

Comprehensive rhythmocardiographic assessment of functional status in elite athletes specializing in skiing disciplines

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Abstract:

Problem statement: In endurance sports, rapid and valid evaluation of functional readiness is essential for balancing performance enhancement with the prevention of maladaptation. Cross-country skiing imposes high demands on the cardiovascular and autonomic regulatory systems, yet routine monitoring in practice still relies predominantly on conventional heart-rate responses and does not fully exploit the diagnostic value of heart rhythm structure. **Approach:** The present study applied a comprehensive rhythmocardiographic strategy that integrated variational pulsometry, spectral heart rate variability analysis, and structural-linguistic interpretation of the heart rhythm wave pattern. **Purpose:** To determine the characteristics of cardiovascular regulation and the overall functional state of qualified cross-country skiers at rest and after intensive exercise. **Material and methods:** Twenty-six qualified athletes aged 18-32 years underwent a standardized examination including 5-min rhythmocardiographic recordings in the supine position before exercise and at the 10th minute after intensive muscular work. The protocol included time-domain and spectral heart rate variability indices, Baevsky-derived regulatory indices, structural-linguistic assessment of spectrum configuration, ergometry, heart-rate monitoring, and non-parametric statistical analysis. **Results:** The post-exercise state was characterized by a marked increase in heart rate, shortening of RR intervals, reduction of overall variability, and a substantial rise in Baevsky's stress index, indicating stronger sympathetic activation and centralization of regulation. Spectral analysis demonstrated significant increases in the very-low-frequency, low-frequency, and especially very-high-frequency components, while structural-linguistic analysis showed a higher total number of spectral lines and a greater contribution of unstable spectral patterns after exercise. Based on the integrated response profile, three functional groups were identified: athletes with an adequate adaptive response ($n = 13$; 50.0%), athletes with pronounced regulatory strain ($n = 7$; 26.9%), and athletes with unstable functional states associated with an unfavorable adaptation prognosis ($n = 6$; 23.1%). **Conclusions:** The combined rhythmocardiographic approach provides a more informative assessment of autonomic balance, regulatory strain, and adaptive stability than isolated indices alone. It can be used for individualized monitoring of training readiness, early detection of maladaptive responses, and short-term prediction of tolerance to intensive training and competitive loads in elite cross-country skiers.

Keywords: autonomic balance; exercise adaptation; variational pulsometry; spectral analysis; cardiovascular monitoring; elite cross-country skiers.

Introduction

Monitoring the functional status of endurance athletes is a central task of contemporary sports science because the effectiveness of training depends not only on the external training load but also on the athlete's momentary regulatory readiness and recovery capacity. In cyclic endurance disciplines, inadequate adaptation may remain clinically silent for a prolonged period while nevertheless reducing performance, impairing recovery, and increasing the likelihood of overreaching or maladaptation. Accordingly, non-invasive tools capable of capturing subtle regulatory shifts are especially valuable for day-to-day training management (Dong, 2016; Jamnick et al., 2020; Fleitas-Paniagua et al., 2024).

Cross-country skiing is among the most physiologically demanding Olympic endurance sports. Successful performance requires a combination of high aerobic power, efficient locomotor coordination, and robust cardiovascular regulation across variable terrain and changing exercise intensity. Because of these demands, autonomic regulation of cardiac rhythm has been widely used to characterize readiness, adaptation,

and fatigue in endurance athletes, including Nordic skiers (Hedelin et al., 2000; Gjerdaalen et al., 2015; Mendia-Izueta et al., 2016). Previous research has shown that well-trained endurance athletes typically demonstrate greater vagal predominance at rest, whereas accumulated fatigue, excessive load, or inadequate recovery may alter the autonomic profile and disturb post-exercise recovery dynamics (Raczak et al., 2006; Seiler & Kjerland, 2006; Schmitt et al., 2018).

Heart rate variability (HRV) is particularly useful in this context because it reflects the interaction of sympathetic, parasympathetic, humoral, and central regulatory influences on the sinoatrial node. Time-domain and frequency-domain approaches have become standard in sports physiology and clinical autonomic assessment (Akselrod et al., 1981; Pomeranz et al., 1985; Task Force, 1996; Shaffer & Ginsberg, 2017). In athlete monitoring, HRV has been associated with training load, adaptation to endurance training, recovery kinetics, and individualized exercise prescription (Kiviniemi et al., 2007; Kaikkonen et al., 2012; Plews et al., 2012; Vesterinen et al., 2013). At the same time, interpretive caution remains necessary because isolated indices do not always capture the full complexity of functional-state transitions during and after exercise (Hottenrott et al., 2006; Michael et al., 2017).

For this reason, an integrated analytical strategy may be more informative than reliance on conventional HRV variables alone. In the present work, three complementary approaches were combined: variational pulsometry, spectral analysis, and structural-linguistic analysis of the heart rhythm wave structure. Variational pulsometry provides integral markers of regulatory tension and autonomic balance, spectral analysis clarifies the contribution of oscillatory components within different frequency bands, and the structural-linguistic approach proposed in previous methodological studies enables classification of stable, quasi-stable, and unstable functional states based on spectral pattern configuration (Ilin et al., 2002; Ilin et al., 2018).

Despite increasing interest in HRV-guided training and recovery management, the use of complex rhythmocardiographic assessment for operational classification of adaptive responses in elite cross-country skiers remains insufficiently described in the international literature. This gap is practically important because skiing-specific training requires early identification of athletes who tolerate intensive loads adequately and those who may be entering a state of regulatory strain or unstable adaptation.

Therefore, the **purpose** of this study was to determine the characteristics of the cardiovascular system and overall functional state at rest and after intensive exercise in qualified cross-country skiers using a comprehensive assessment of heart rhythm variability that combined statistical, spectral, and structural-linguistic analyses.

Material & methods

Study design. The study used an observational cross-sectional design with repeated measurements before and after an exercise stimulus. The objective was to characterize autonomic and cardiovascular regulation in qualified cross-country skiers at rest and during the early recovery period after intensive muscular work.

Participants. Twenty-six qualified cross-country skiers aged 18-32 years participated in the investigation. Their sports qualification ranged from First and Second Class to Candidate for Master of Sport and Master of Sport. All athletes were examined according to a standardized protocol.

Ethical considerations. The study was conducted in accordance with the principles of the Declaration of Helsinki. All participants were informed about the purpose and procedures of the investigation and provided written informed consent before testing. The protocol was approved by the local institutional ethics committee.

Procedures. Rhythmocardiograms were recorded for 5 min in the supine position before exercise and again at the 10th minute after intensive muscular work using an automated rhythmocardiographic system with a photoplethysmographic sensor placed on the earlobe. The software corrected motion artifacts and extrasystoles when the proportion of artifacts did not exceed the accepted system threshold. Power spectra were calculated using a full discrete Fourier transform. The examination also included ergometry, heart-rate monitoring, and standard descriptive assessment of functional status.

Time-domain and variational analysis. Statistical analysis of the cardiointerval series included mean value (M), standard deviation, coefficient of variation, skewness, and kurtosis. Variational pulsometry according to Baevsky's method was used to quantify autonomic balance and regulatory strain. The following indices were analyzed: mean RR interval (RRNN), mode (Mo), amplitude of mode (AMo), variation range (Δ RR), stress index (SI), vegetative balance index (VBI), regulation adequacy index (RAI), and vegetative rhythm index (VRI). Lower SI values were interpreted as relative predominance of parasympathetic influences, whereas higher SI values indicated increased sympathetic activation and centralization of heart rhythm control.

Spectral analysis. Spectral HRV analysis followed internationally accepted recommendations for short-term recordings (Task Force, 1996). The following bands were considered: very-low-frequency (VLF, < 0.04 Hz), low-frequency (LF, 0.04-0.15 Hz), high-frequency (HF, 0.15-0.40 Hz), and very-high-frequency (VHF, 0.40-1.00 Hz). In accordance with the study's original concept, the VHF component was interpreted as a marker of rapid regulatory processes and potential instability of the quasi-stationary physiological state.

Structural-linguistic analysis. To improve the practical interpretation of HRV responses, structural-linguistic analysis of the spectrum was additionally performed. This approach classifies the wave structure of the spectrum using symbolic formulas and wave numbers that reflect the number of spectral lines in the LF, HF, and VHF ranges. The parameters α , β , and γ represented the number of lines in the LF, HF, and VHF ranges, respectively, whereas Σ denoted the total number of spectral lines. According to the concept proposed by Ilin and colleagues, higher γ and Σ values indicate higher regulatory activity and a greater probability of unstable functional states (Ilin et al., 2002; Ilin et al., 2018).

Statistical analysis. Quantitative and qualitative data were processed using standard mathematical and statistical methods. Normality was assessed before inferential analysis. Because part of the dataset was non-normally distributed, differences between paired measurements were evaluated with the Wilcoxon non-parametric test. Descriptive statistics included the mean value, standard deviation, variance, standard error of the mean, and coefficient of variation. Statistical processing was performed with SPSS and Microsoft Excel.

Results

Physical exercise was accompanied by a clear intensification of cardiovascular regulation and by a shift toward more centralized autonomic control. Across the whole sample, the most informative descriptive statistics of the integrated HRV assessment are presented in Table I.

Table I. Mean values of variational, spectral, and structural-linguistic heart rate variability indicators in qualified cross-country skiers before and after exercise

Parameter	Before exercise (Mean $\pm$ SEM)	After exercise (Mean $\pm$ SEM)
HR (beats·min ⁻¹)	69.20 $\pm$ 1.69	103.44 $\pm$ 1.41
RRNN (ms)	886.79 $\pm$ 22.37	583.77 $\pm$ 8.26
Variance (ms ²)	5869.26 $\pm$ 581.05	1094.29 $\pm$ 470.53
CV (%)	8.25 $\pm$ 0.35	4.41 $\pm$ 0.62
Skewness	0.02 $\pm$ 0.09	1.01 $\pm$ 0.87
Kurtosis	0.37 $\pm$ 0.06	1.76 $\pm$ 0.83
Mode (Mo, ms)	857.69 $\pm$ 25.41	554.29 $\pm$ 7.77
AMo (%)	29.82 $\pm$ 1.50	70.61 $\pm$ 2.53
RRmax (ms)	1087.21 $\pm$ 26.14	804.83 $\pm$ 90.36
RRmin (ms)	700.67 $\pm$ 17.33	479.54 $\pm$ 13.98
Δ RR (ms)	386.54 $\pm$ 18.70	325.29 $\pm$ 91.06
Stress Index (SI)	55.52 $\pm$ 5.72	453.03 $\pm$ 57.41
Vegetative Balance Index	91.12 $\pm$ 9.99	490.90 $\pm$ 61.18
Regulation Adequacy Index	36.28 $\pm$ 2.25	128.53 $\pm$ 5.17
Vegetative Rhythm Index	3.43 $\pm$ 0.20	12.55 $\pm$ 1.34
α_0	1 $\pm$ 0.10	0 $\pm$ 0.09
α_2	1 $\pm$ 0.10	0 $\pm$ 0.08
α_1	1 $\pm$ 0.12	1 $\pm$ 0.17
β	3 $\pm$ 0.38	3 $\pm$ 0.44
γ	1 $\pm$ 0.24	5 $\pm$ 0.93
Σ	7 $\pm$ 0.57	11 $\pm$ 1.34
VLF (ms ²)	5064.83 $\pm$ 429.80	9501.60 $\pm$ 688.14
LF (ms ²)	4826.84 $\pm$ 286.59	6708.02 $\pm$ 455.90
HF (ms ²)	5762.74 $\pm$ 295.19	5126.00 $\pm$ 245.83
VHF (ms ²)	2355.58 $\pm$ 200.37	5886.29 $\pm$ 324.56

Note. HR = heart rate; RRNN = mean RR interval; CV = coefficient of variation; AMo = amplitude of mode; SI = Baevsky stress index; VLF = very-low-frequency power; LF = low-frequency power; HF = high-frequency power; VHF = very-high-frequency power.

Compared with the resting condition, the post-exercise state was characterized by a substantial increase in heart rate (from 69.20 $\pm$ 1.69 to 103.44 $\pm$ 1.41 beats·min⁻¹) and a marked shortening of the mean RR interval (from 886.79 $\pm$ 22.37 to 583.77 $\pm$ 8.26 ms). Overall variability decreased, as reflected by lower variance and coefficient of variation, whereas the increase in skewness and kurtosis suggested a more asymmetric and centralized rhythm structure after exercise.

Variational pulsometry confirmed a pronounced increase in regulatory strain. According to Baevsky's variational pulsometry method, which enables assessment of regulatory strain and autonomic balance, the obtained results are consistent with previous reports.

In particular, the stress index and related regulatory indicators increased substantially after exercise, reflecting pronounced activation of central regulatory mechanisms. At the same time, the relatively large standard error of the variation range observed after exercise may indicate the presence of an unstable functional state in a subset of athletes (Fig. 1).

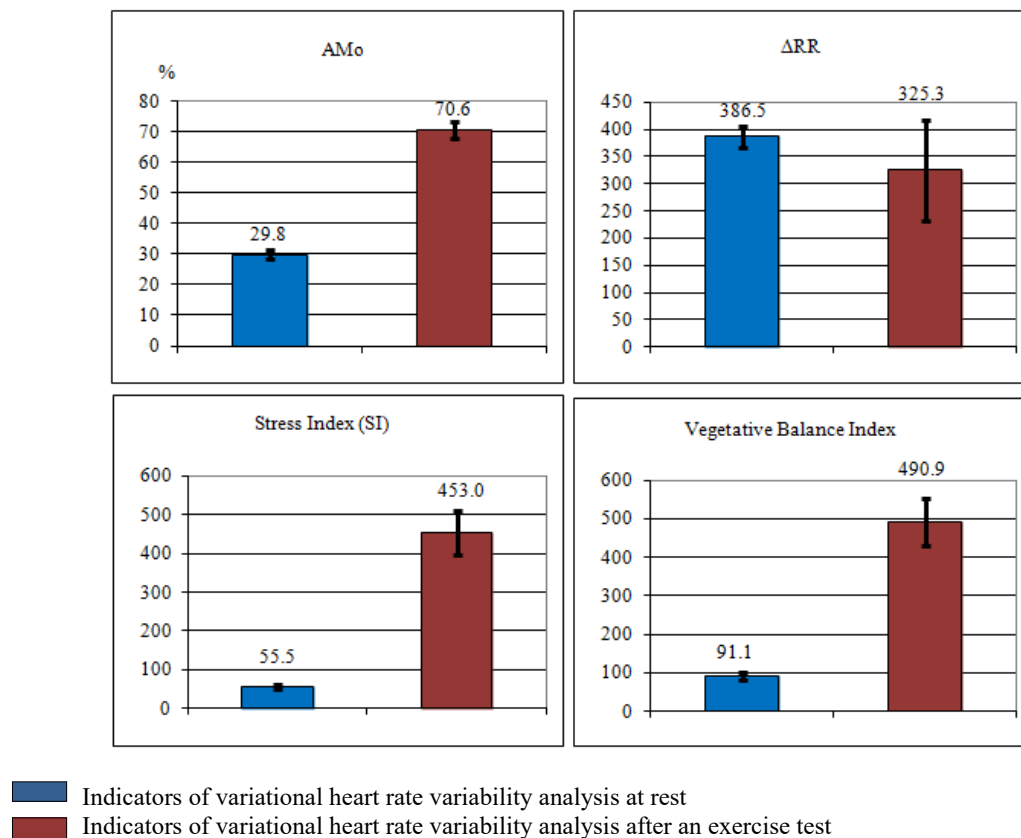


Fig. 1. Indicators of variational heart rate variability analysis in cross-country skiers at rest and after an exercise test.

For most highly trained cross-country skiers, the resting condition (supine position) is characterized by a predominance of parasympathetic autonomic regulation of heart rhythm and a humoral pathway of central stimulation. Overall, the state of cardiac rhythm regulatory mechanisms at rest in highly qualified skiers indicates a high level of autonomic response economization, which represents a typical outcome of long-term systematic training.

The response of heart rhythm control mechanisms during the exercise test is manifested by an increased influence of the sympathetic division of the autonomic nervous system. A significant increase in the amplitude of mode (AMo) was observed, rising from 29.82 ± 1.50 to $70.61 \pm 2.53\%$, together with a reduction in RR interval duration. The contribution of neural pathways in central stimulation increased, reflecting enhanced activity of neurohumoral regulatory mechanisms. The Baevsky stress index increased substantially after intensive muscular work, from 55.52 ± 5.72 to 453.03 ± 57.41 arbitrary units. This expected rise in regulatory system strain is associated with the need for rapid compensation of changes occurring in somatic systems. The primary cause of shifts in regulatory channel activity is the alteration of internal physiological variables, which serve as adequate stimuli for autonomic functions such as circulation and respiration.

Since variational pulsometry alone does not allow precise differentiation between sympathetic and parasympathetic influences within regulatory mechanisms, spectral and structural-linguistic analyses were additionally applied to characterize the contribution of these systems.

Analysis of individual changes in the fine structure of the heart rhythm power spectrum after exercise revealed, in most cases, an increase in the very-high-frequency component. The dynamics of HRV spectral power components in qualified skiers following the exercise test demonstrated two main patterns. First, a statistically significant increase ($p < 0.01$) in spectral power within the very-low-frequency (VLF) and low-frequency (LF) ranges was observed, which is consistent with previously reported findings. Second, a

statistically significant increase ($p < 0.01$) in the very-high-frequency (VHF) component was detected. Spectral analysis showed that the response to exercise was not limited to conventional LF-HF redistribution. In addition to higher VLF and LF power, a notable increase in the VHF component was observed, which was one of the key findings of the study. The VHF power rose from 2355.58 ± 200.37 to 5886.29 ± 324.56 ms², and the number of VHF spectral lines (γ) increased from 1 ± 0.24 to 5 ± 0.93 . At the same time, the total wave number (Σ) increased from 7 ± 0.57 to 11 ± 1.34 , indicating greater complexity and regulatory energy expenditure.

This finding represents an additional observation in the study of this issue and indicates an increased number of power spectra dominated by very-high-frequency components in skiers after exercise (Fig. 2). The results of variational and spectral analyses of heart rate variability were further supported by the findings of the structural-linguistic analysis of heart rhythm wave organization.

Although the number of studies employing spectral HRV analysis has increased substantially in recent years, allowing identification of frequency-domain characteristics of cardiac rhythm under the influence of various factors, insufficient attention has been paid to changes in spectral shape and the regular patterns of its transformation.

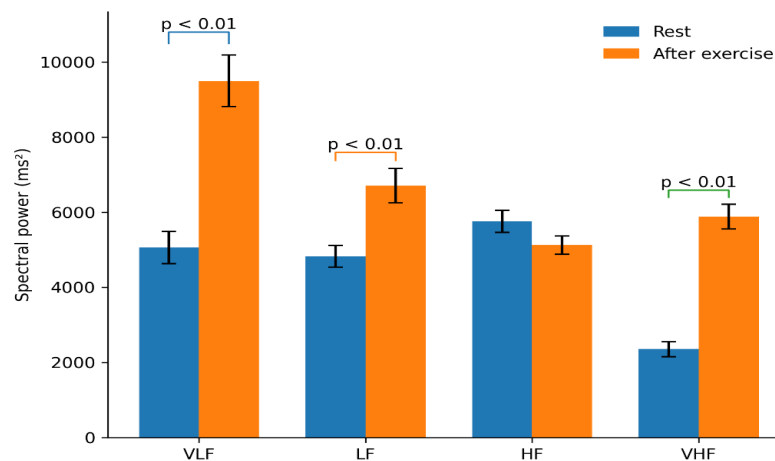


Fig. 2. Spectral power of heart rate variability components (VLF, LF, HF, and VHF) in qualified cross-country skiers measured at rest and after intensive exercise.

Therefore, an improved approach to evaluating the functional state of the human organism is proposed, combining established concepts of physiological regulatory systems with the notion that the human organism functions as an ultrastable system.

For a living organism considered as an ultrastable system, frequent small external influences do not cause deviations beyond physiological limits. As a result, the organism remains in one of several stationary or stable states. Under extreme influences that disturb equilibrium, the organism transitions to a new stationary state through changes in specific parameters. These transitions are invariant, occur according to defined rules, are time-limited, may include several transitional or quasi-stationary states, and can be described by step-like functions (Ilin, 2002; Ilin, 2018).

To analyze changes in the wave organization of heart rhythm, a structural-linguistic method was applied. According to this approach, the description of periodic heart rhythm components in the form of spectral formulas, indices, wave numbers, and amplitude-frequency characteristics of principal spectral lines forms the basis for classification of regulatory system states and for formalizing transition rules between major physiological states.

A spectral formula represents a sequence of symbols describing the characteristics of spectral lines within the heart rhythm power spectrum.

For example, if no spectral maxima (lines) are present, the spectrum is denoted as S_0 . If maxima are observed only in the low-, high- (respiratory), or very-high-frequency ranges, the spectra are denoted as S_m , S_b , S_f , respectively. If maxima are present in two of the three frequency ranges, the spectra are represented as S_mS_b , S_mS_f , S_bS_m , or S_bS_f , with the component having the largest amplitude listed first.

Three-component spectra are represented as $S_mS_bS_f$, $S_mS_fS_b$, $S_bS_mS_f$, $S_bS_fS_m$, $S_fS_mS_b$, or $S_fS_bS_m$. In general, if a spectrum contains n components, its formula consists of n symbols arranged in descending order of amplitude (Fig. 3) (Ilin, 2002; Ilin, 2018).

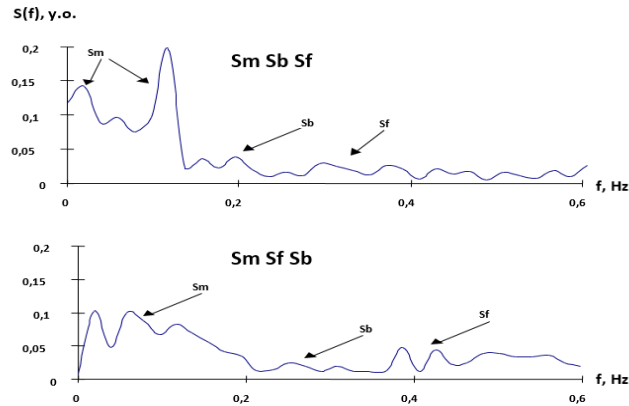


Fig. 3. Representation of the coarse structure of the heart rate power spectrum containing maxima in the three main frequency ranges.

Alongside the traditional analysis of low-frequency Sm (0.03–0.15 Hz) and high-frequency Sb (0.15–0.40 Hz) components of the power spectrum, the present analysis also considered the very-high-frequency component Sf (0.40–1.00 Hz), the predominance of which represents a key indicator of an unstable physiological state. In addition, splitting of spectral maxima across frequency ranges was evaluated in the rhythmocardiographic spectrum using wave numbers (α , β , γ , Σ). The very-high-frequency wave number (γ) corresponds to the number of maxima in the very-high-frequency range and may take values of 0, 1, 2, 3, ... k. The total wave number (Σ) corresponds to the total number of spectral maxima across the entire frequency range and may take values of 0, 1, 2, 3, ... ($i + j + k$). The greater the value of Σ , the higher the activity of regulatory systems and the greater the energy expenditure required to maintain the given physiological state.

Due to dispersion, each stable state may include multiple substates (sublevels). In this case, the principal state Sm contains i substates, denoted as $Sm(\alpha)$, while state Sb contains j substates $Sb(\beta)$. High-energy states such as SmSb and SbSm include multiple substates $Sm(\alpha)Sb(\beta)$ and $Sb(\beta)Sm(\alpha)$, the number of which is determined by combinations of i and j. Similarly, principal quasi-stationary states may include multiple substates; for example, SbSmSf contains substates $Sb(\beta)Sm(\alpha)Sf(\gamma)$, whose number is determined by combinations of i, j, and k. Each substate and transitions between them are determined by the principal physiological state of the organism, the ratio of β , α , and γ , and the complex of external conditions. Transitions between substates within a principal state occur spontaneously without transition into a quasi-stationary state.

According to the theory of organism ultrastability and the structural-linguistic analysis of heart rate variability, high values of spectral power (Sf) and a large number of spectral lines (γ) in the very-high-frequency range indicate a high probability of transition to a highly unstable functional state with an unfavorable prognosis, including the possible development of negative adaptive effects to physical loads and a decline in functional capacity during sports training (Figs. 4, 5). As shown in Fig. 4, an important observation in the distribution of heart rate power spectrum types in cross-country skiers is that after physical exercise the number of spectra dominated by very-high-frequency components, or containing such components, increases.

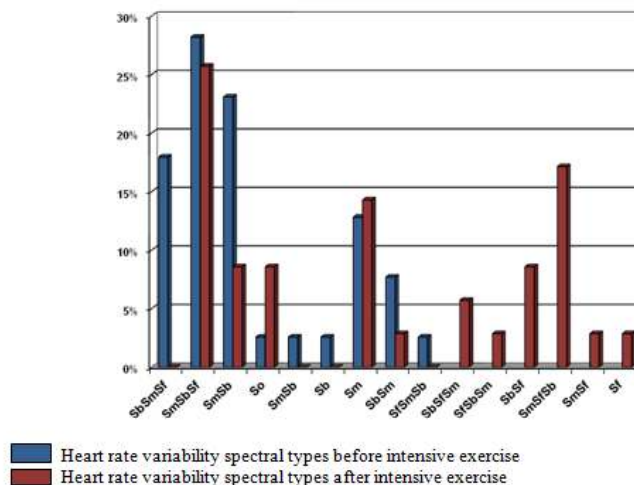


Fig. 4. Distribution of heart rate variability spectral types in highly trained cross-country skiers measured before and after intensive exercise

Analysis of the fine spectral structure before and after exercise revealed an increase in the number of spectral maxima within the high-frequency range and a rise in spectral lines in the very-high-frequency range. This indicates activation of fast regulatory control loops aimed at stabilizing the organism's functional state. In addition, the total wave number increased, reflecting enhanced regulatory system involvement (Fig. 5). Thus, the rhythmocardiographic approaches used for assessing cardiovascular system function enable a comprehensive evaluation of the functional state of qualified cross-country skiers based on an integrated analysis of heart rate variability.

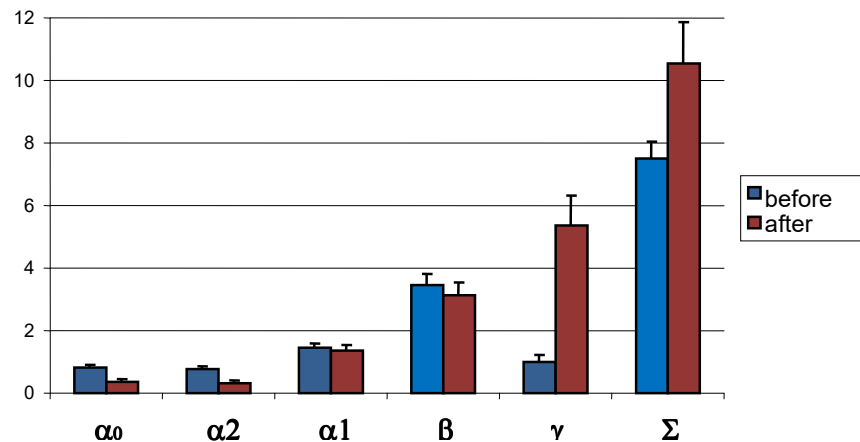


Fig. 5. Exercise-induced changes in wave-number parameters reflecting the fine spectral structure of heart rate variability in athletes before and after intensive exercise.

The integrated interpretation of variational, spectral, and structural-linguistic indicators made it possible to classify the examined athletes into three functional groups according to their physiological response to the exercise test. Group I included athletes with an adequate adaptive response to intensive muscular work ($n = 13$; 50.0%). Group II included athletes with pronounced regulatory strain and signs of insufficient adaptation to exercise ($n = 7$; 26.9%). Group III comprised athletes with unstable functional states and an unfavorable adaptation prognosis ($n = 6$; 23.1%). The group-specific data are summarized in Table II.

The results of variational, spectral, and structural-linguistic HRV analyses were in good agreement with each other. For example, in the first group identified as the most functionally favorable based on structural-linguistic analysis, post-exercise variational pulsometry indicators characterizing regulatory strain (AMo, ΔRR , CV, stress index, and regulation adequacy index) were lower than those observed in athletes of the second group.

Table II. Indicators of variational, spectral, and structural-linguistic heart rate variability in the three functional groups of cross-country skiers

Parameter	Group I Adequate response ($n = 13$) Pre / Post	Group II Regulatory strain ($n = 7$) Pre / Post	Group III Unstable state / unfavorable prognosis ($n = 6$) Pre / Post
RRNN	884.6 $\pm$ 32.50 578.88 $\pm$ 11.38	892.08 $\pm$ 56.07 607.97 $\pm$ 21.41	819.87 $\pm$ 31.55 572.06 $\pm$ 11.52
CV	8.65 $\pm$ 0.62 4.88 $\pm$ 1.03	7.69 $\pm$ 0.73 2.95 $\pm$ 0.34	7.79 $\pm$ 0.51 4.77 $\pm$ 1.25
Mo	850.00 $\pm$ 36.60 547.22 $\pm$ 10.28	887.50 $\pm$ 67.97 581.25 $\pm$ 18.75	783.33 $\pm$ 35.36 544.44 $\pm$ 13.03
AMo	28.70 $\pm$ 2.42 65.52 $\pm$ 3.20	33.07 $\pm$ 3.66 77.75 $\pm$ 6.31	32.12 $\pm$ 2.14 74.47 $\pm$ 4.17
ΔRR	384.94 $\pm$ 30.29 339.67 $\pm$ 153.26	351.00 $\pm$ 30.05 179.38 $\pm$ 44.82	359.00 $\pm$ 29.21 426.22 $\pm$ 178.74
SI	55.87 $\pm$ 9.54 417.39 $\pm$ 59.24	62.51 $\pm$ 11.97 637.06 $\pm$ 185.15	63.36 $\pm$ 9.12 360.72 $\pm$ 88.01
VBI	94.02 $\pm$ 19.01 448.63 $\pm$ 61.11	102.79 $\pm$ 16.02 704.76 $\pm$ 191.94	95.60 $\pm$ 11.14 385.34 $\pm$ 92.99
RAI	34.77 $\pm$ 3.09 120.72 $\pm$ 6.44	39.30 $\pm$ 5.66 136.89 $\pm$ 14.80	42.43 $\pm$ 4.48 136.71 $\pm$ 7.13
VRI	3.52 $\pm$ 0.32 12.85 $\pm$ 1.70	3.57 $\pm$ 0.44 14.80 $\pm$ 3.44	3.80 $\pm$ 0.32 9.96 $\pm$ 2.41

α_0	1 ± 0.14 6 ± 0.6	1 ± 0.00 1 ± 0.00	1 ± 0.26 0 ± 0.24
α_2	1 ± 0.13 0 ± 0.11	0 ± 0.13 0 ± 0.16	1 ± 0.20 0 ± 0.18
α_1	2 ± 0.17 1 ± 0.23	2 ± 0.26 1 ± 0.18	1 ± 0.33 2 ± 0.39
β	4 ± 0.50 4 ± 0.55	2 ± 0.50 0 ± 0.00	3 ± 0.50 4 ± 0.75
γ	1 ± 0.39 6 ± 1.13	1 ± 0.50 0 ± 0.00	1 ± 0.33 10 ± 1.74
Σ	8 ± 0.78 12 ± 1.56	5 ± 1.36 2 ± 0.30	7 ± 0.78 16 ± 2.56
VLF	543.99 ± 62.07 1034.34 ± 113.15	591.42 ± 63.22 1019.95 ± 91.78	452.07 ± 114.90 719.77 ± 91.73
LF	485.58 ± 38.95 720.57 ± 71.57	545.12 ± 50.01 720.00 ± 61.60	488.97 ± 78.92 527.53 ± 78.58
HF	570.71 ± 45.47 572.77 ± 34.75	584.16 ± 76.23 493.37 ± 34.02	571.39 ± 46.67 409.36 ± 40.97
VHF	231.88 ± 32.50 566.93 ± 45.76	236.58 ± 45.09 498.33 ± 51.12	281.60 ± 32.42 712.29 ± 59.52

Note. Group differences in the original dataset were interpreted at $p < 0.05$. Group III showed the highest post-exercise indices of instability, especially in VHF power and in the wave-number parameters γ and Σ .

Athletes in Group I showed the most favorable post-exercise profile, with lower AMo, SI, and other tension-related indices than the less favorable groups. Group II was characterized by particularly high indices of regulatory strain, including the highest post-exercise AMo, SI, and VBI values. Group III demonstrated the most pronounced indicators of instability, especially in the VHF domain and in the values of γ and Σ , which were significantly higher than in the other groups ($p < 0.05$). This pattern supports the interpretation that excessive very-high-frequency activity and increased wave-number complexity are associated with unstable recovery dynamics and a less favorable adaptation prognosis.

Figure 6 presents the distribution of different classes of power spectra across the three identified athlete groups.

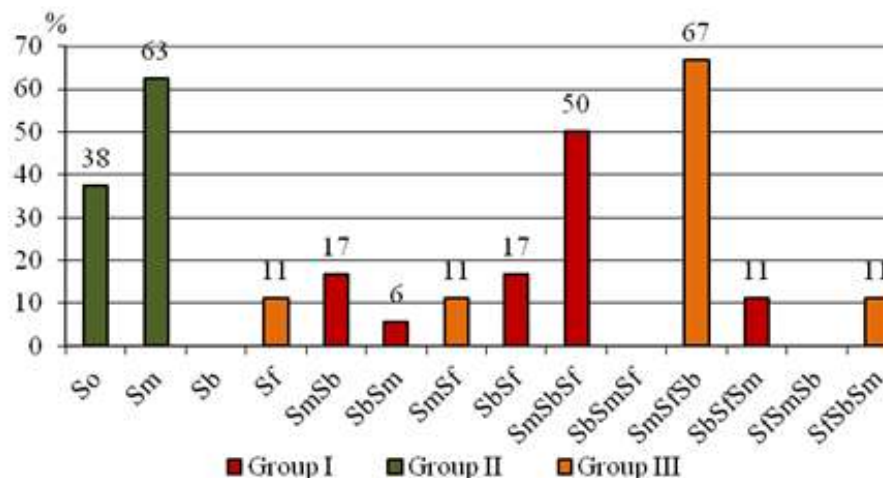


Fig. 6. Distribution of power spectrum types in the three identified groups of cross-country skiers after exercise.

Spectra of classes SmSb, SbSm, SbSf, SmSbSf, and SbSfSm correspond to stable functional states of the organism and indicate an adequate physiological response to exercise. Spectra Sm and So reflect pronounced regulatory system strain and insufficient adaptive mechanisms that do not ensure an optimal physiological response to physical load. Spectra of classes SmSf, SmSfSb, and Sf are observed in unstable states characterized by an increased probability of transition to preclinical or premorbid conditions.

Further confirmation of these findings is provided by the schematic representations shown in Figure 7, which illustrate possible spontaneous transitions between functional states in athletes. In these cases, no unfavorable prognosis is assumed, since after recovery the athletes are expected to return to their initial or near-initial state, indicating satisfactory functioning of adaptive mechanisms.

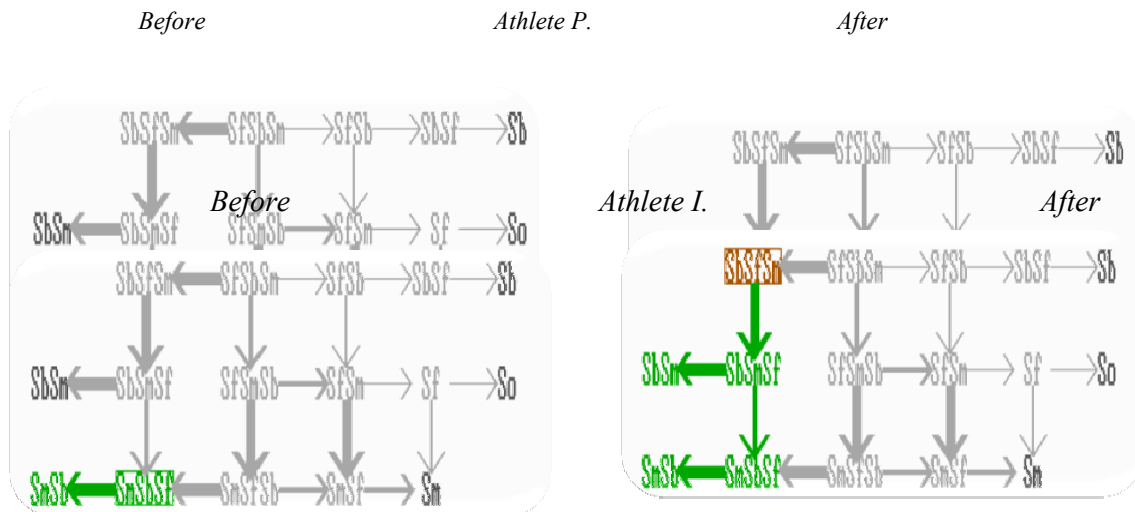


Fig. 7. Schematic illustration of spontaneous transitions between functional states in athletes before and after exercise, demonstrating adaptive responses without an unfavorable prognosis.

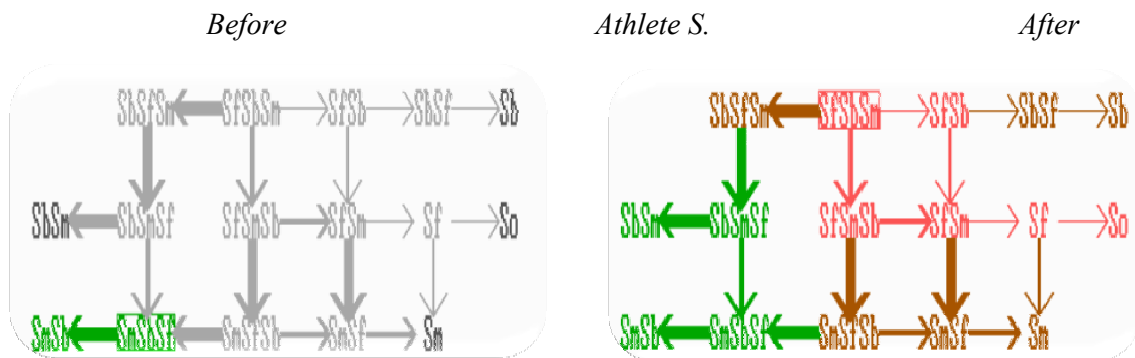


Fig. 8. Schematic illustration of spontaneous transitions in the functional state of Athlete S. before and after exercise, suggesting a risk of an unfavorable adaptive prognosis.

Figure 8 presents an example of changes in power spectra and functional states that allow the possibility of an unfavorable prognosis. This represents a less favorable type of response to exercise, as there is a probability of spontaneous transition of the organism into a state characterized by high regulatory strain (Sm) or disruption of adaptive mechanisms (So).

Moreover, this probability increases if an additional external factor is applied during the recovery period. For example, exposure to further physical load at this stage may increase the risk of transition into a state of regulatory strain or failure of adaptive control systems.

Discussion

The present study demonstrates that a comprehensive rhythmocardiographic analysis can reveal functionally relevant differences in post-exercise regulation that are not fully described by conventional heart-rate monitoring alone. The three analytical approaches used in this investigation converged on the same central finding: intensive exercise in qualified cross-country skiers is followed by stronger sympathetic-central regulation, greater regulatory tension, and, in a substantial proportion of athletes, signs of unstable recovery dynamics.

The resting profile of most athletes was characterized by relative parasympathetic predominance and a high degree of autonomic economization, which is consistent with the adaptive profile commonly reported in well-trained endurance athletes (Raczak et al., 2006; Hedelin et al., 2000; Gjerdalen et al., 2015). After exercise, however, the pattern shifted markedly toward sympathetic activation, as evidenced by higher heart rate, shorter RR intervals, elevated AMo, and a sharp rise in the stress index. Such post-exercise reorganization is physiologically expected, yet the magnitude and quality of the response are important because they may distinguish between adequate mobilization and excessive regulatory strain (Michael et al., 2017; Fleitas-Paniagua et al., 2024). A particularly important result was the increase in the VHF component and in the wave-

number indices γ and Σ . In the conceptual framework used in this study, these changes reflect fast regulatory oscillations and a higher probability of unstable quasi-stationary states. This interpretation extends standard HRV analysis by moving beyond the LF-HF dichotomy and is in line with methodological arguments that complex cardiovascular responses during exercise recovery are not always adequately captured by traditional summary indices alone (Hottenrott et al., 2006; Shaffer & Ginsberg, 2017).

The classification of athletes into three functional groups is of direct practical value. Group I showed an efficient adaptive response and may be considered the most favorable phenotype for tolerating intensive training. Group II displayed pronounced regulatory strain, suggesting that the recovery cost of intense exercise was elevated despite the absence of overt clinical symptoms. Group III combined instability-related spectral characteristics with the most unfavorable structural-linguistic profile, indicating a greater risk of maladaptation if additional stressors are imposed before full recovery. Similar HRV-based differentiation of fatigue and adaptation states has been described in elite endurance athletes and Nordic skiers (Schmitt et al., 2013; Schmitt et al., 2015; Schmitt et al., 2018).

From an applied perspective, these findings support the use of integrated HRV monitoring for individualized decision-making in high-performance skiing. Rather than relying only on absolute heart-rate values, coaches and sport scientists may benefit from combining conventional autonomic indices with rhythm structure analysis to identify athletes who are ready for further intensive loading and those who may require recovery-oriented adjustments. Such an approach is conceptually aligned with the growing literature on HRV-guided training and individualized endurance prescription (Kiviniemi et al., 2007; Kaikkonen et al., 2012; Plews et al., 2012; Vesterinen et al., 2013).

Conclusions

The functional status of elite cross-country skiers can be assessed more comprehensively when variational, spectral, and structural-linguistic analyses of heart rhythm are used together rather than separately. At rest, most athletes demonstrated an autonomically economical profile typical of well-trained endurance performers, whereas after intensive exercise the regulatory pattern shifted toward sympathetic activation and stronger centralization of control.

The integrated analysis identified three response profiles: an adequate adaptive response (50.0%), pronounced regulatory strain (26.9%), and unstable functional states with an unfavorable adaptation prognosis (23.1%).

Therefore, comprehensive rhythmocardiographic monitoring may serve as a practical tool for short-term prediction of training tolerance, early identification of maladaptive responses, and individualized management of training and recovery in elite cross-country skiers.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI GPT-based language assistance via the Genspark platform in order to improve academic English, refine manuscript structure, and align the text with the JPES template requirements. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflicts of interest

The authors declare no conflicts of interest related to this study.

Limitations

The study was conducted in a relatively small single-center sample of qualified cross-country skiers, which limits the generalizability of the findings. In addition, the interpretation focused on short-term recovery responses obtained at the 10th minute after exercise and did not include biochemical markers or longitudinal follow-up. Future studies should combine the present rhythmocardiographic model with repeated monitoring across training cycles and with external load variables.

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Author contributions

Conceptualization, Y.K. and L.S.; methodology, Y.K., H.O., and R.T.; software and data processing, R.T. and T.O.; validation, O.K.; formal analysis, Y.K., L.S., R.B., and Y.L.; investigation, V.E., Z.S., and D.K.; resources, Y.K.; data curation, H.O. and R.T.; writing-original draft preparation, Y.K. and L.S.; writing-review and editing, O.K., Y.L., and V.E.; supervision, Y.K.; project administration, Y.K. and L.S. All authors have read and agreed to the published version of the manuscript.

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