23, 24). Lamberts et al. (23) observed positive relationships between the changes of HRR after the 40 km cycling time trial and peak power output (r = 0.73) and 40 km time trial time (r = 0.95) after 4 weeks of high intensity training. In the present study, HRR and lnRMSSD remained unaltered during the training period. Furthermore, contrary to our hypothesis no relationships were observed between the individual change of post-exercise HRR and HRV with the change of RS_{peak} or VO_{2max}, like in our previous study (43) and the study by Buchheit et al. (4) in team-sports. The absence of the relationships between post-exercise HRR and HRV, and endurance performance may be explained by the relatively homogeneous group of the subjects. The relationship seems to be weaker in homogeneous groups (33, 35), which may be due to the relation between genetic polymorphism in acetylcholine receptor M2 and post-exercise HRR (14). Thus, it may be possible that post-exercise HRR may indicate overall aerobic fitness but the change in HRR is not sensitive enough to track changes in endurance performance and aerobic capacity, especially in homogeneous groups. The discrepancies between studies can also be explained with different protocols in the measurements. The mode, duration and intensity of exercise may affect post-exercise HRR and HRV (8). Exercise intensity has been proposed to have a graded effect on post-exercise HRV during the initial minutes of recovery, with a greater preceding intensity resulting in a lower HRV (32). It has been suggested that exercise intensity below LT1 should be used for assessing the actual post-exercise cardiac autonomic regulation by HRV measures (5). The greater relative exercise intensity causes the greater blood acidosis and metaboreflex stimulation, and post-exercise HRV is very largely related to exercise intensity rather than cardiac autonomic regulation (5, 39). Therefore, the relatively high exercise intensity (90% of HR_{max} ~ LT2) in the present study, may explain the non-significant findings between the changes in post-exercise HRV and the training adaptation.

CMJ in predicting and monitoring endurance performance

In addition to cardiorespiratory and metabolic factors, neuromuscular factors have an important role in endurance performance. We found a large correlation (r = 0.57) between CMJ_h and RS_{peak} (all pooled). The finding supports that muscle power of the lower extremities is related with running performance (9, 16). However, the relationship was found only in women, but not in men, when sexes were analysed separately. It needs to be emphasized that the present subjects performed one muscle endurance training session per week, but no explosive strength training of any kind. As it was hypothesized, no remarkable changes in CMJ occurred during the training period. The individual changes of CMJ_h were not related to changes of RS_{peak} during the present training period neither in women, men or in the whole group. It has been proposed that reduced CMJ_h performance could be an indicator of neuromuscular fatigue (7, 12, 30), which could also be observed in impairment of endurance performance. The declining trend could be observed in CMJ_h during weeks 4 – 18 in the lowest responders (Fig. 3.G), but the change was not statistically significant. It is possible that it may be an early signal of neuromuscular fatigue, but there were no indicators of that at the group mean level. In addition, it is possible that other variables than jumping height would be more sensitive for detecting neuromuscular fatigue (12) in endurance running performance. However, these results cannot endorse the use of CMJ_h as a valid method for monitoring endurance training adaptation.

PRACTICAL APPLICATIONS

Nowadays, the measurements of running speed, HRR, HRV and CMJ can be easily performed by mobile applications and heart rate monitors with GPS and accelerometers, without expensive and solid measurement methods. However, the data is commonly used for determining training intensity, volume and load, but the data is not often fully utilized for systematic monitoring of training adaptation and training prescription. The present results support that the non-invasive and practical running speed and post-exercise measurements can be used to track changes in endurance performance. Changes in running speeds at 80-90% of HR_{max} in the SRT may provide the most valuable information about the training adaptation for athletes and coaches. An increment in the submaximal running speed may reflect the positive change in maximal endurance performance and a decrement may suggest declined maximal endurance performance. Thus, SRT may inform if training has led to undesirable outcomes and if a training program should be changed. In addition, the present results suggest that the submaximal running test could be performed regularly, e.g. once per week, as a standardized warm-up without interfering normal training habits. Post-exercise cardiac vagal activity reflects aerobic capacity, but may not be sensitive enough for monitoring individual training adaptation. Similarly, the individual changes of neuromuscular function did not correlate with endurance training adaptation, but CMJ performance was related to maximal running performance in the present subject population. Furthermore, SRT together with HRR, HRV and CMJ measurements may serve a useful tool for athletes and coaches to evaluate individual adaptation to endurance training on a weekly basis and, therefore, could be used in training prescription.

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FIGURE LEGENDS

Figure 1. An example of an arbitrary subject' training monitoring test including heart rate and running speed during the submaximal running test (SRT).

Figure 2. Correlations between the changes of maximal oxygen consumption (VO_{2max}) and peak running speed (RS_{peak}), and the changes of running speed during the first (70% HR_{max}), second (80% HR_{max}) and third stage (90% HR_{max}) in the submaximal running test (n = 33) after 18 weeks of training.

Figure 3. Changes in running speed (RS) in the first (A), second (B) and third stage (C) of the submaximal running test (SRT), rate of perceived exertion (RPE, D), post exercise heart rate recovery

(HRR, E), post-exercise the natural logarithm of the square root of the mean squared differences of successive R-R intervals (lnRMSSD, F) and the countermovement jump height (CMJ_h, G) in the first (high) and fourth (low) quartiles of percentage training adaptation. Circles around symbols denote significant ($p < 0.05$) within-group difference from week 0 and between-groups differences: # $p < 0.05$, ## $p < 0.01$ (revealed by Bonferroni post hoc analysis).

TABLES:

Table 1. Physiological and performance variables of the submaximal running test.

	Week 0	Week 4	Week 9	Week 13	Week 18
Stage 1 (70% of HR_{max})					
Running speed ($km \cdot h^{-1}$)	8.2 ± 1.4	8.5 ± 1.4	8.9 ± 1.4***	8.8 ± 1.4***	9.0 ± 1.4***
Heart rate (bpm)	131 ± 8	132 ± 7	131 ± 7	132 ± 7	132 ± 7
% HR_{max}	70 ± 2	70 ± 1	70 ± 1	71 ± 1	70 ± 1
RPE (0-10)	2 ± 1	2 ± 1	1 ± 1	1 ± 1	2 ± 1
Stage 2 (80% of HR_{max})					
Running speed ($km \cdot h^{-1}$)	10.1 ± 1.5	10.3 ± 1.6	10.6 ± 1.6**	10.6 ± 1.5**	10.8 ± 1.5***
Heart rate (bpm)	150 ± 8	150 ± 8	150 ± 8	150 ± 8	150 ± 8
% HR_{max}	80 ± 1	81 ± 1	80 ± 1	80 ± 1	80 ± 1
RPE (0-10)	3 ± 1	3 ± 1	3 ± 1	3 ± 1	3 ± 1
Stage 3 (90% of HR_{max})					
Running speed ($km \cdot h^{-1}$)	12.6 ± 1.6	13.0 ± 1.7**	13.3 ± 1.7***	13.4 ± 1.7***	13.7 ± 1.7***
Heart rate (bpm)	168 ± 9	168 ± 8	168 ± 9	167 ± 9	168 ± 9
% HR_{max}	90 ± 1	90 ± 1	90 ± 1	90 ± 1	90 ± 1
RPE (0-10)	6 ± 2	5 ± 2	5 ± 2	5 ± 2	5 ± 1
Recovery period					
HRR (bpm)	42 ± 10	42 ± 9	43 ± 14	43 ± 12	43 ± 10
lnRMSSD (ms)	1.5 ± 0.7	1.6 ± 0.8	1.6 ± 0.8	1.6 ± 0.7	1.6 ± 0.7

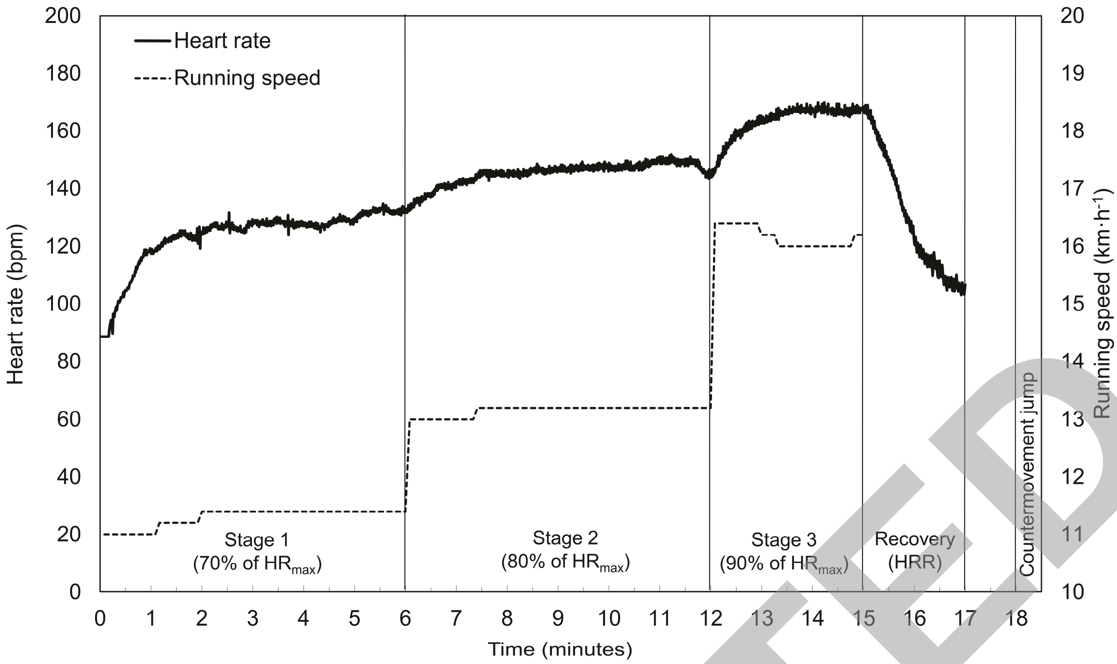
Significant difference from week 0. ** $p < 0.01$, *** $p < 0.001$ (repeated measures of ANOVA). HRR, heart rate recovery during the first minute after the end of the submaximal running test; lnRMSSD, the natural logarithm of the square root of the mean squared differences of successive R-R intervals as calculated during the last minute of the 2-min recovery period after the submaximal running test.

Table 2. Performances before and after the 18-week training period in quartiles of the training adaptation.

		Percentage change at 18 weeks			
		1st quartile (n=9)	**2nd quartile (n=9)**	**3rd quartile (n=9)**	**4th quartile (n=8)**
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	Pre	48.3 ± 4.5	49.3 ± 4.8	53.4 ± 6.3	48.8 ± 7.8
	Change (%)	8.3 ± 0.8^{b}	2.9 ± 5.4^{c}	$0.2 \pm 4.3^{\#, d}$	$-2.6 \pm 4.3^{\#\#\#, c}$
RS_{peak} ($km \cdot h^{-1}$)	Pre	14.8 ± 0.6	14.4 ± 1.1	15.4 ± 1.5	15.0 ± 1.9
	Change (%)	8.3 ± 6.2^{a}	$4.4 \pm 1.1^{\#\#\#, a}$	$1.9 \pm 0.5^{\#\#\#, a}$	$-2.2 \pm 2.7^{\#\#\#, c}$
SRT RS 1 ($km \cdot h^{-1}$)	Pre	7.7 ± 1.2	7.6 ± 1.1	8.3 ± 1.3	8.6 ± 1.6
	Change (%)	11.4 ± 10.4^{b}	10.8 ± 9.1^{b}	10.7 ± 10.2^{b}	5.1 ± 5.3^{b}
SRT RS 2 ($km \cdot h^{-1}$)	Pre	9.4 ± 1.3	9.6 ± 1.3	10.3 ± 1.5	10.3 ± 1.9
	Change (%)	10.9 ± 8.4^{b}	5.9 ± 4.7^{b}	7.8 ± 9.2^{c}	1.3 ± 2.3^{c}
SRT RS 3 ($km \cdot h^{-1}$)	Pre	12.0 ± 1.5	11.9 ± 1.4	12.9 ± 1.6	12.6 ± 2.2
	Change (%)	13.5 ± 7.4^{a}	6.6 ± 3.9^{b}	9.1 ± 4.8^{b}	$3.9 \pm 2.0^{\#\#, b}$
SRT HRR (bpm)	Pre	41 ± 9	46 ± 9	47 ± 12	39 ± 11
	Change (%)	8.1 ± 19.5^{d}	8.2 ± 17.9^{d}	4.8 ± 13.6^{d}	11.8 ± 23.0^{d}
SRT RPE	Pre	6 ± 1	6 ± 2	6 ± 2	6 ± 2
	Change (%)	-7.1 ± 13.9^{c}	-5.9 ± 27.4^{d}	12.8 ± 34.0^{d}	-0.4 ± 13.4^{d}
SRT RMSSD (ms)	Pre	1.6 ± 0.6	1.8 ± 0.6	1.6 ± 0.9	1.1 ± 0.3
	Change (%)	15.7 ± 50.0^{d}	-4.2 ± 22.7^{d}	20.1 ± 51.1^{d}	6.2 ± 37.0^{d}
CMJ_h (cm)	Pre	31.1 ± 5.9	$23.1 \pm 4.6^{\#}$	29.8 ± 5.9	25.0 ± 4.7
	Change (%)	1.9 ± 5.3^{d}	4.1 ± 4.8^{b}	-2.2 ± 7.3^{d}	-1.2 ± 6.1^{d}

Significant difference to the first quartile. $^{\#}$ $p < 0.05$, $^{\#\#}$ $p < 0.01$, $^{\#\#\#}$ $p < 0.001$. [a] large effect size, [b] moderate effect size, [c] small effect size, [d] trivial effect size.

VO_{2max}, maximal oxygen consumption; RS_{peak}, peak treadmill running speed; SRT, submaximal running test; RS, running speed; HRR, heart rate recovery; lnRMSSD, the natural logarithm of the square root of the mean squared differences of successive R-R intervals; CMJh, the countermovement jump height.


Heart rate
Running speed
Heart rate (bpm)
Running speed (km·h-1)
Time (minutes)
Stage 1
(70% of HRmax)
Stage 2
(80% of HRmax)
Stage 3
(90% of HRmax)
Recovery
(HRR)
Countermovement jump
0
20
40
60
80
100
120
140
160
180
200
10
11
12
13
14
15
16
17
18
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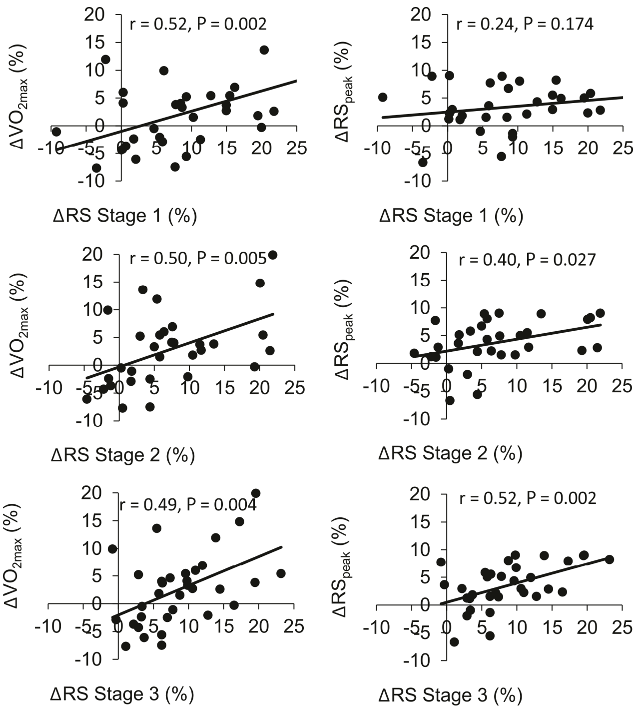
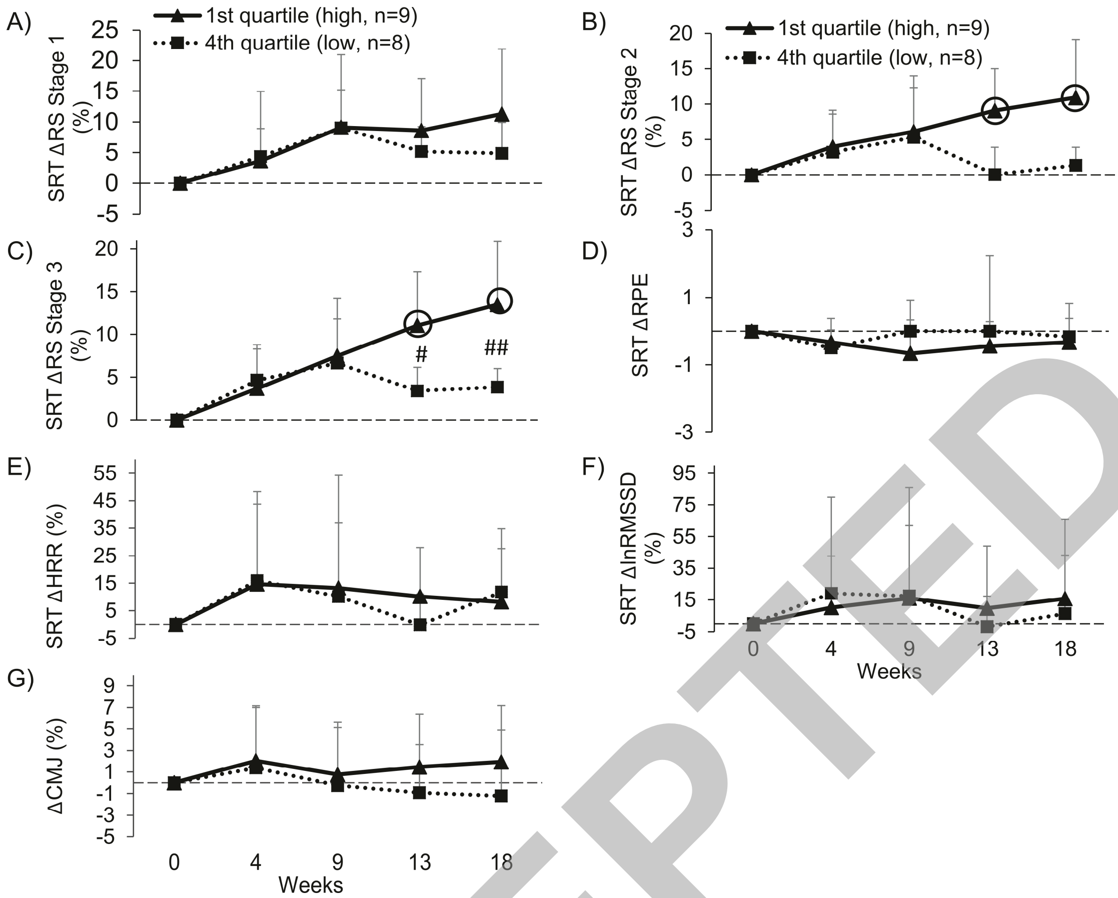
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18


r = 0.52, P = 0.002
ΔVO2max (%)
ΔRS Stage 1 (%)
r = 0.24, P = 0.174
ΔRSpeak (%)
ΔRS Stage 1 (%)
r = 0.50, P = 0.005
ΔVO2max (%)
ΔRS Stage 2 (%)
r = 0.40, P = 0.027
ΔRSpeak (%)
ΔRS Stage 2 (%)
r = 0.49, P = 0.004
ΔVO2max (%)
ΔRS Stage 3 (%)
r = 0.52, P = 0.002
ΔRSpeak (%)
ΔRS Stage 3 (%)


A)
B)
C)
D)
E)
F)
G)
1st quartile (high, n=9)
4th quartile (low, n=8)
SRT ΔRS Stage 1 (%)
SRT ΔRS Stage 2 (%)
SRT ΔRS Stage 3 (%)
SRT ΔRPE
SRT ΔHRR (%)
SRT ΔlnRMSSD (%)
ΔCMJ (%)
#
##
0
4
9
13
18
Weeks