

Change in Performance in Response to Training Load Adjustment Based on Autonomic Activity

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Key words

- heart rate variability
- exercise
- vagal activity
- adaptability
- athlete

Abstract

The primary aim of this study was to assess performance (Perf) changes in response to a new training strategy. Specifically, based on spectral analysis of heart rate variability (SA HRV) to determine autonomic nervous system (ANS) activity, training doses were adjusted to maintain vagal activity at a high and relatively stable level during training preparation. Trained athletes (5 male and 5 female) aged 23.2 ± 4.2 years voluntarily participated in the study. ANS activity was assessed during an orthoclinostatic test, and was represented by calculating HRV variables and a total score index. Over 17 weeks, improvement

(1.4–8.5%) and deterioration (0.1–8.8%) in Perf were detected in 7 and 3 athletes, respectively. A relationship ($r_s = 0.684$; $P < 0.05$) between the change in Perf (Δ Perf) and supine PHF during season was found. Supine HRV indices (P_{HF} , P_T , and MSSD) for the last 3 weeks of the HRV-adjusting period correlated ($r_s = 0.636$; 0.648 ; 0.648 , $P < 0.05$) with Δ Perf. Based on the results, a high and relative stable vagal activity during preparation may indicate a readiness to train or appropriate recovery that positively affects Perf. In conclusion, daily quantification of ANS activity by SA HRV seems to be a promising tool for the enhancement of Perf.

Introduction

Several cross-sectional studies have shown that training and/or non-training stress stimuli induce modifications in heart rate variability (HRV) [3, 4, 6–10, 16, 17, 19–26]. Spectral analysis (SA) of RR intervals to determine HRV is commonly accepted as a non-invasive method for autonomic nervous system (ANS) activity assessment [1]. The high-frequency (HF) oscillations in R-R intervals, has been shown to reflect the cardiac vagal outflow [1, 36], while reciprocal changes between vagal and sympathetic activity are assessed via analysis of low frequency power (P_{LF}) [44] and LF/HF [31], respectively. Very low frequency power (P_{VLF}) is possibly related to the renin-angiotensin system and/or thermoregulatory peripheral blood flow adjustment [44], while the VLF/HF ratio has also been recognized as a marker of sympathovagal balance [41]. Previous studies demonstrated individual differences in the response to the same endurance load [19, 22]. This inter-individual variation in adaptation to training may depend on the level of baseline ANS activity, particularly vagal activity [19].

In the context of competition, a high vagal activity has been associated with both enhanced performance [3, 9, 12, 13, 16] and improved aerobic capacity [4, 19–21, 34]. On the other hand, both fatigue, and a state of overreaching, the result of an imbalance between intensified training and subsequent recovery, are linked with a withdrawal of vagal activity and a shift towards sympathetic dominance [6, 19, 23, 35]. These negative training consequences are coupled with a transient reduction in performance [3, 11, 23, 27]. However, a shift in sympathovagal balance towards sympathetic dominance was also linked with an increase in cardiovascular performance [25] and served as a predictor of athletic achievement [29] during a peak training period.

To date, only a few studies have used the SA HRV method for the longitudinal adjustment of training load according to vagal activity in trained individuals [9, 26]. However, in these studies, the resting HRV analysis was performed either supine or standing. It is well known that orthostatic stress decreases vagal activity and stimulates sympathetic activity [15, 28], whereas clinostasis stimulates vagal activity [44]. In order

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Bibliography

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Table 1 Basic characteristics of the athletes.

Parameter [unit]	Male [N = 5]	Female [N = 5]
age	22.82	21.00
[years]	5.76	3.39
career length	8.40	6.03
[years]	4.50	2.52
BMI	22.38	20.19
[kg m ⁻²]	1.87	0.87
body fat	7.81	12.95
[%]	2.39	5.42
HRmax	199.00	199.00
[BPM]	11.41	3.67
HRrest	49.00	47.80
[BPM]	8.21	5.26
VO ₂ max	64.43	55.04
[ml min ⁻¹ kg ⁻¹]	3.97	4.68

N – number of subjects; HRrest – resting heart rate; HRmax – maximal heart rate; BMI – Body Mass Index; BPM – beats per minute; VO₂max – maximal oxygen consumption; % – percent. Values are presented as means ± SD

to enhance the sensitivity of measuring small reciprocal changes in the vagal and sympathetic pathways, ANS was quantified from electrocardiogram (ECG) sampling in both a standing and supine position.

Based on previous research that examined athletic adaptation capacity or “trainability” to aerobic and anaerobic training based on HRV [8, 19, 20, 22], the current study hypothesised that high level of vagal activity, before training, represented a recovered state and readiness for intensive training. This in turn would ensure a better adaptation capacity and training response to exercise.

The main purpose of this study was to assess the change in athletic performance (Δ Perf) in response to HRV-adjusted training load in trained athletes. Specifically, based on SA HRV determination of ANS activity, training doses would be adjusted to maintain vagal activity at a high and relatively stable level during training preparation in order to both maximise the training response and avoid chronic fatigue.

Methods



Participants

10 national level athletes [5 male (σ) and 5 female (φ)] volunteered to participate in this study. They specialised in athletics events [decathlon (N=1, σ); heptathlon (N=1, φ); 400m hurdles (N=2, φ); 1500m (N=2, φ), 110m hurdles, (N=1, σ), long jump (N=1, σ); inline skating (N=1, φ), and fin-swimming (N=1, φ). The study was performed in conformity with the ethical guidelines according to International Journal of Sports Medicine [18]. Basic characteristics of the subjects are presented in **Table 1**. The research design was approved by the ethics committee of the Faculty of Physical Culture at the Palacký University, and the subjects provided written informed consent.

Experimental procedures

7 days prior to the start of the HRV-adjusting period the athletes underwent preliminary medical screening to determine the presence of any limitations that may prevent them from performing maximal exertion testing. The subjects were required to avoid eating, drinking coffee, tea and/or any substance affecting

the ANS activity for a minimum of 2 h before the preliminary measurements. In addition, they were instructed to avoid vigorous physical activity and alcohol for 48 h before testing. The HRV-guided training period consisted of 17 successive training weeks over the spring and summer preparation phases that were then followed by competitions. During this period, the athletes followed periodised training programs set by their coaches. The fundamental idea underlying the adjusting process was to manipulate training load in order to avoid progressive and long-term impairment in ANS activity, represented by a reduction in vagal activity accompanied by sympathetic domination. The load adjustment, if necessary, was primarily focused on the manipulation of the exercise intensity, since intensity has been shown to cause a significant reduction in vagally modulated HRV variables [2, 33, 41]. In addition, exercise intensity has been shown to play an important role in the time course of recovery [20, 39]. Therefore, a progressive vagal activity reduction and a relative sympathetic increase resulted in the instruction to decrease training intensity in order to enhance recovery and to improve the level of vagal cardiac regulation. In contrast, appropriate recovery, reflected by a high level of vagal activity, represented a favourable condition for an increase in training intensity [26]. However, if there was no improvement in ANS activity after intensity manipulation, the training volume was altered in the same manner. All athletes performed 5 training bouts per week (1 training session per day).

Testing procedures

Anthropometrical assessment

Each athlete had their body mass (digital SOEHNLE scale, Germany) and stature measured. Percentage body fat was estimated from the measurement of 10 skin-folds using a Best's caliper II K-501 (Trystom, Czech Republic) and using the prediction equation provided by Pařízková [32].

Maximal stress test

The athletes performed a graded maximal stress test on a treadmill (Lode Valiant, Netherlands) in order to obtain maximal oxygen consumption (VO₂max) and maximal heart rate (HRmax). The protocol design differed according to gender. For female/male, the protocol consisted of an 8-min warm-up period (4 min at 7/8 km·h⁻¹ and 4 min 8/10 km·h⁻¹) followed by an increased in speed to 10/12 km·h⁻¹ for 1 min. Thereafter, the inclination increased by 2.5% every min until exhaustion. Breath-by-breath ventilation and gas exchange (ZAN 600 Ergo USB, Germany) were continuously analysed during the exercise with the data averaged to 30s for analysis. The VO₂max was recorded as the highest oxygen consumption value in the final 30s of the test. The following criteria were used to document that VO₂max had been attained during each test: i) a lack of increase in VO₂ upon an increase in work rate; and ii) a respiratory exchange ratio >1.10 [40]. HR responses (Polar, Finland) were monitored continuously during maximal stress test.

Heart rate variability analysis

For determination of ANS activity and resting HR (HRrest), ECG was sampled using a microprocessor diagnostics device VarCor PF 7 and software VarCorSport PC (DIMEA Group, Czech Republic). The measurement protocol for ANS assessment was as follows: sitting resting period of 10 min, supine, standing, and supine. The supine or standing position lasted at least 5 min, and at least 300 beats were recorded [38]. The raw ECG record was

examined, and all premature ventricular contractions, missing beats or any artefacts were filtered. Average HR_{rest} was calculated over the second supine period. "Short term" SA HRV was used for the assessment of the ANS activity. A set of 256 artefact-free subsequent R-R intervals was obtained from each period (supine or standing), and the Fast Fourier Transform with a partly modified Coarse-Graining Spectral Analysis algorithm [46] was performed. The power spectra were quantified by integrating the area under the power spectral density curve. 3 frequency bands were used [38]: very-low-frequency power (P_{VLF}) from 0.02 to 0.05 Hz, low-frequency power (P_{LF}) from 0.05 to 0.15 Hz and high-frequency power (P_{HF}) from 0.15 to 0.50 Hz. Total power (P_T) was calculated from the whole frequency band from 0.02 to 0.50 Hz. The P_{VLF}/P_{HF} ratio and P_{LF}/P_{HF} ratio were also calculated. For time domain analysis, the mean square successive difference (MSSD) of R-R intervals was computed for each period.

Algorithms used for training load adjustment

Before the HRV-adjustment started, all athletes were familiarised with the use of both the diagnostic system (VarCor PF 7) and software (VarCorSport PC). The daily home-based ANS activity assessments were performed in a quiet room (ambient temperature of 22–24°C) according to the described measurement protocol. The ECG record was saved to the athlete's personal computer using the diagnostic software (VarCorSport PC). The software performed an automated HRV analysis for training load recommendation according to the algorithm described below. Assessments were performed upon awaking between 6:30 AM to 8:00 AM on each training day. The athletes were instructed to maintain their same dietary and hydration habits throughout the study.

An adjustment algorithm that is part of the VarCorSport PC diagnostics software was used to calculate the complex indices of SA HRV [42], specifically the total score (TS) index. The TS index was calculated taking into account the effects of age [43] and exercise intensity [41] on the commonly used short-term SA HRV parameters [44] obtained from the standing and second supine position of the orthoclinostatic manoeuvre. The TS index was calculated from a previously developed algorithm [42]. In summary, using factor analysis, the age-dependent parameters were combined into 5 factors (F1–F5), as well as independently based on their relation to age (for %HF in supine position, R-R, and LF/HF in standing). These factors were named: F1–CCV_{HF} [supine]; F2–CCV_{LF} [standing]; F3–CCV_{HF} [standing]; F4– P_{LF}/P_{HF} [standing]; and F5– P_{VLF}/P_{HF} [supine]). Based on the coefficient of correlation of the factor, each factor was assigned a distinct weighting. Following this, parameters that were similarly affected by age were divided into the following 4 groups (G₁–G₄), with supine (F1+% P_{HF}) and standing (F2+F3) parameters that decrease with age being placed in G1 and G2, respectively. Supine (F4+F5) and standing (R-R, P_{LF}/P_{HF}) parameters that increase with age were placed in G3 and G4, respectively. The TS index combines the factors and parameters that decrease with age (F1, F2, F3, and % P_{HF}) and were considered to represent the vagal activity (positive interpretation) with factors and parameters that increase with age (F4, F5, RR in standing, and P_{LF}/P_{HF} in standing) and indicate the sympathovagal balance (negative interpretation). The reference values for the TS index range from –5.0 to +5.0 points. The physiological values for the TS index range from –1.5 to +1.5 points [42].

It is assumed that the TS changes occurring with aging are negative. Based on this understanding the TS value can be used to represent the "age" of the level of ANS activity. A special variable, the so-called the Functional Age (FA) [42], calculated based on TS index, was used for the general assessment of the ANS. The unit for FA is years and hence the FA provides more meaningful and straightforward information compared with the TS. Specifically, the higher the TS value, the lower the FA of the ANS compared to the calendar age of the tested individual indicating a better ANS state, and vice versa [42].

Adjustment of the training load occurred according to the following algorithm: Adjustment only occurred after a minimum of 5 ANS assessments (1 actual and 4 previous) or a maximum of 20 ANS assessments (1 actual and 19 previous). When more assessments were available, the algorithm processed the newest 20 assessments only and the older ones were omitted. The arithmetic mean FA_{AP} was calculated from all (actual and previous) evaluations of FA. The arithmetic mean (FA_p) and standard deviation (SD) were calculated from previous evaluations of FA. If the difference between FA_{AP} and FA_p did not exceed one year, $|FA_{AP} - FA_p| \leq 1$, it meant that the current assessment was consistent with previous assessments and all assessments described the long-term state of the ANS. If the condition was met, the current assessment was included with the previous assessments and further analysis continued. If the condition was not met the current assessment was included, but the algorithm was not processed until the next ANS examination was performed.

The whole range of FA was divided into 4 intervals using percentiles taken from the normal distribution $N(FA_p, SD)$. The selected percentiles were 20%, 70% and 95%. The recommended training load depended on the interval in which the actual value FA_A fell.

- Interval I: $FA_A < FA_p - 0.842 \cdot SD$. This meant that FA_A was below the 20th percentile value → Recommendation I: The functional state of the heart regulatory system is optimal. We recommend an increase in training quality, where athlete is able to perform the training at a high intensity.
- Interval II: $FA_A \geq FA_p - 0.842 \cdot SD$ and $FA_A < FA_p + 0.524 \cdot SD$. This meant that FA_A was between the 20th and 70th percentile values → Recommendation II: The functional state of the heart regulatory system is optimal. We recommend continuing with the existing training model.
- Interval III: $FA_A \geq FA_p + 0.524 \cdot SD$ and $FA_A < FA_p + 1.645 \cdot SD$. This meant that FA_A was between the 70th and 95th percentile values → Recommendation III: The functional state of the heart regulatory system has deteriorated slightly. We recommend reducing the training load to below the existing level and focusing on recovery.
- Interval IV: $FA_A \geq FA_p + 1.645 \cdot SD$. This meant that FA_A was above the 95th percentile value → Recommendation IV: The functional state of the heart regulatory system deteriorated excessively, we recommend a temporary interruption of the training process and substituting training with valuable regeneration. Further training was possible only after assessment of the autonomic nervous system.

Change in performance determination

An individual Δ Perf was determined as the difference between the best sport result achieved during the last 6 weeks of the HRV-adjusting period and the best result from the previous season. The Δ Perf value was further expressed as a percentage (% Δ Perf). The Perf level of the athletes was assessed during the control contests (except decathlon and heptathlon) and the

official competitions, respectively. Each athlete underwent a minimum of 2 performance assessments.

Training loads quantification

Despite the heterogeneity relating to their specific training, all athletes used HR monitors (Polar S810i, Polar Electro, Kempele, Finland) during the majority of their training sessions to assess training intensity. HR record was transmitted by a Polar infrared interface and saved onto the athlete's pc or laptop after each training unit. All HR records were sent to the laboratory by e-mail after each experiment for further analysis via Polar software (Polar Precision Performance 4.0). The calculation of the training impulse (TRIMP) proposed by Banister [5] was performed according to the following formula: $TRIMP = TD * R * W$, where TD was the training session duration expressed in minutes. The reserve (R) was determined by the following formula: $R = (HR_t - HR_{rest}) / (HR_{max} - HR_{rest})$, where HR_t was the mean HR of the training session. The weighting factor (W) was determined using the following formula: $W = 0.64 * \exp(1.92 * R)$, where exp denotes the exponential function.

Statistical methods

All statistical analyses were performed using StatisticaCZ version 10.0. Normal distribution of the analysed data was checked using the Kolmogorov-Smirnov test. Because of the non-normal distribution of the data as well as the low number of subjects, the Spearman correlation coefficient (r_s) was calculated to examine relationships between the given variables. The Wilcoxon test was conducted to examine the differences in assessed spectral and time domain HRV parameters between the starting (the first of 15 HRV measurements) and the ending phase (the last of 15 HRV measurements) in order to analyse the tendency of HRV variables during preparation. Differences in TRIMP between the starting and the ending phase were analysed by

paired Student's t-test. In all analyses, $P < 0.05$ was considered to be statistically significant. The probability value for trends was set at level of $P < 0.10$. Data are expressed as means $\pm$ SD.

Results



An average of 85.87 ± 5.61 /athlete ANS activity assessments was performed during the training preparation. Athletes received a mean of 79.00 (7.01) recommendations with 50.85% (9.32) thereof serving to maintain a predefined training load, 19.65% (5.97) to increase in training load, 20.50% (13.09) to decrease exercise load and 9.10% (4.09) to temporally interrupt the training to enhance recovery. The mean of TRIMP/training during the starting period (108.16 ± 23.05) was significantly higher ($P < 0.008$) than in the ending period (100.56 ± 19.33) in the group of athletes.

In standing HRV, there was a significant increase in mean P_T in the ending period compared to the starting period. The mean HR and P_{HF} tended to decrease and increase ($P < 0.093$) in the standing position, respectively (● Table 2). None of the supine HRV variables changed significantly between the starting and the ending period (● Table 3). No significant changes in the mean TS were found between the starting and the ending period (● Fig. 1). Improvement (1.4–8.5%) and deterioration (0.1–8.8%) in Perf between subsequent periods within the seasons were detected in 7 and 3 athletes, respectively. A relationship ($r_s = 0.684$; $P \leq 0.05$) between $\Delta Perf$ and mean supine P_{HF} was demonstrated throughout the preparation period (● Fig. 2). The mean supine P_{HF} , P_T , and MSSD during the last 3 weeks of the HRV-adjusting period were positively correlated ($r_s = 0.636$; 0.648; 0.648, $P \leq 0.05$) with $\Delta Perf$ (● Fig. 2).

Parameter (unit)	over season	S ₁₅	E ₁₅	P (S ₁₅ vs. E ₁₅)
P_{VLF} (ms ²)	527.17 $\pm$ 362.80	500.56 $\pm$ 462.80	574.70 $\pm$ 343.60	0.386
P_{LF} (ms ²)	1085.21 $\pm$ 842.77	977.00 $\pm$ 778.60	1128.39 $\pm$ 795.92	0.114
P_{HF} (ms ²)	1266.69 $\pm$ 2330.30	1099.64 $\pm$ 2053.81	1504.53 $\pm$ 2854.77	0.093
P_T (ms ²)	2879.07 $\pm$ 3074.06	2577.19 $\pm$ 2939.34	3207.62 $\pm$ 3489.25	0.017
P_{VLF}/P_{HF}	1.80 $\pm$ 1.63	1.74 $\pm$ 1.44	1.81 $\pm$ 1.63	0.721
P_{LF}/P_{HF}	4.02 $\pm$ 3.37	4.07 $\pm$ 3.44	3.79 $\pm$ 2.99	0.386
MSSD (ms ²)	3507.44 $\pm$ 6348.61	3202.41 $\pm$ 5799.69	3947.81 $\pm$ 7274.74	0.139
HR (BPM)	76.02 $\pm$ 14.27	77.77 $\pm$ 15.04	74.18 $\pm$ 12.98	0.093

P_{VLF} – very low frequency power; P_{LF} – low frequency power; P_{HF} – high frequency power; P_T – total power; MSSD – mean square successive difference; HR – heart rate, BPM – beats per minute, S₁₅ – starting period; E₁₅ – ending period; P – significance level (Wilcoxon test). Values are presented as means $\pm$ SD

Table 2 Differences in standing heart rate variability parameters and heart rate between the starting and the ending period.

Parameter (unit)	over season	S ₁₅	E ₁₅	P (S ₁₅ vs. E ₁₅)
P_{VLF} (ms ²)	591.13 $\pm$ 362.55	489.29 $\pm$ 239.94	603.80 $\pm$ 343.60	0.508
P_{LF} (ms ²)	1326.36 $\pm$ 894.43	1035.14 $\pm$ 588.50	1387.19 $\pm$ 1128.17	0.646
P_{HF} (ms ²)	4772.73 $\pm$ 3051.60	4666.37 $\pm$ 2851.88	4543.58 $\pm$ 2937.63	0.241
P_T (ms ²)	6690.22 $\pm$ 3620.52	6190.81 $\pm$ 3230.99	6514.87 $\pm$ 3647.99	0.721
P_{VLF}/P_{HF}	0.26 $\pm$ 0.22	0.22 $\pm$ 0.26	0.22 $\pm$ 0.16	0.575
P_{LF}/P_{HF}	0.56 $\pm$ 0.49	0.36 $\pm$ 0.30	0.52 $\pm$ 0.51	0.415
MSSD (ms ²)	18673.19 $\pm$ 11614.52	18332.12 $\pm$ 10933.87	16941.09 $\pm$ 10711.21	0.169
HR (BPM)	51.55 $\pm$ 9.50	51.61 $\pm$ 8.76	51.59 $\pm$ 10.14	0.959

P_{VLF} – very low frequency power; P_{LF} – low frequency power; P_{HF} – high frequency power; P_T – total power; MSSD – mean square successive difference; HR – heart rate, BPM – beats per minute, S₁₅ – starting period; E₁₅ – ending period; P – significance level (Wilcoxon test). Values are presented as means $\pm$ SD

Table 3 Differences in supine heart rate variability parameters and heart rate between the starting and the ending period.

Discussion

An adjustment of training doses based on ANS activity measured by SA HRV during an orthoclinostatic manoeuvre prior to each training session over a 17 week period was associated with ΔPerf that ranged from -8.8% to $+8.5\%$.

It has been repeatedly shown that a reduction in vagal activity mirrors insufficient recovery from previous exercise [13, 19, 21]

which may indicate an unfavourable physiological condition for high intensity training [26]. On the other hand, high vagal activity before training was associated with a good training response [20, 22] and better adaptation capacity to aerobic and anaerobic exercise training [8, 19]. In the present study, a decline in morning vagal activity resulted in a reduction of training load in order to enhance recovery, while a high level of vagal activity represented a favourable condition for an increase in training quality. The results demonstrated that the TS index, representing overall ANS activity, calculated from HRV variables obtained in both standing and second supine positions of the orthoclinostatic manoeuvre [42], did not change significantly from the starting to the ending period in the athletes as a result of the daily training load adjustment. The findings demonstrate that a daily training load adjustment induced a significant increase in standing ANS activity. In this position, there was a tendency for an increase in vagal activity with a simultaneous reduction ($P < 0.093$) in HR from the ending to the starting period. On the other hand, there were no significant changes in any of the supine HRV variables or HR from the starting to the ending period. In supine position, the mean resting HR ranged from 37–56 BPM, except in the case of one athlete with a resting HR of 73 BPM. Previous studies [17, 45] reported that when resting HR reached a level ≤ 50 BPM a plateau or even a decrease in vagally related HF power may occur. In this regard, Kiviniemi et al. [26] noted that HF power, when assessed in individuals with a low resting HR, may be unable to detect changes in cardiac vagal regulation in training intervention studies. Taken together, we

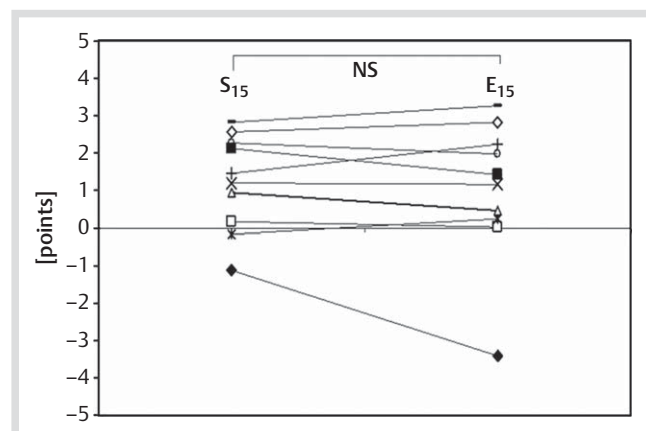


Fig. 1 Statistical analysis of differences in the total score index between the starting and the ending period. S₁₅ = starting period; E₁₅ = ending period; NS = non-significant (Wilcoxon test), one geometric shape represents one measured athlete.

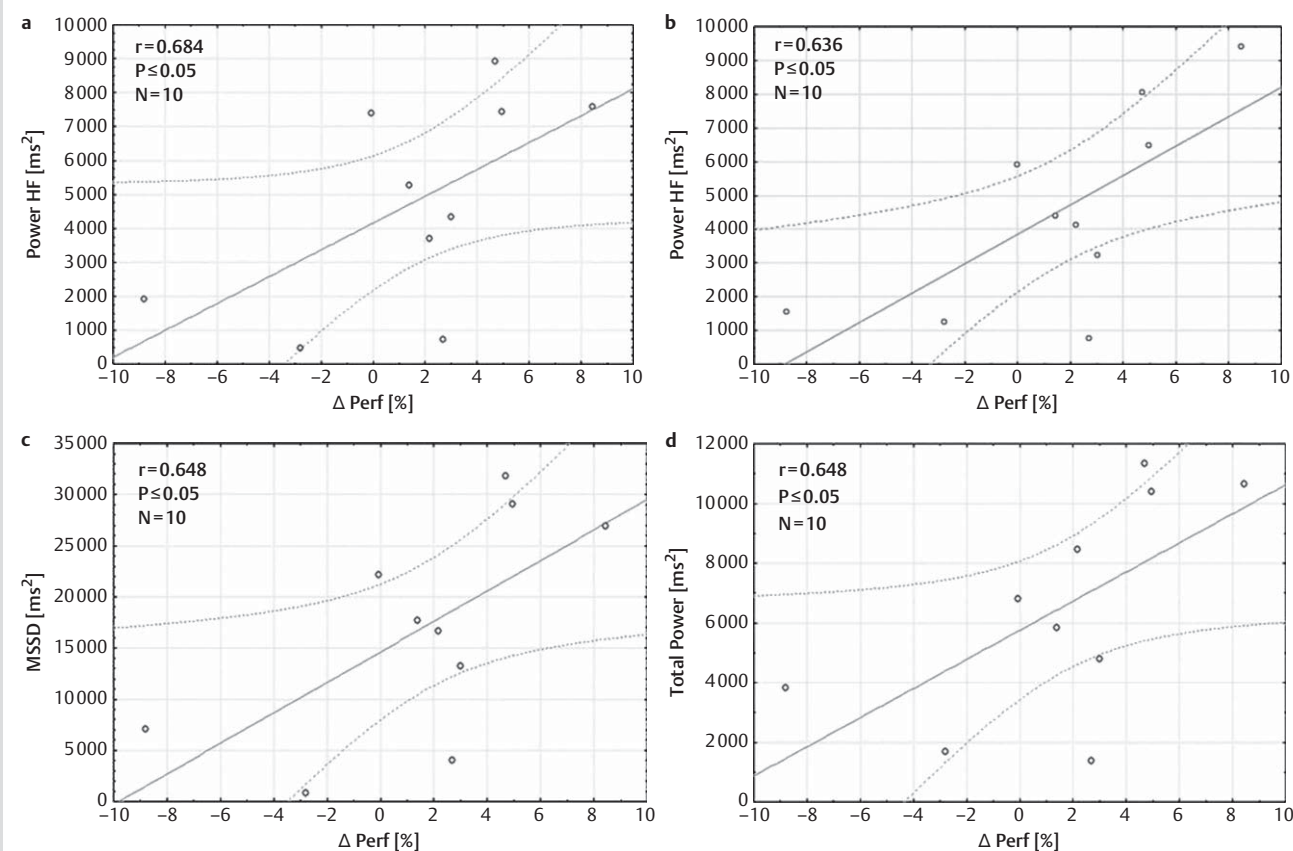


Fig. 2 Correlation between the change in athletic performance and supine heart rate variability parameters sampled during different phases of training preparation. ΔPerf [%] = change in athletic performance expressed in percentage; MSSD = mean square successive difference; A = calculated from all morning measurements during the whole preparation period; B, C, D = calculated from the last fifteen measurements of HRV-adjusting period.

suggest that an orthoclinostatic manoeuvre seems to be more suitable for identifying changes in autonomic regulation induced during preparation compared to only a clinostatic challenge in well trained athletes.

Our results show an association between ΔPerf and the morning level of vagally modulated HRV spectral component supine P_{HF} ($r_s=0.684$; $P<0.05$) measured throughout the preparation period. In addition, the results demonstrate a close relationship between ΔPerf and both the level of overall ANS activity and the vagally related HRV variables measured in supine position 3 weeks before the end of HRV-adjusting period. Based on these findings, we assume that the high level of ANS activity, particularly vagal activity, accompanies an enhancement in ΔPerf . Recently, Chalencon et al. [12] demonstrated that the dynamics of vagal activity monitored throughout 30 weeks of training preparation in elite swimmers could have a direct bearing on performance. In addition, Garet et al. [16] reported that the modelling of training process powered by a nocturnal ANS activity assessment is very useful for attempting to predict the performance of swimmers. Interestingly, a reduction in vagal activity together with the shift of sympathovagal balance towards sympathetic dominance was associated with an increase in cardiovascular performance [25] and served as a predictor of athletic achievement [29] during a peak training period. However, our own research as well as that of others suggests that performance is predominantly affected by vagal activity dynamics than by reciprocal changes in the sympathetic system.

Broad heterogeneity in the response to training has been linked with differences in age, gender, race, baseline and genetic factors [7,37]. In our research, an increase in ΔPerf occurred primarily in athletes who had a high vagal activity. In contrast, deterioration in ΔPerf was more likely found in athletes who had the lowest vagal activity. Therefore, in spite of many known performance factors, we suggest that high basal vagal activity may indicate that athletes have a higher training potential in terms of their training adaptability and “readiness” [14] to train. This readiness provides an advantage that enhances the quality of their training and ΔPerf . Hautala et al. [19] concluded that the pre-training level of vagal activity represents the most powerful determinant of the training response independently after adjustment for age, baseline fitness and body mass index in healthy subjects. Research has suggested that the level of vagal activity is an inherited quality that sets the limits on further improvements in the $\text{VO}_{2\text{max}}$ of trained subjects [22]. Based on this suggestion, that heritability plays a substantial role in the determination of vagal activity, we feel that in the future, the assessment of vagal activity level by SA HRV method could be taken into account during sport talent identification, particularly in individual sporting events with high demands on aerobic output.

The results of this study showed that the TRIMP significantly decreased from the starting to the ending period of training preparation as a result of the tapering period that is usually applied before and/or during the competition period. This phase is characterised by a reduction in training volume and the maintenance of high intensity training [30]. In our study, training load had to be adjusted on approximately half the number of training days during the training period. This meant that each athlete's training capacity demonstrated a relatively high variability throughout preparation. Theoretically, based on the standard training model, this finding indicates that without knowledge of their ANS state, athletes could be training either above or below their actual training capacity. In this regards, Chen et al.

[13] reported an important finding that the level of vagally modulated HRV spectral power corresponded with performance dynamics, but was unaffected by muscle pain during recovery after weightlifting training. From this point of view, a daily quantification of ANS activity by SA HRV may represent a promising biofeedback mechanism for the objective assessment of individual training response and appropriate trainability level. This statement is supported by a previous study [26] that clearly demonstrated that HRV-guided training seemed to be more suitable for performance enhancement than standard guided training since it provided an adjustment of both the timing and amount of high-intensity exercise on an individualised level.

In summary, a relationship was observed between ΔPerf and morning vagal activity during training preparation and the end of HRV-adjusting period. Elevated basal ANS activity, particularly vagal activity, could be associated with enhanced training potential in terms of high adaptability, allowing for an improvement in Perf. In conclusion, daily quantification of ANS by SA HRV seems to be a promising biofeedback tool for the individualisation of the training process and the enhancement of in Perf that could be limited by vagal activity level in trained athletes.

Study Limitations



1) The content of the training sessions was specific to the sport specialisation of each athlete. In this regard, despite using HR monitors during most of the training sessions, an exact recommendation relating to the alteration in training load (intensity and/or volume) was difficult to quantify. The alteration depended primarily on the goal of the current training bout (e.g. agility, endurance, strength and/or speed). 2) Differences in career length and former Perf may have affected the ΔPerf . 3) Low number of participants. 4) Absence of a matched training control group precludes exact verification of the effect of the load adjustment on the ΔPerf . However, it was difficult to find athletes with similar training capacities, actual performance and lifestyle (stress stimuli level) willing to undertake daily ANS assessment.

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