

Adaptation potential of young football players under submaximal physical loads

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Abstract:

Optimization of the training process for young football players through understanding their body's adaptation to physical activity is a critical task. **Purpose.** To optimize the training regimen for football players aged 12–13 by examining their body's adaptive capacity, focusing on the characteristics of autonomic reactivity during a submaximal stress test. **Materials and methods.** The study involved 17 male football players, aged 12–13, who trained at least five times per week. Screening diagnostics included recording and analyzing heart rate variability (HRV) both at rest and following a submaximal exercise protocol consisting of a 3 × 10 m shuttle run and arm flexion–extension performed in a prone position at maximum effort. **Results.** The results of the cluster analysis identified two distinct groups differing in their patterns of satisfactory and unsatisfactory adaptation to physical activity, illustrating a broad spectrum of individual responses—from typical sympathetic activation accompanied by parasympathetic suppression to paradoxical or subtle changes. Application of the logistic regression model showed strong classification performance, achieving a high accuracy rate of 88.2%. This demonstrates a robust capability to accurately differentiate individuals with satisfactory versus unsatisfactory adaptation to physical activity. **Conclusions.** The HRV assessment method is an effective tool for evaluating the adaptive capacity of young football players during submaximal physical activity. The results obtained provide opportunities to implement a personalized approach to training load management, improving training effectiveness and preventing athlete overfatigue. The data reveal significant variability in the autonomic responses of young football players, reflecting the concept of individual differences in adaptation mechanisms, which is well recognized in contemporary sports science.

Key Words: physical activity, autonomic reactivity, heart rate variability, physical training, physical education

Introduction

The adaptation of children's and adolescents' bodies to physical activity and stress is a critical issue in sports, particularly for young athletes actively engaged in sports such as football (Alexandrou et al., 2025; Mischenko et al., 2021). Adolescence is marked by high bodily plasticity, considerable cardiovascular system restructuring, and the development of stable adaptive mechanisms (Fischer et al., 2025; Vorozheikin et al., 2021; Romanova et al., 2022). During this period, substantial changes occur in the body's regulatory systems (Romanova et al., 2024; D'Amours et al., 2025; Jiang et al., 2025), making it an ideal time to apply highly informative methods for assessing an athlete's functional state and enabling early detection of potential risks of overfatigue and maladaptation (Recuenco Serrano et al., 2022; Kataev et al., 2024; Wen et al., 2025).

The most common approach to assessing the body's adaptive capacity is through heart rate variability (HRV), which reflects the interaction between the sympathetic and parasympathetic branches of the autonomic nervous system in regulating cardiovascular activity (Vescovi et al., 2022; Guryanov et al., 2024).

Because heart rate (HR) fluctuates in response to both external and internal stimuli, regular monitoring of HRV enables early detection of signs of overtraining, reduced adaptive capacity, and decline in functional state (Bocharin et al., 2024; Addleman et al., 2024). In sports practice, tracking HRV dynamics is commonly used to monitor the body's adaptive responses to increased physical activity, identify signs of overtraining, and guide training planning. Research shows a strong correlation between decreased HRV, cumulative training loads,

and the onset of fatigue-related adverse effects (Li Volsi et al., 2023). This condition in athletes leads to reduced physical performance and a higher risk of sports injuries (Cerezal et al., 2025). A characteristic feature of adolescence is the active morphofunctional development, which increases the body's sensitivity to external stimuli, including physical activity. The resulting compensatory responses from the cardiovascular and autonomic nervous systems provide a foundation for studying adaptation processes. Accordingly, some researchers have identified a direct relationship between HRV indicators and an athlete's fitness level. Studies show that experienced players exhibit greater resilience and better stress adaptation, whereas novices tend to reach the limits of their adaptive reserves more quickly (Fudge et al. 2023; Nakamura et al., 2022). Other studies highlight sex-related differences in the cardiovascular responses of adolescents, noting variations in HRV indices and recovery rates following exercise (Kamandulis et al., 2022; Madziak et al., 2024). These investigations focus on improving algorithms for individualized training load selection and determining the optimal training structure and intensity to minimize the risk of adverse effects from excessive physical stress on adolescent bodies. HRV diagnostics are recommended as a key component of regular monitoring for young athletes, serving as the basis for a safe and effective training process (Kolokoltsev et al., 2023; Vorozheikin et al., 2020). This paves the way for developing effective strategies to optimize training and support young athletes on their path toward success in professional sports. However, the application of HRV monitoring in adolescent football players remains insufficiently addressed in the scientific literature.

Research aim. To optimize the training process for football players aged 12–13, their adaptive capacity should be assessed based on the identified characteristics of autonomic reactivity under submaximal stress test conditions.

Material & methods

The study was conducted at the sports base of the Department of Physical Education and Sports of the Privolzhsky Research Medical University (Nizhny Novgorod, Russia). The experiment involved 17 young male athletes aged 12-13 (12.4 ± 1.3), who trained at least 5 times a week for 120 minutes at the Vorsma physical education complex (Vorsma, Nizhny Novgorod Region). The subjects were participants and prize-winners of regional, all-Russian and international tournaments and had a high level of physical fitness. The participants in the experiment underwent a medical examination confirming that they had no contraindications to participation in the observation. The study was conducted in strict accordance with ethical standards and rules for the protection of the rights of minors. Parents or legal representatives of the participants gave written consent for the child to participate in the study. The procedure was approved by the local ethics committee of the sports school. This fully complies with the provisions of the Helsinki Declaration of 2008. Researchers and specialists from multiple universities in Russia, Kyrgyzstan, and Kazakhstan collaborated on this project.

The screening diagnostics procedure included several stages. First, the participants rested for 10-15 minutes in a calm environment, getting acquainted with the study procedure. Then we recorded a sphygmogram in a state of relative physiological rest, before performing physical exercise (background). Then the subjects sequentially performed submaximal motor tests. They included shuttle running 3 x 10 m at maximum speed, s; flexion and extension of the arms from a prone position (maximum possible number of repetitions). Rest between exercises was no more than 1-2 minutes.

The experiment used the hardware and software complex "Sports testing system "MedicalSoft" (modification MS FIT-01, Moscow, Russia). The number of registered cardiocycles was at least 256. The sphygmogram was recorded, and then the duration of cardiointervals was determined and the values of the time and spectral indicators of HRV were calculated. The following parameters were used for monitoring: heart rate (HR), standard deviation of NN intervals (SDNN), root mean square deviation of the mean difference of NN intervals (RMSSD), variation range (MxDMn), low-frequency, high-frequency and very low-frequency spectral powers in relative values (LF, HF, VLF), total spectrum power (TP), the ratio of low-frequency and high-frequency spectrum powers (LF/HF), and the stress index (SI).

The Statistica 10.0 and Microsoft Excel 2016 for Windows software packages were used. The normality of distribution was determined by the Shapiro-Wilk criterion. Given the lack of normality of data distribution, the nonparametric Wilcoxon test was used to test the statistical significance of differences in the indicators before and after the stress testing. Before cluster analysis, the difference (delta) of the values of each indicator was calculated to assess individual changes in heart rate regulation. Based on the deltas of the indicators before and after physical activity, to identify homogeneous groups by the nature of the autonomic response, we used K-means cluster analysis with the Euclidean distance between the centroids and extreme points, with a preliminary Z-transformation to eliminate the influence of differences in the measurement scales. The optimality of separation was assessed by intra-cluster variance and biological interpretability of the results. The variables with belonging to a group by the level of adaptation to physical activity were determined using logistic regression analysis. Cluster membership was used as a dependent variable (Y), and changes in the deltas of the HRV indicators before and after physical activity were used as independent variables (X) with the determination of logistic regression coefficients and odds ratios (OR). To assess the reliability of the obtained model, the area

under the error curve coefficient (AUC ROC) was used. Differences were considered statistically significant at $p < 0.05$.

Results

Significant changes in HRV indicators were observed in adolescent subjects in response to submaximal physical activity. Sympathetic–adrenal activation, reduced HRV, and enhanced central regulatory control reflect well-developed adaptive mechanisms that ensure adequate oxygen and energy supply to tissues. The most pronounced exercise response was the SI, which increased by 136% (Figure 1)

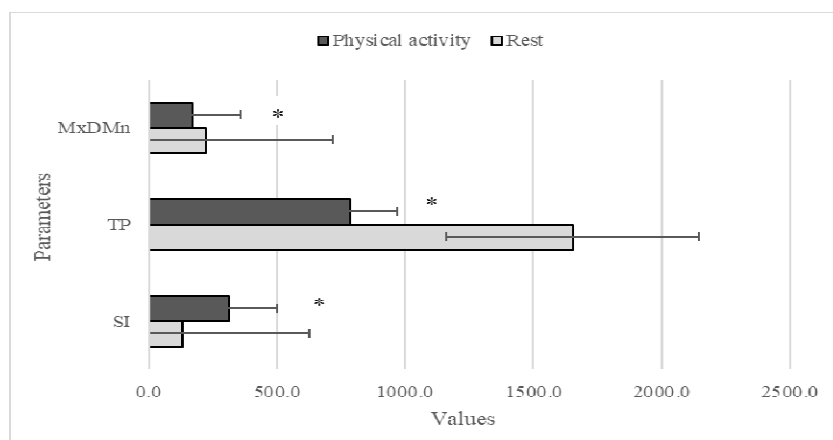


Fig. 1. Stress index, total spectral power, and range of cardiointerval duration oscillations in young football players at rest and after physical activity

Note: * $p < 0.05$ compared to the resting state, Wilcoxon test

High values indicate substantial strain on the body's regulatory systems, caused by increased sympathetic activity and reduced parasympathetic influence. This represents a normal physiological response to intense physical exertion. Significant changes were also observed in the range of cardiointerval duration oscillations (MxDMn), shown in Figure 1. This parameter decreased by 24.6%, reflecting a narrowed range of HR variability associated with the body's increased demand to stabilize hemodynamics under load. Additionally, total spectral power declined by 52.5% after the test.

This may result from a reduced combined contribution of the HF and LF components of the spectrum, reflecting a decrease in overall HR variability as central regulatory mechanisms become activated. The increased HR stability in response to exercise represents a protective restriction of oscillations, aimed at maintaining stable cardiac function under increased energy demands. The 55.3% increase in HR following the exercise test is a natural response. Additionally, a significant 28.7% decrease in SDNN was observed in response to physical activity ($p < 0.05$, Figure 2).

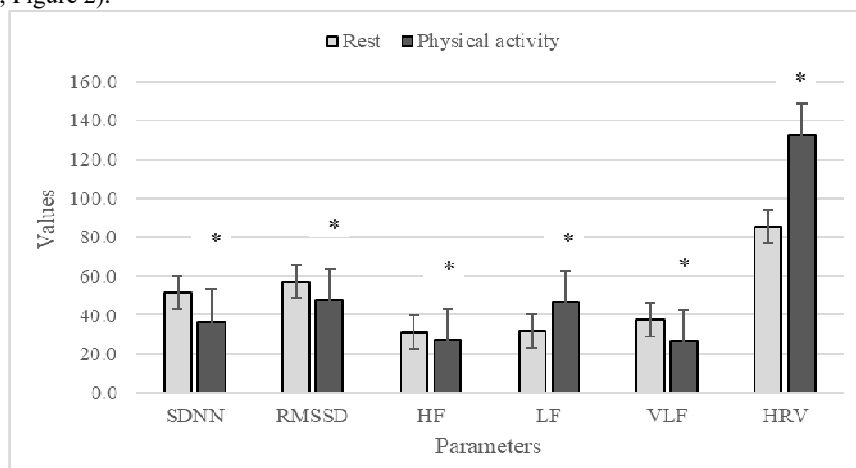


Fig. 2. Standard deviation of NN intervals, root mean square of successive NN interval differences, heart rate, and spectral power in the very low, low, and high frequency ranges of football players at rest and after exercise

Note: * $p < 0.05$ compared to the resting state, Wilcoxon test

This confirms the well-established pattern of decreased HRV in response to exercise. Moderate activation of the sympathetic branch of the autonomic nervous system was observed. Specifically, a 12.9% reduction in the HF component indicates diminished vagal activity, reflecting reflexive inhibition of parasympathetic regulation to increase cardiac output and oxygen delivery to skeletal muscles. At the same time, a significant 46.4% increase in LF waves confirms sympathetic system activation during the stress test. Additionally, a 28.7% decrease in the VLF component reflects a shift in regulatory center activity toward sympathetic dominance, aimed at accelerating metabolic processes and substance delivery to working muscles.

A 72.7% increase in the LF/HF ratio following physical activity indicates a shift in HR regulation toward sympathetic stimulation of the myocardium ($p < 0.05$), which is characteristic of the body's adaptive response to intense exercise. To evaluate the nature of athletes' adaptive responses, individual changes (deltas) in key HRV parameters were calculated, as shown in Table 1.

To assess the nature of athletes' adaptive responses to physical activity, individual changes (deltas) in the main HRV parameters were calculated, Table 1. For this, a pool of indicators was used: SI, TP, SDNN, LF/HF, RMSSD, MxDMn, HF, LF and VLF. Delta was calculated as the difference between the value of each indicator after the load and the corresponding value at rest. This made it possible to quantitatively reflect the dynamics of the physiological reactions of the autonomic nervous system to the load.

Table 1. Individual autonomic responses to physical activity based on HRV indicator dynamics in young football players

Indicators									
No.	ΔSI	ΔTP	$\Delta SDNN$	$\Delta LF/HF$	$\Delta RMSSD$	$\Delta MxDMn$	ΔHF	ΔLF	ΔVLF
1	233.0	-1224.0	-30.1	1.9	-44.3	-32.0	-17.7	17.8	-0.1
2	-218.0	2726.0	52.4	-0.9	80.1	133.0	32.1	12.1	-33.2
3	317.0	-1165.0	-30.4	1.8	-35.5	-99.0	-14.3	25.3	-11.0
4	-12.0	-98.0	-0.9	1.0	-3.3	-16.0	-1.3	32.4	-31.1
5	332.0	-1234.0	-27.7	1.9	-15.0	-98.0	-6.0	25.8	-19.8
6	177.0	-612.0	-5.0	0.6	10.9	-83.0	4.4	22.6	-27.0
7	860.0	-1947.0	-59.4	0.5	-59.7	-213.0	-23.8	28.2	44.6
8	209.0	-2463.0	8.7	1.1	37.6	33.0	15.1	23.6	-18.9
9	226.0	-1410.0	-16.0	1.1	-11.1	-183.0	-4.5	32.9	-28.4
10	225.0	-1779.0	-24.8	1.4	-19.3	-97.0	-7.8	25.5	-17.7
11	101.0	-1822.0	-40.2	1.7	-48.0	-149.0	-18.8	10.9	11.3
12	407.0	-2596.0	-41.0	1.7	-36.9	-132.0	-14.8	11.3	3.5
13	36.0	-904.0	-16.9	1.3	-24.6	16.0	-10.8	13.3	-9.3
14	-255.0	843.0	14.7	-0.6	5.0	83.0	1.9	14.5	-25.4
15	416.0	-983.0	-16.6	1.2	-17.4	-93.0	-7.9	20.0	-12.2
16	24.0	-708.0	-1.2	0.3	8.9	-18.0	3.5	13.8	-17.3
17	-15.0	-1838.0	-2.9	1.1	15.2	-126.0	6.1	35.1	-4.1

The most pronounced changes were observed in the SI, with most subjects exhibiting increases, in some cases exceeding +400 units. This increase in SI reflects activation of the sympathetic branch of autonomic regulation in response to physical exertion. Additionally, nearly all athletes demonstrated a decrease in TP, sometimes exceeding -1800 ms^2 , indicating a substantial reduction in overall autonomic regulation and HRV.

Most subjects also exhibited decreases in SDNN and RMSSD, with values decreasing by up to 59.7 ms, suggesting a reduction in overall and predominantly parasympathetic activity following exercise. However, some cases showed positive changes in these indicators, potentially reflecting more stable adaptation to the load or stronger activation of recovery mechanisms. The LF/HF ratio, representing sympathovagal balance, increased in nearly all athletes, confirming a shift toward sympathetic dominance in the post-exercise period. Meanwhile, changes in HF and LF varied among athletes: in some, HF decreased by up to 23.8 ms^2 , indicating suppression of the vagal component, while others showed increases, suggesting incomplete sympathetic dominance. In most cases, LF exhibited a positive delta, consistent with increased sympathetic activity. The VLF parameter, related to humoral and metabolic regulatory mechanisms, also decreased in the majority of participants, reaching reductions of up to 33.2 ms^2 .

Thus, the presented results demonstrate a wide range of individual reactions to physical activity, from typical sympathetic activation with suppression of parasympathetic activity to paradoxical or smoothed changes, which may indicate different levels of training and adaptive potential of athletes. Multidirectional vegetative shifts served as the basis for subsequent clustering of athletes in order to identify groups with different levels of adaptation to the load.

The cluster analysis results allowed the classification of athletes into groups exhibiting different types of autonomic HRV regulation in response to physical load, forming the basis for interpreting their levels of functional adaptation. The first cluster comprised 7 subjects, while the second included 10 football players (Table 2).

Table 2. Mean changes (deltas) in heart rate variability indicators in young football players based on cluster analysis using the K-means method

Indicator	Clusters	
	1 cluster (n = 7)	2 cluster (n = 10)
ΔSI	335.4	51.3*
ΔTP	-693.9	551.2*
ΔSDNN	-15.1	5.7*
ΔLF/HF	0.91	-0.17*
ΔRMSSD	-44.2	5.3*
ΔMxDMn	-119.6	7.8*
ΔHF	-36.1	2.7*
ΔLF	-68.1	12.6*
ΔVLF	-57.4	4.3*

Note: * indicates statistically significant differences in HRV indicators between the first and second clusters ($p < 0.05$)

The analysis revealed a clear division of subjects into two groups, differing in both the direction and magnitude of changes. In the second cluster (n = 10), moderate and predominantly positive changes in HRV were observed. Specifically, the average delta values for TP (+551.2 ms²), SDNN (+5.7 ms), and RMSSD (+5.3 ms) indicate activation of the parasympathetic component of autonomic tone following physical activity, likely reflecting restorative regulation supported by highly effective adaptive mechanisms. Additionally, this group showed a decrease in the sympathovagal ratio (LF/HF by 0.17), reflecting physiologically favorable dynamics. The increase in the HF component (+2.7), alongside increases in LF (+12.6 n.u.) and VLF (+4.3), indicates a functional balance among different regulatory levels, with vagal activity remaining dominant. This group exhibits characteristics of a positive adaptation level to physical activity.

In the first cluster (n = 7), the indicator dynamics showed a contrasting pattern: a substantial increase in the SI (+335.4 conventional units) was accompanied by considerable decreases in TP (-693.9 ms²), SDNN (-15.1 ms), RMSSD (-44.2 ms), and HF (-36.1 n.u.). This combination reflects pronounced sympathetic activation alongside a sharp reduction in parasympathetic influence, serving as a marker of functional stress and the body's impaired ability to effectively undergo neuroautonomic adaptation in response to physical activity. Further evidence of sympathetic dominance is seen in the increase of the LF/HF ratio (+0.91) and a marked decrease in the slow spectral components (VLF -57.4 n.u.), which may indicate a limited reserve of central regulation and potentially suboptimal humoral adaptation mechanisms. Thus, this cluster is characterized by unstable adaptation to stress testing. The scatterplot of the HRV deltas is shown in Figure 3.

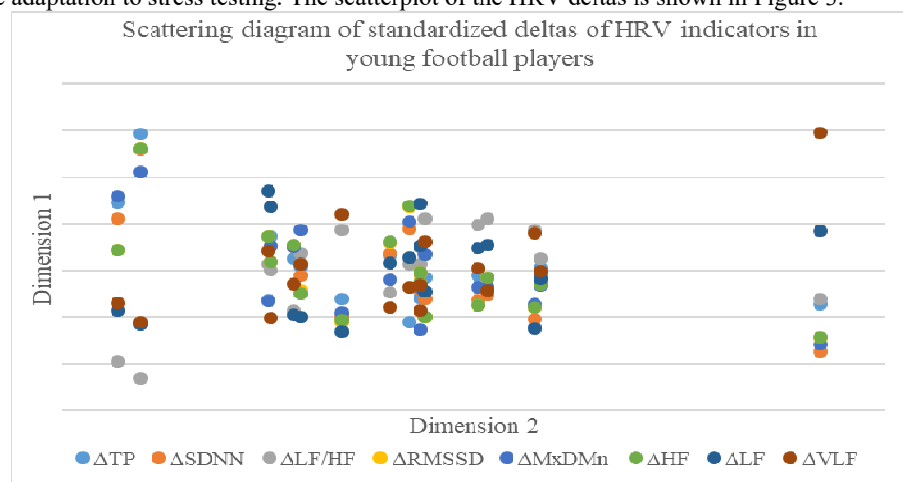


Fig. 3. Scatter plot of changes (deltas) in heart rate variability indicators in young football players

The conducted cluster analysis revealed the presence of pronounced heterogeneity in the adaptive reactions of adolescents to a standard load. The second group of subjects demonstrates signs of adaptive, balanced regulation with the involvement of the parasympathetic link, while the first group is distinguished by an imbalance of vegetative regulation with a predominance of sympathetic influences, a decrease in variability and signs of functional stress. These data emphasize the importance of taking into account the individual profile of the neurovegetative response when planning the training process in adolescents, as well as the feasibility of regular monitoring of HRV parameters as part of the functional control system.

At the final stage of the analysis, the mechanism of binary logistic regression was used with the determination of logistic regression coefficients and the odds ratio, an assessment of the quality of the model (AUC ROC) with visualization on the ROC curve. The values of the logistic regression coefficients among young athletes during physical activity are presented in Table 3.

Table 3. Logistic regression coefficients, odds ratios (OR), 95% confidence intervals and significance levels in the analysis of deltas of heart rate variability indicators before and after physical activity in young athletes (n=17)

Variable	β	SE	OR (95% CI)	p-value
ΔSI	-0.007	0.003	0.99 (0.98–1.00)	0.054
ΔTP	0.000	0.000	1.00 (1.00–1.00)	0.278
$\Delta SDNN$	0.087	0.028	1.09 (1.03–1.15)	0.002
$\Delta LF/HF$	0.313	0.295	1.37 (0.77–2.44)	0.289
$\Delta RMSSD$	0.061	0.024	1.06 (1.01–1.13)	0.012
$\Delta MxDMn$	-0.004	0.001	0.99 (0.99–1.00)	0.008
ΔHF	-0.015	0.006	0.99 (0.98–1.00)	0.021
ΔLF	-0.002	0.001	1.00 (0.99–1.00)	0.107
ΔVLF	-0.007	0.003	0.99 (0.98–1.00)	0.021

The data showed that the most significant positive predictor of membership in the cluster with unsatisfactory adaptation was the ΔSI indicator ($B = 0.008$, $OR = 1.008$, $p = 0.020$). This suggests that an increase in the SI after exercise significantly increases the likelihood of belonging to the group with impaired adaptation. Similarly, the ΔLF indicator demonstrated a significant positive association ($B = 0.053$, $OR = 1.054$, $p = 0.027$), indicating that increased sympathetic activity is related to an inadequate regulatory response. At the same time, the $\Delta RMSSD$ indicator showed a strong negative association with the likelihood of belonging to the cluster with unsatisfactory adaptation ($B = -0.042$, $OR = 0.959$, $p = 0.024$), indicating reduced vagal activity in this group of athletes. Similar inverse relationships were observed for $\Delta SDNN$ ($B = -0.073$, $OR = 0.930$, $p = 0.035$) and ΔHF ($B = -0.109$, $OR = 0.897$, $p = 0.015$), further reflecting suppression of parasympathetic regulation.

No statistically significant associations were found for other variables such as ΔTP , $\Delta LF/HF$, $\Delta MxDMn$, and ΔVLF ($p > 0.05$). Thus, the constructed model identified several key autonomic predictors of membership in the cluster with unsatisfactory adaptation, reflecting a predominant increase in sympathetic activity alongside a decrease in parameters related to parasympathetic regulation of HR.

The constructed logistic model demonstrated high classification quality characteristics. The overall accuracy of the model was 88.2%, indicating a high ability to correctly distinguish between subjects with satisfactory and unsatisfactory adaptation to physical activity. The discriminatory ability of the model was assessed using the area under the receiver-operator error curve (ROC AUC), the value of which was 0.90, Figure 4.

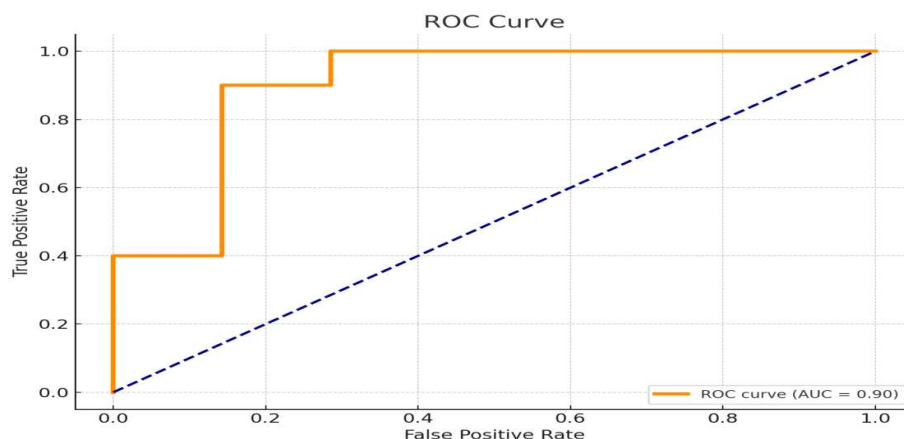


Fig 4. ROC curve illustrating the accuracy of predicting the adaptation reactions of young athletes to stress testing

This indicator corresponds to the high sensitivity of the model to the recognition of true positive and negative outcomes, indicating a good balance between sensitivity and specificity. The precision values were also calculated for each of the classes. For the group with unsatisfactory adaptation (class 0), the accuracy was 0.86, and for the group with satisfactory adaptation (class 1), it was 0.90. These values emphasize the reliability of the model in correctly classifying subjects according to their belonging to the corresponding types of adaptation response.

This is additionally indicated by the value of the area under the ROC curve, which demonstrates a pronounced deviation from the diagonal of random classification, indicating a high discriminatory ability of the model. Thus, the proposed logistic model demonstrates high prognostic value and can be recommended as a tool for preliminary assessment of the state of autonomic regulation in young athletes based on the HRV response to standard physical activity.

Discussion

In recent years, sports science has seen a growing interest in using HRV indicators as an objective tool for assessing the functional state and adaptation of the body to physical activity (Bocharin et al., 2024). Modern studies emphasize the high prognostic significance of temporal and spectral parameters of heart rate variability in monitoring the training process, especially in young athletes.

Thus, according to a meta-analysis (Oliveira et al., 2023), the dynamics of RMSSD, SDNN and LF/HF indicators can serve as a reliable indicator of the balance of the autonomic nervous system and the level of recovery after physical activity.

The study (Tiwarei et al., 2021) showed that systematic monitoring of HRV allows identifying early signs of functional maladaptation in adolescent athletes long before clinical manifestations of overtraining. Moreover, the data (Figueiredo et al., 2021) confirmed that autonomic patterns of response to exercise have significant individual variability, due not only to the level of training, but also to age-related features of neurovegetative regulation.

The results of our study confirm the high information content of heart rate variability indicators in assessing the adaptive responses of the adolescent body to submaximal physical activity. The data obtained indicate a pronounced heterogeneity of the autonomic responses of young football players, which is consistent with the concept of individual variability of adaptive mechanisms, widely reflected in modern sports science.

The two distinctly differentiated clusters representing satisfactory and unsatisfactory adaptation align with findings from several international studies that highlight the heterogeneity of neuroautonomic responses among young athletes. For example, the studies (Pichot et al., 2000; Plews et al., 2013) emphasize the importance of monitoring heart rate variability to identify the state of overtraining and assess the balance between sympathetic and parasympathetic activity.

In particular, a decrease in the RMSSD parameters and the HF component, characteristic of the cluster with unsatisfactory adaptation, coincides with the patterns described in studies where such changes were associated with an increased risk of overfatigue and a decrease in athletic performance.

In addition, logistic regression revealed key autonomic markers reliably associated with impaired adaptation, among which the stress index (ΔSI) and the change in low-frequency spectrum power (ΔLF) act as positive predictors, while the indicators reflecting parasympathetic activity ($\Delta RMSSD$, $\Delta SDNN$, ΔHF) show an inverse relationship.

This emphasizes the role of imbalance in autonomic regulation, in particular, the predominance of the sympathetic link, as a fundamental mechanism of maladaptation in young athletes. We note the high quality of the prognostic model ($AUC = 0.90$, accuracy = 88.2%), which indicates the practical applicability of these indicators for the early diagnosis of functional disorders and assessment of the body's adaptive reserve.

Such a tool can significantly improve the efficiency of the athletes' condition monitoring system, providing an individual approach to adjusting training loads.

Thus, the prospects for applying the research results lie in integrating HRV monitoring into the regular practice of sports schools and training centers, which will allow for timely detection of fatigue risks and optimization of the training process taking into account individual physiological characteristics.

Further research involving larger samples and extended monitoring periods will broaden the range of biomarkers and improve prediction algorithms, paving the way for the implementation of personalized medicine in adolescent sports training.

Conclusion

Cluster analysis identified two groups of young football players with distinct levels of neuroautonomic adaptation—satisfactory and unsatisfactory—highlighting the individual variability in responses to physical activity. Logistic regression revealed that key predictors of unsatisfactory adaptation included an increase in the SI and LF HR oscillations, along with a decrease in parameters indicative of parasympathetic activity.

The developed model demonstrates high classification accuracy and has potential for integration into functional monitoring systems for young athletes.

HRV is a highly sensitive and informative marker for assessing the adaptive capacity of young football players during submaximal exercise. These findings pave the way for a personalized approach to training load planning, aiming to improve training effectiveness and prevent overfatigue in adolescents.

Conflicts of interest. The authors declare no conflict of interest.

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