Heart Rate–Running Speed Index May Be an Efficient Method of Monitoring Endurance Training Adaptation

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TITLE PAGE

Heart Rate - Running Speed–index May Be an Efficient Method of Monitoring Endurance Training Adaptation

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Running head: Monitoring training adaptation

ABSTRACT

The aim of this study was to investigate whether a novel heart rate-running speed index could be used in monitoring adaptation to endurance training. Forty-five recreational runners underwent a two-phased 28-week training regime. The first 14-weeks included basic endurance training whereas the second 14-weeks were more intensive (increased volume and intensity). A maximal treadmill running test was performed in the beginning of the experiment, in the middle of basic endurance training, and at the end of each training period (PRE, WEEK7, WEEK14 and POST). The novel heart rate-running speed index was calculated from every continuous-type running exercise during the 28-week experiment based on exercise heart rate - running speed relation accompanied by individual information on resting and maximal HR and speed. The change in the novel index correlated significantly with the changes of peak running speed in the treadmill tests (r = 0.43-0.61, $P < 0.01$) and speed at respiratory compensation threshold (r = 0.35-0.39, $P < 0.05$) during the experiment. The change in the index also correlated significantly (r = 0.49, P = 0.001) with the relative changes in maximal oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$). According to these findings, it seems that the novel index based on exercise heart rate and running speed may serve a practical tool for daily monitoring individual's training adaptation without needing to realize a maximal running test in laboratory conditions.

Key Words: marathon training, monitoring, running performance

INTRODUCTION

The ultimate aim of the endurance training process is to improve endurance performance. An optimal training program would create sufficient training stimuli, prevent overtraining and stress related injuries and produce favourable adaptations towards desired outcomes at specific times. For achieving optimal adaptation to endurance training, it is necessary to adjust training stimuli according to individual's ability to adapt and tolerate training induced load. The ability to measure and monitor positive and negative adaptations to training would ideally make a valuable contribution to the design of effective training programs. Maximal laboratory tests are used to determine training adaptation precisely. However, they are impractical and expensive to be used on weekly or even monthly basis for continuous monitoring of training adaptation. Therefore, the development of a non-invasive, inexpensive and practical training monitoring method which provides valid information on adaptation to training is important.

Heart rate (HR) is probably the most frequently used method to quantify the training intensity and training load in running. A linear relationship exists between HR and exercise intensity (i.e. energy expenditure, oxygen uptake, running speed) over a wide range of submaximal intensities (2,9). Furthermore, it has been reported that the autonomic nervous system (ANS) has a direct effect on HR and is an important factor in acute and chronic adaptation to training (8,10,16). In addition, it is widely accepted that HR at submaximal exercise decreases after endurance training (6,15,19,20). Buchheit et al. (6) observed a progressive and continued decrease in exercise HR throughout 8 weeks of endurance training (3-4 training sessions·week^{-1}) in recreational endurance runners. The authors concluded that submaximal exercise HR may be an efficient method of assessing autonomic status and thus may be used to track changes in maximal aerobic running speed, at least during the first 2 months of training. However, there are many well-established factors (i.e. duration and intensity of exercise, cardiac drift, dehydration, day-to-day variation, environmental factors) which influence HR response and may disturb relationship between HR and RS in a single exercise (1,5,15). Consequently, the relationship between HR and RS needs to be assessed daily from each exercise for determining adaptation to training.

The aim of this study was to investigate whether HR and RS from each sub-maximal running exercise could be used in monitoring the adaptation to endurance training. Based on the previous researches (6,15,19,20), we expected that submaximal exercise HR would decrease progressively during the training period as a consequence of an increase in cardiorespiratory fitness. Further, we hypothesized that the relationship between exercise HR and RS would be able to track changes in endurance performance during a 28-week endurance training period. We expected that if HR-RS relationship increases (HR at given running speed decreases or if RS at given HR level increases), it means improved endurance performance.

METHODS

Experimental Approach to the Problem

To investigate the practical usefulness of the relationship between HR and RS from in determining adaptation to endurance training, 62 recreational endurance runners were trained for 28 weeks. In addition, the subjects collected training data from all training sessions and they performed a maximal running test on treadmill four times during the training period. The linear relationship between HR and RS accompanied by individual information on resting and maximal HR and speed at VO_{2max} were selected for the basis of the HR-RS index, a novel method for submaximal non-invasive assessment of training adaptation in distance running.

Subjects

A total of 62 (21 women, 41 men) recreational endurance runners (age 35 ± 7 years) enrolled to a 28-week marathon training study which prepared the subjects for a marathon run after the study. All subjects were healthy, non-smokers, non-obese (BMI < 30 $kg \cdot kg^{-1}$), and they did not have any diseases or use regular medication. Most of the subjects had a training background of many years and had already run at least one half or full marathon before they volunteered for this study. Total of 45 participants (15 women, 30 men) were included in the final analyses because 17 subjects dropped out due to prolonged injuries, insufficient training or inadequate use of heart rate monitor and/or GPS pod. The subjects were informed about the design of the study, with special information on possible risks and benefits, and subsequently signed an informed consent document before the start of the study. The study was approved by the Ethics Committee of the local university.

Procedures

Training consisted of progressively increasing endurance training with a 14-week basic training period (BTP) during winter followed by a 14-week intensive training period (ITP) during spring and summer (Table 1). Incremental treadmill tests were performed at weeks 0, 7, 14 and 28. Training mode, duration of the training session, running distance, average HR (HR_{avg}) and rate of perceived exertion (RPE) with Borg's 1–10 scale were collected from each training session by a training diary throughout the whole experiment (3). Subjects used Suunto t6 heart rate monitors with Suunto GPS pod (Suunto Ltd., Vantaa, Finland) to collect the accurate HR and RS data from each training session.

Table 1 about here

Training. The subjects were asked to maintain the same training volume as before the study (3 – 6 times per week) during BTP. The intensity of training was mostly below the lactate threshold (LT), which was individually determined for each subject from the incremental treadmill test (13). Training was periodized into 4-week mesocycles, where 3 hard weeks of training was followed by an easier recovery week. Training consisted mainly of running but occasionally included also other endurance sports such as cycling, Nordic walking and cross-country skiing. Furthermore, the runners were asked to complete strength training 1 – 2 times per week. ITP included higher running training volume (prolonged duration of the training sessions) and intensity compared with BTP. During ITP the ratio between hard training and recovery weeks was 2:1. Training intensity increased in a progressive manner. During the hard weeks the runners were programmed to perform two intensive training sessions, in which the intensity was in the beginning of ITP between LT and respiratory compensation threshold (RCT). Thereafter the intensity was progressively increased above RCT at the end of the ITP. The other endurance training sessions during hard training weeks were performed below LT. Furthermore, the subjects were asked to complete one strength training session per week throughout the ITP.

Incremental treadmill test. Incremental treadmill test was performed by running in the laboratory conditions. Peak running speed (S_{peak}), maximal oxygen uptake (VO_{2max}), RCT and LT were determined from the test (13). The treadmill tests were run for to repeat during at the same time of day (morning, afternoon) and the subjects were advised to avoid eating two to three hours before the treadmill tests. The treadmill test started at 7 $km \cdot h^{-1}$ for women and 8 $km \cdot h^{-1}$ for men and the speed increased by 1 $km \cdot h^{-1}$ every third minute until volitional exhaustion. The incline was kept at 0.5 degrees throughout the whole test. HR (Suunto t6, Suunto Ltd., Vantaa, Finland), and oxygen consumption (Oxygen Mobile®, Viasys Health Care GmbH, Würzburg, Germany) were measured during the whole test. HR and VO_2 were averaged from the last minute of each load for the analyses. Blood samples (20 µL) were taken from fingertip at the end of each load to analyze blood lactate concentrations (La) (Biosen S_line Lab+ lactate analyzer, EKF Diagnostic, Magdeburg, Germany). S_{peak} was considered as the speed at exhaustion. If the subject could not complete the whole 3 min load until exhaustion, S_{peak} [$km \cdot h^{-1}$] was calculated as follows: S [$km \cdot h^{-1}$] + t [s] / (150 [s]) · 1 [$km \cdot h^{-1}$], where S = speed of the last completed stage; t = running time at exhaustion during the last run subtracted by 30 s. Corresponding speed at RCT was determined as S_{RCT}. VO_{2max} was determined as the highest 60 s average VO_2 value during the test.

HR-RS index. The basis of the HR-RS index equation is the linear relationship between HR and RS. HR-RS index represents the absolute difference between the theoretical and actual running speed. The equation of the HR-RS index includes average speed and HR from a submaximal running exercise. In addition, individual standing and maximal HR ($HR_{standing}$ and HR_{max}) as well as running speed corresponding to VO_{2max} or HR_{max} (S_{peak}) from a baseline maximal test (e.g. 3000 m or cooper test) are needed. $HR_{standing}$ was calculated from resting HR (HR_{rest}) with an equation $HR_{standing} = HR_{rest} + 26$ (based on observations of Hynynen et al. (12)). HR_{rest} was measured in the beginning of the study using nocturnal HR recording. HR_{rest} was considered as the lowest average value of 50 consecutive heart beats achieved during the nocturnal HR recording. With these points of reference, a novel equation was created [1]:

$$HR\text{-}RS\ index = (S_{avg}) - \left(\frac{HR_{avg} - HR_{standing}}{k}\right) \quad [1]$$

Where k represents slope and is counted with an equation [2] according to $HR_{standing}$, HR_{max}, S_{peak}, and a speed of standing ($S_{standing}$) (Fig. 1). Since, $S_{standing}$ is 0 (km·h^{-1}), it is not included in the equation [2].

$$k = \left(\frac{HR_{max} - HR_{standing}}{S_{peak}}\right) \quad [2]$$

Figure 1 about here

HR-RS index was calculated from every continuous-type running exercise during the 28-week experiment performed on the flat with correct HR data, running distance and duration. Accuracy of data was visually confirmed using Suunto Training Manager 2.2.0.8 software (Suunto Ltd., Vantaa, Finland). The data was then averaged to a time-dependent factor of average HR-RS index per week in order to achieve reliable comparison in a group of recreational runners with various amounts of running exercises per week. In addition, HR-RS index was calculated from the incremental treadmill tests at the speed of 10 km·h^{-1} which corresponded to the subjects' representative speed of low intensity training.

Statistical Analyses

Values are expressed as mean ± standard deviation (SD) and 95% confidence interval (CI) for mean. The change in HR-RS index was calculated as absolute differences and the change in physiological performance variables as relative differences between the measurement points. The data was analyzed with SPSS Software (SPSS Statistics 17.0 Inc, Chicago, IL). The normal distribution of the data was estimated with Q-Q Plots test. Repeated measures analysis of variance (ANOVA) was used for statistical testing, followed by Bonferroni as a post hoc test. Pearson product moment correlation coefficient was used to determine the relationship between HR-RS index and the training adaptation. The P < 0.05 criterion was used for establishing statistical significance.

RESULTS

Training volume in h/week did not differ between the two training periods, but in km/week it was significantly higher in ITP than in BTP (Table 2). The relative amount of moderate and high intensity training were significantly higher during ITP than in BTP (Table 2).

Table 2 about here

Endurance performance characteristics (VO_{2max}, S_{peak} and S_{RCT}) increased significantly throughout the whole experiment (Table 3). Submaximal HR in the treadmill test at 10 km·h^{-1}

decreased significantly throughout the whole experiment (161 ± 16 bpm, 153 ± 17 bpm, 148 ± 18 bpm, respectively in PRE, WEEK14 and POST, $P < 0.001$ in all cases).

Table 3 about here

HR-RS index calculated from running exercises (HR-RS $index_{exerc}$) and from the treadmill tests (HR-RS $index_{treadmill}$) at the speed of 10 $km \cdot h^{-1}$ increased throughout the experiment, without significant differences between the training periods (Table 3). The change in HR-RS $index_{exerc}$ (ΔHR-RS $index_{exerc}$) correlated significantly with the changes of S_{peak} and S_{RCT} (ΔS_{peak}, ΔS_{RCT}) throughout the experiment (Table 4). The only exception was a non-statistically significant correlation between ΔHR-RS $index_{exerc}$ and ΔS_{RCT} during ITP. ΔHR-RS $index_{treadmill}$ correlated significantly with ΔS_{peak} and ΔS_{RCT} during BTP and from PRE to POST but not during ITP. In addition, ΔHR-RS $index_{exerc}$ correlated with relative changes of VO_2max ($mL \cdot kg^{-1} \cdot min^{-1}$), but only between PRE and POST measurements ($r = 0.49$, $P = 0.001$). Figure 2 illustrates examples of how HR-RS data from daily exercises was related with the changes in the running performance. There were not differences between sexes in any variables related to the change of training adaptations and HR-RS index.

Table 4 about here

Figure 2 about here

DISCUSSION

HR-RS index was created to be a simple, inexpensive and practical method for monitoring the adaptation to endurance training in running. The results of the present study showed that the change in HR-RS index calculated from exercises and treadmill tests correlated significantly with the changes of S_{peak} and S_{RCT} during the 28-week training period. The change in $HR\text{-}RS_{exerc}$ index also correlated significantly with the relative changes in VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$) between PRE and POST measurements. Therefore, the main finding of the present study was that HR-RS index may be an efficient method of monitoring changes in endurance running performance.

Association between HR-RS index and improvements in running performance

In addition to the improvements in running performance, a significant improvement was also observed in HR-RS index calculated from exercises and treadmill tests during the training periods. A significant positive correlation between ΔHR-RS index (calculated from exercises and treadmill tests) and the change in endurance performance (ΔS_{peak}, ΔS_{RCT}) suggest that HR-RS index can be used in monitoring the adaptation to endurance training. HR-RS index improves if HR at given running speed decreases or if RS at given HR level increases. Therefore, the improvement in HR-RS index reflects the changes in cardiorespiratory fitness and endurance performance.

In various previous studies the endurance training has resulted into decreased exercise HR (6,19). Scharhag-Rosenberger et al. (19) reported that submaximal running HR decreased significantly during the beginning of the 12 months of endurance training with constant training intensity, but seemed to plateau after the ninth week of training among previously untrained subjects. The authors suggested that exercise HR does not seem to be an appropriate parameter to indicate fitness changes in long-term training studies of several months (19). Buchheit et al. (6) observed also a progressive and continued decrease in exercise HR throughout 8 weeks of endurance training (3-4 training sessions·week^{-1}) in recreational endurance runners. The authors concluded that submaximal exercise HR may be an efficient method of assessing autonomic status and thus may be used to track changes in maximal aerobic running speed, at least during the first 2 months of training. In the present study, the sub-maximal HR decreased and HR-RS index increased significantly throughout the whole 28 weeks of training. The correlations between the changes in HR-RS and running performance ($\Delta S_{peak,}$ ΔS_{RCT}) in both training periods suggest that HR-RS index indicate fitness changes also during prolonged training among women and men. Using only submaximal exercise HR in monitoring training adaptation does not serve possibility to compare exercises with different intensities in appropriate way because exercise intensity has effect on relation between HR and running speed. During high intensity running exercises, HR increases more than speed causing lower S/HR –ratio compared with low intensity exercises. HR-RS index takes into account this by including individual background factors (HRmax, HRstanding, Speak, Standing) in the equation and calculating theoretical running speed for whole intensity scale (from rest to maximal performance). And further, HR-RS index represents the absolute difference between the theoretical and actual running speed.

The change in HR-RS index$_{exerc}$ also correlated significantly with ΔVO_{2max} (mL·kg^{-1}·min^{-1}) between PRE and POST measurement points, but not during BTP or ITP. It has been previously reported that cardiovascular autonomic function is more closely related to endurance running performance than to oxygen uptake (11,14). The findings of the present study support these findings, since a higher correlation was observed between the changes in HR-RS index and

ΔS_{peak} than HR-RS index and ΔVO_{2max}. It is remarkable since maximal aerobic running speed is thought to be a superior predictor of endurance performance (4,18). These findings support observations that HR-RS index may be used to track changes in maximal endurance performance.

Considerations of the HR-RS index method

The reliability of the HR-RS index is highly dependent on the accuracy of the measurement of distance or speed in exercises. The speed determined by the GPS receiver is within 0.2 $m \cdot s^{-1}$ of the true speed measured for 45% of the values with a further 19% lying within 0.4 $m \cdot s^{-1}$ (22). GPS data loggers are therefore accurate for the determination of speed over-ground on relatively straight courses. It has been reported that internal factors such level of dehydration, body temperature and cardiac drift may disturb the relationship between HR and RS in single exercise, especially in high intensity and prolonged exercises (1,5,15). External factors such as running surface, ascent/descent during the exercise, wind, air temperature, humidity and time of day have also effect on relationship between HR and RS in single exercise. Hot and humid environments, windy conditions, hilly terrain and the hypoxic conditions at higher altitudes can all increase exercise HR, and thus decrease HR-RS index (15,17). To overcome these limitations, HR-RS index was also calculated from the treadmill tests with standard protocols and environmental conditions. One may assume that HR-RS index is more reliable when it is calculated from treadmill running at constant velocity than when it is calculated from outdoor exercises, since the conditions and running speed can be standardized in laboratory but not in outdoor conditions. However, similar correlations were observed between the changes in endurance performance characteristics and HR-RS index calculated from treadmill running at 10 $km \cdot h^{-1}$ and when the

HR-RS index was calculated from the outdoor exercises. The reason for this may be that only one measurement was included when the HR-RS index was calculated from the treadmill test and the average value of 2 – 4 exercises were used in outdoor HR-RS index. Consequently, it seems to be that by using one week average value of HR-RS index the effect of external and internal factors can be minimized or decreased (see trendlines in Fig. 2). This may also help to avoid possible misinterpretation due to day-to-day variation in HR (15) or abnormal HR and/or RS of one single exercise (e.g. due to special environmental conditions). Lambert et al. (15) concluded that under non-competitive conditions HR-RS relationship is fairly constant but during competition HR is not an accurate indication of RS. It is possible that the same phenomenon exists in laboratory tests which could explain generally weaker correlation between the change of $HR\text{-}RS_{treadmill}$ and running performance in spite of standardized conditions.

It seems that HR-RS index serves the most valid information about the training adaptation when exercise conditions, duration and intensity of exercise have been standardized and HR-RS index data have been averaged for a longer period. The method compares the current training status to pre-training status and therefore does not take into account the possible changes in $HR_{standing}$, HR_{max} or S_{peak} caused by endurance training. If training has led to positive training adaptation, the current training status is better than pre-training status which exists as a positive HR-RS index. The significant correlations between ΔHR-RS index and the change in endurance capacity (ΔS_{peak}, ΔS_{RCT}, ΔVO_{2max}) show that ΔHR-RS index may be used in monitoring the training adaptation. This, however, is shown in this study to be true after a minimum of 14 weeks of training. Further investigations are required for evaluating the use of HR-RS index during shorter time periods and to examine additional aspects of HR-RS index.

PRACTICAL APPLICATIONS

The practical implications from the present study are that athletes and coaches can be confident in monitoring changes in endurance performance during training in the novel method. HR-RS index provides daily information about the adaptation to endurance training from different kind of running exercises without need to repeat laboratory tests during training. HR-RS index does require a baseline maximal field test (e.g. 3000m, cooper test) for determining HR_{max} and running speed corresponding to VO_{2max} but after that normal running training with training information collections (running speed, HR) is adequate for monitoring changes in endurance performance during training. With the help of modern technology, like heart rate monitors and smartphones with GPS systems, it is able to get easily required information from every continuous-type running exercises for determining HR-RS index. The novel method is more practical and it provides daily information on adaptation to training for athletes and coaches compared to impractical and expensive maximal laboratory tests, which provide usually information on the adaptation a few times per year. Further, HR-RS index enables faster changes in training programs if training has led undesirable outcomes and help to achieve better adaptation to endurance training.

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FIGURE LEGENDS:

Figure 1. The basis of HR-RS index formula is the linear relationship between heart rate and running speed. Individual background information of standing heart rate ($HR_{standing}$), maximal heart rate (HR_{max}) and running speed corresponding to VO_{2max}/HR_{max} (S_{peak}) were used to calculate a theoretical running speed for any heart rate value.

Figure 2. HR-RS index from each running exercise of an arbitrary male (A) and female (B) subject is presented with bars and a moving average trendline. Change (%) in S_{peak} measured

from incremental treadmill tests are presented with squares and in S_{RCT} with dots.

TABLE LEGENDS:

Table 1. The progressive training design for 28 weeks of training.

! = exercises were not performed during recovery weeks.

High intensity = above respiratory compensation threshold, moderate intensity = between respiratory compensation threshold and lactate threshold, low intensity = below lactate threshold.

Table 2. Training volume and relative intensity during the training periods are means ± SD (95%

CI).

/ * = significant difference between the periods (*P*< 0.01 / *P* < 0.001).

Low intensity training = below lactate threshold, moderate intensity training = between respiratory compensation threshold and lactate threshold, high intensity training = above respiratory compensation threshold.

Table 3. Endurance performance variables and HR-RS index are means ± SD (95% CI).

* = Significant difference to preceding measurement point, # = significant difference to PRE. (*/#*P* < 0.05, **/## *P* < 0.01, ***/### *P* < 0.001).

VO_{2max} = maximal oxygen consumption, S_{peak}, peak treadmill running speed; S_{RCT}, speed at respiratory compensation threshold, HR-RS index = heart rate - running speed index.

Table 4. Correlations between ΔHR-RS index and changes in endurance performance.

*/ **/ *** = significant correlation (*P* < 0.05 / *P* < 0.01 / *P* < 0.001, respectively)

HR-RS index_{exerc} = heart rate - running speed index from exercises, HR-RS $\text{index}_{treadmill}$ = heart rate - running speed index from treadmill tests, VO_{2max} = maximal oxygen consumption, S_{peak}, peak treadmill running speed; S_{RCT}, speed at respiratory compensation threshold.

Table 1. The progressive training design for 28 weeks of training.

	Basic training period	Intensive training period		
	weeks 1-14	weeks 15-19	weeks 20-24	weeks 25-28
High intensity training	-	-	1 session [!], 4 - 5 km	2 sessions [!], 4 - 5 km
Moderate intensity training	-	2 sessions [!], 8 - 10 km	1 session [!], 8 - 10 km	-
Long low intensity training	1 session, 15 - 20 km	1 session, 20 - 25 km	1 session, 20 - 30 km	1 session, 25 - 30 km
Normal low intensity training	2 - 5 sessions, 5 - 15 km	1 - 4 sessions, 5 - 15 km	1 - 4 sessions, 5 - 15 km	1 - 4 sessions, 5 - 15 km
Strength training	1 - 2 sessions	1 session	1 session	1 session

! = training sessions were not performed during recovery weeks.

High intensity = above respiratory compensation threshold, moderate intensity = between respiratory compensation threshold and lactate threshold, low intensity = below lactate threshold.

Table 2. Training volume and relative intensity during the training periods are means ± SD (95% CI).

	Basic training period	Intensive training period
Training sessions·week^{-1}	4.7 ± 1.0	4.3 ± 0.8***
	(4.5 - 5.0)	(4.0 - 4.6)
h·week^{-1}	5.6 ± 1.4	5.7 ± 1.5
	(5.2 - 6.1)	(5.3 - 6.2)
km·week^{-1}	33.5 ± 14.0	46.2 ± 16.2***
	(29.3 - 37.7)	(41.3 - 51.1)
Low intensity training (%)	86.1 ± 9.8	76.0 ± 14.0***
	(83.2 - 89.1)	(71.8 - 80.2)
Moderate intensity training (%)	11.4 ± 8.8	19.7 ± 12.7***
	(8.8 - 14.0)	(15.8 - 23.5)
High intensity training (%)	2.5 ± 2.1	4.4 ± 3.6**
	(1.8 - 3.1)	(3.3 - 5.4)

/ * = significant difference between the periods ($p < 0.01$ / $p < 0.001$).

Low intensity training = below lactate threshold, moderate intensity training = between respiratory compensation threshold and lactate threshold, high intensity training = above respiratory compensation threshold.

Table 3. Endurance performance variables and HR-RS index are means ± SD (95% CI).

	PRE	WEEK7	WEEK14	POST
VO_{2max} ($L \cdot min^{-1}$)	3.4 ± 0.8	3.5 ± 0.8	3.5 ± 0.8##	3.5 ± 0.8###
	(3.1 - 3.7)	(3.2 - 3.7)	(3.2 - 3.8)	(3.3 - 3.8)
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	46.4 ± 8.5	47.3 ± 8.8#	48.1 ± 8.8##	49.2 ± 9.1*###
	(43.7 - 49.1)	(44.5 - 50.1)	(45.2 - 50.9)	(46.3 - 52.2)
S_{peak} ($km \cdot h^{-1}$)	13.9 ± 2.3	14.1 ± 2.4###	14.4 ± 2.4***###	15.0 ± 2.5***###
	(13.2 - 14.5)	(13.5 - 14.8)	(13.7 - 15.2)	(14.2 - 15.7)
S_{RCT} ($km \cdot h^{-1}$)	11.3 ± 2.0	11.6 ± 2.0###	12.0 ± 2.1***###	12.5 ± 2.1***###
	(10.7 - 11.9)	(11.1 - 12.2)	(11.4 - 12.6)	(11.9 - 13.2)
HR-RS index	0.7 ± 0.9	1.0 ± 1.0#	1.1 ± 1.0###	1.6 ± 1.1** ###
(from exercises)	(0.4 - 0.9)	(0.7 - 1.3)	(0.8 - 1.5)	(1.3 - 1.9)
HR-RS index	-0.6 ± 1.0	0.1 ± 1.0###	0.3 ± 1.2###	0.9 ± 1.3***###
(from treadmill tests)	(-0.9 - -0.3)	(-0.2 - 0.3)	(0.0 - 0.7)	(0.5 - 1.3)

* = Significant difference to preceding measurement point, # = significant difference to PRE.

(*/# $p < 0.05$, **/## $p < 0.01$, ***/### $p < 0.001$).

VO_{2max} = maximal oxygen consumption, S_{peak}, peak treadmill running speed; S_{RCT}, speed at respiratory compensation threshold, HR-RS index = heart rate - running speed index.

Table 4. Correlations between ΔHR-RS index and changes in endurance performance.

	PRE-WEEK14		WEEK14-POST		PRE-POST	
	ΔHR-RS $index_{exerc}$	ΔHR-RS $index_{treadmill}$	ΔHR-RS $index_{exerc}$	ΔHR-RS $index_{treadmill}$	ΔHR-RS $index_{exerc}$	ΔHR-RS $index_{treadmill}$
ΔVO_{2max} ($L \cdot min^{-1}$)	0.17	0.07	-0.11	-0.30	0.29	0.06
ΔVO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	0.23	0.24	-0.08	-0.18	0.49**	0.27
ΔS_{peak} ($km \cdot h^{-1}$)	0.43**	0.53***	0.43**	0.17	0.61***	0.49**
ΔS_{RCT} ($km \cdot h^{-1}$)	0.39*	0.34*	0.23	0.21	0.35*	0.41**

*/ **/ *** = significant correlation ($p < 0.05$ / $p < 0.01$ / $p < 0.001$, respectively)

HR-RS $index_{exerc}$ = heart rate - running speed index from exercises, HR-RS $index_{treadmill}$ = heart rate - running speed index from treadmill tests, VO_{2max} = maximal oxygen consumption, S_{peak}, peak treadmill running speed; S_{RCT}, speed at respiratory compensation threshold.

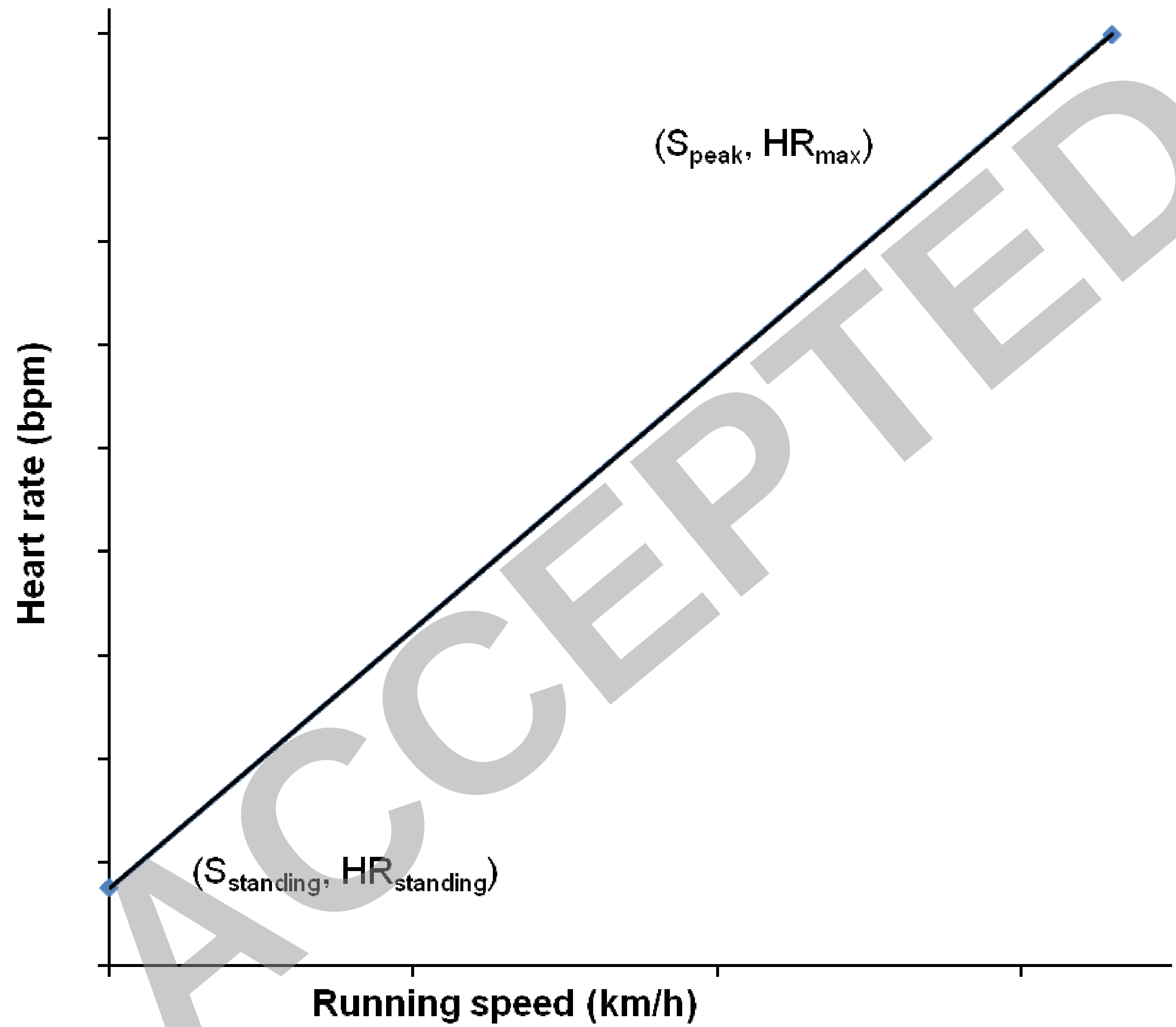

Figure 1. The basis of HR-RS index formula is the linear relationship between heart rate and running speed. Individual background information of standing heart rate ($HR_{standing}$), maximal heart rate (HR_{max}) and running speed corresponding to VO_{2max}/HR_{max} (S_{peak}) were used to calculate a theoretical running speed for any heart rate value.

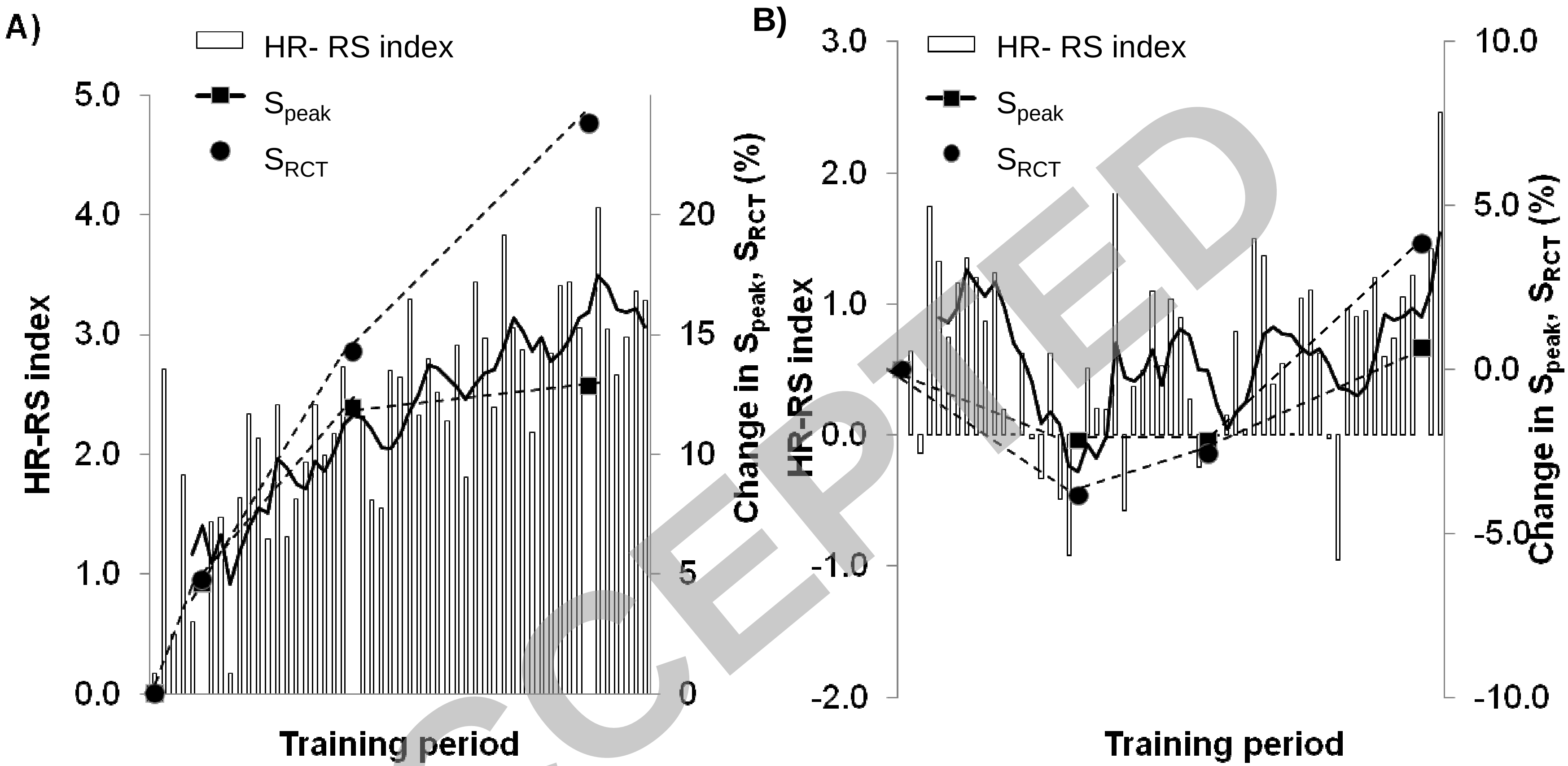

Figure 2. HR-RS index from each running exercise of an arbitrary male (A) and female (B) subject is presented with bars and a moving average trendline. Change (%) in S_{peak} measured from incremental treadmill tests are presented with squares and in S_{RCT} with dots.