American Impact Review

RESEARCH ARTICLE

Diagnostic Capabilities of Hardware-Software Systems in Sports Medicine

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OPEN ACCESS

Citation:

V.M. Alekseev (2026) Diagnostic Capabilities of Hardware-Software Systems in Sports Medicine. American Impact Review. E2026002. https://americanimpactreview.com/article/e2026002

Received:

January 11, 2026

Accepted:

February 3, 2026

Published:

February 10, 2026

Abstract

The achievement of peak athletic performance while preserving athlete health requires coordinated functioning of organs and systems at multiple physiological levels. This article examines the diagnostic capabilities of modern hardware-software systems applied in sports medicine for comprehensive assessment of athlete functional status. The study addresses three principal domains: (1) psychophysiological assessment, including cognitive function evaluation, motor and sensory analyzer testing, and psychological status profiling; (2) current functional state evaluation using heart rate variability (HRV) analysis in accordance with the International Standard (Task Force of ESC and NASPE, 1996), incorporating cross-analysis of HRV and respiratory cycle duration variability (RCDV); and (3) physical work capacity assessment through stress ergometry with individualized training load optimization. The multi-level diagnostic approach encompasses spectral analysis of cardiac rhythm, autonomic nervous system balance evaluation through orthostatic testing, and real-time ECG radiotelemetry monitoring during training sessions. Key findings demonstrate that HRV spectral power dynamics - specifically, the relationship between high-frequency (HF), low-frequency (LF), and very-low-frequency (VLF) components - serve as early prognostic indicators of maladaptation and overtraining, detectable one to three weeks before decline in athletic performance. Cross-analysis of cardiac and respiratory rhythms provides additional diagnostic precision by revealing desynchronization between regulatory centers. The integration of psychophysiological testing, HRV-based functional diagnostics, stress ergometry, and real-time telemetric monitoring constitutes a rational multi-level approach to training process optimization and early detection of pathological deviations in athletes.

1. Introduction

The achievement of maximal athletic results while preserving the health of the athlete is possible only on the basis of coordinated functioning of organs and systems at various physiological levels. To assess the functional state of an athlete, their readiness for competition (or a game), to provide timely diagnosis of overtraining, and to detect the initial stages of disease, it is necessary to evaluate:

- the psychological state and psychophysiological status of the individual;
- the current functional state, adaptive reserves, and stress resistance of the organism;
- physical work capacity.

From these standpoints, modern instrumental diagnostic computer-based systems have been developed for application in sports medicine. Specialized hardware-software diagnostic platforms enable psychophysiological testing, heart rate variability analysis, stress ergometry, and real-time electrocardiographic monitoring during training - collectively providing a comprehensive multi-level assessment of athlete functional status.

2. Psychophysiological Assessment in Sports Medicine

For psychological and psychophysiological testing, specialized hardware-software psychophysiological testing platforms are employed, enabling the investigation of cognitive functions (thinking, memory, attention) and the assessment of motor, auditory, and visual analyzers. The range of methodologies implemented in such systems includes the following tests: simple visual-motor reaction time, critical flicker fusion frequency, tapping test, interference resistance, attention assessment, reaction to a moving object, red-black tables (Schulte-Gorbov test), choice reaction and discrimination reaction, muscle endurance index and muscle endurance index with biofeedback, contact coordination testing and contact coordination testing along a profile, including variants with biofeedback.

Objective psychophysiological parameters should be supplemented by assessment of psychological status, including subjective evaluation of well-being, activity, and mood; anxiety level; severity of depression; level of emotional burnout; and other relevant psychological dimensions.

When an in-depth assessment of the central and peripheral nervous system is required, psychophysiological investigations may be complemented by such diagnostic methods as electroencephalography (EEG), electromyography (EMG), and evoked potential (EP) studies.

3. Assessment of Current Functional State Using Heart Rate Variability

3.1. Methodological Foundation

The current functional state (FS), adaptive reserves, and stress resistance of the organism can be assessed using heart rate variability (HRV) analysis systems. The foundation for evaluating the current functional state of the organism is the methodology of HRV investigation, conducted in accordance with the International Standard (Task Force of ESC and NASPE, 1996).

The conceptual framework for FS assessment based on HRV investigation proceeds from the premise that all organs and systems of the human organism are under constant neurohumoral control. The close symbiosis of the sympathetic and parasympathetic divisions of the autonomic nervous system and humoral influences provides a coordinating function and the achievement of optimal results in terms of adaptation to changing conditions of the internal and external environment. Deviations arising in the regulatory systems precede hemodynamic, metabolic, and energetic disturbances and, consequently, represent the earliest prognostic signs of an unfavorable state in the individual examined. The cardiac rhythm serves as an indicator of these deviations, and therefore the investigation of heart rate variability has important prognostic and diagnostic significance both in healthy individuals and in a wide variety of pathologies, including psychoemotional (stress-related) disturbances.

3.2. Objectives of HRV Investigation in Athletes

The objectives of HRV investigation in athletes include:

1. Assessment of the current functional state, adaptive potential, and stress resistance of the individual;
2. Early detection of maladaptation and overtraining;
3. Immediate monitoring of the physical training process with the aim of its optimization.

Assessment of HRV parameters enables a scientific approach to forecasting the physical capabilities of athletes, resolving questions of selection for athletic training, more rationally constructing training regimens, and conducting ongoing monitoring of the functional state of athletes.

3.3. Influence of Training Orientation on Adaptation

However, it is necessary to take into account the fact that different orientations of the training process exert an influence on the directionality of adaptive processes. In particular, the following patterns of the adaptive process have been identified (Zemtsovskii, 1995). In athletes with high-intensity dynamic loads (those training endurance), the proportion of random influences on the pacemaker activity of the sinoatrial (SA) node decreases. In other words, the SA node becomes relatively "independent" of the morphometric and hemodynamic indicators of cardiac activity. The increase in the number of "degrees of freedom" ultimately contributes to the achievement of a functional optimum during the performance of work within a relatively narrow power range over a sufficiently prolonged duration.

The structure of correlations between morphometric, hemodynamic, and HRV parameters in the group of athletes developing strength is substantially less extensive than in the group developing speed.

Thus, the orientation of the training process is the principal and determining factor in the organization of the circulatory system's function - this reflects the principle of preferential structural support of systems dominant in the adaptation process (Meerson, 1986). This principle implies the formation of a system ensuring successful performance of physical exercise of a given orientation at the expense of the capacity to perform physical exercises of a different orientation. The study of HRV and cross-correlation relationships between cardiac rhythm parameters, morphometric indicators, hemodynamic parameters, respiratory patterns, and psychophysiological parameters of the central nervous system at rest and during functional tests provides the most complete understanding of the functional state of the athlete, enables the assessment of training process dynamics, and identifies pathways toward its optimization.

4. Cross-Analysis of HRV and Respiratory Cycle Duration Variability

4.1. Rationale and Methodology

In advanced diagnostic systems, ECG recording is performed synchronously with pneumogram registration, which enables cross-analysis of HRV and respiratory cycle duration variability (RCDV). As is well known, the respiratory rhythm, as a particular case of physiological rhythms, evidently plays a definite regulatory role in the human organism, which, like all living systems, is fundamentally an oscillatory system (Molchanov, 1967). From this perspective, the cross-analysis of HRV and RCDV is of considerable interest. Furthermore, the correct calculation of the spectral power of high-frequency oscillations (the HF component) is impossible without accounting for individual characteristics of the respiratory pattern. This assertion is particularly relevant in sports medicine, since a decrease in respiratory rate below 9 breaths per minute (0.15 Hz) in athletes is a common phenomenon.

The cross-analysis of HRV and RCDV is implemented as follows. Synchronous registration of the cardiac rhythm and the respiratory pneumogram is performed. From the pneumogram, a histogram of respiratory cycle durations is constructed, which is graphically superimposed on the HRV spectrogram. The mode of the RCDV histogram and the most prominent peak of the spectrogram in the high-frequency component region are visually compared. The assessment of RCDV parameters includes counting the number of histogram bars, determining the position of the histogram mode (in Hz), and establishing the position of the histogram mode relative to the most prominent peak of the HRV spectrogram in the high-frequency component region ("D" - the distance between the histogram mode and the HF component peak).

4.2. Normal and Pathological Patterns

Under normal conditions, there are one to two peaks on the respiratory histogram in the range of 0.20-0.30 Hz (respiratory rate of 12-18 breaths per minute). Such a variant of the RCDV histogram indicates an optimal functional state (rhythmic operation of the respiratory center at an optimal frequency). The distance (D) between the RCDV histogram mode and the HF component peak of HRV typically does not exceed 0.05 Hz. This fact indicates synchronous operation of the respiratory center and the activity of centers regulating the cardiac rhythm.

In pathological states, the appearance of multiple peaks on the RCDV histogram may be observed (a large scatter of respiratory cycle duration oscillations - "uneven breathing"), which, as a rule, occurs during states of psychoemotional tension. Alternatively, a pronounced divergence between the respiratory histogram peak and the HF component peak of HRV may be present. Such a pattern may indicate disrupted synchronous operation of the respiratory center and the centers modulating cardiac rhythm through the parasympathetic division of the autonomic nervous system. Disrupted coherence of functioning between elements of the functional system, deterioration of their synchronization, and weakening of correlational linkages among them are objective signs of strain and even exhaustion of the organism's regulatory systems. A disturbed or abnormal respiratory pattern provides the basis for implementing respiratory training.

4.3. Practical Significance of Respiratory Pattern Assessment

In the preparation of athletes - and not only marksmen - the establishment of a correct respiratory pattern is an important task. The ability to regulate ("hold") breathing enables control of one's behavior on the field (playing area, running track, in combat sports, and so forth). Comparative assessments of functional state in athletes and adolescents from general education schools confirm the diagnostic value of the respiratory pattern analysis in athletic populations.

5. HRV Dynamics During the Training Process

Summarizing published data and our own observations, the dynamics of HRV changes during the training process can be represented as follows. As the functional state of the organism improves and adaptive potential increases, the total spectral power (TP) grows, predominantly due to an increase in the power of respiratory waves (the HF component).

During physical overstrain, one to three weeks before a decline in athletic performance, HF power decreases and the power of slow and very slow oscillations (LF and VLF) relatively increases against a background of bradycardia (Aksenov, 1986). Zhemaitite et al. (1982), in studying rhythmograms (RGs) of athletes training endurance, found that a significant proportion of them exhibited a decrease in respiratory wave amplitude against a background of rhythm deceleration as they approached peak athletic form.

During prolonged physical loads and with declining fitness, a change in RG type is observed, transitioning from a parasympathetic-type RG (predominance of the HF component) to an RG in which LF and VLF components predominate in the cardiac rhythm structure. Pronounced maladaptation and encephalopathy are accompanied by desynchronization of the respiratory and vasomotor centers.

5.1. Orthostatic Testing

Substantial changes are also observed during orthostatic testing. In particular, reactivity of the parasympathetic division of the autonomic nervous system decreases (a marked deviation from the individual norm of the 30:15 ratio), and there is insufficient or, conversely, excessive activation of the sympathetic division of the autonomic nervous system.

With further progression of maladaptation processes in response to excessive loads, two types of cardiac rhythm response are possible: the formation of a low-variability rhythm against a background of bradycardia, and a sharply pronounced rhythm irregularity accompanied by an increase in heart rate (Zemtsovskii, 1995). In the first case, an extreme degree of "emancipation" of the SA node from autonomic and hemodynamic influences apparently occurs. In the second case, with sharply pronounced rhythm irregularity, hypersensitivity of the SA node to extracardiac influences is likely present.

5.2. Diagnostic Significance and Limitations

The conduct of functional tests (orthostatic and exercise tests) in these situations enables a more detailed assessment of the athlete's state and degree of fitness. It should be noted that HRV parameters play only a signaling role in establishing a "diagnosis" reflecting the presence and degree of pathological deviations. Decisive significance for the "diagnosis" belongs to specific signs of structural, metabolic, and energetic changes, which are investigated by other laboratory and instrumental methods. However, the simplicity and rapidity of HRV assessment make this method an indispensable tool for operative monitoring of the probability of pathological deviations.

6. Assessment of Physical Work Capacity

Although HRV investigation permits an indirect determination of the degree of an athlete's physical readiness, the principal purpose of this methodology is to assess the current functional state and the adequacy of the training load on the organism. In selecting the specific optimal training load, it is also necessary to account for such factors as the species-specific classification of physical exercises and the optimization of the dosage of volume (duration) and power (intensity) of the physical load (Postolovskii, 2001). If the volume and power of the physical load exceed the actual adaptation reserves of the organism in a given period of the training process, disruption of inter-system interaction is provoked and, as a consequence, athletic performance declines.

For the selection of an adequate physical load intensity during training, preliminary stress testing (cycle ergometry, treadmill) is necessary. Determination of the "threshold" or, more precisely, the "maximal" heart rate for each individual enables the construction of an individualized training regimen. Modern stress ergometry systems allow examination on any type of cycle ergometer or treadmill, with a broad selection of standard or user-configurable protocols. Examination results, presented in the form of tables and graphs, enable rapid and accurate prescription of the optimal training regimen.

7. Real-Time Monitoring During Training (ECG Telemetry)

7.1. System Description

Medical monitoring systems (MMS) based on radiotelemetry enable continuous monitoring of the current functional state of the individual through the registration of two-channel electrocardiography and one-channel respiratory recording directly during the training process. Display and assessment of physiological signals in the form of graphs and tables are performed on the monitor screen in real time.

7.2. Applications and Capabilities

The application of telemetric monitoring systems during training sessions has enabled, in addition to observation of cardiac rhythm, the monitoring of the degree of physical load on the organism and the timely modification of load intensity. Figure 1 presents a fragment of a rhythmogram recorded during the training of an ice hockey player using radiotelemetric registration.

Figure 1. Rhythmogram of one of the training stages (radiotelemetric registration).

ECG monitoring enables the selection of an individualized work rhythm (tempo), the detection of possible arrhythmias, conduction disturbances, myocardial overload, and myocardial ischemia should it occur.

7.3. Training Process Management

Training process management consists of selecting a training regimen that ensures the achievement of peak athletic form at the required moment and/or the maintenance of functional state and physical work capacity at an optimal level for a specified duration. Telemetric monitoring systems enable real-time (online) monitoring of the course of athletic training, allowing timely adjustments to the training process through modification of load power and intensity and variation in the duration of rest periods.

8. Conclusions

The integration of specialized diagnostic systems - encompassing psychophysiological testing platforms, HRV analysis systems, stress ergometry programs, and medical monitoring systems for remote ECG transmission - provides the following capabilities:

1. **Comprehensive functional assessment.** Evaluation of the psychophysiological and current functional state, adaptive reserves of the organism, and the level of physical work capacity, thereby forming the basis for developing an optimal training regimen.

1. **Quantification of the physiological cost of training.** Registration of HRV parameters before and after training enables quantitative characterization of the concept of "physiological cost of activity" - in other words, determining the cost at which training is accomplished. This approach enables, in addition to optimization of training loads, the practical implementation of principles and concepts for preserving professional health.

1. **Individualized exercise prescription.** Stress ergometry is essential for assessing physical work capacity and calculating the optimal regimen of training loads.

1. **Real-time training control.** The application of telemetric monitoring systems during training sessions enables control of the power and volume of physical load on the organism and timely modification of its intensity directly during training. In addition to individualization of the training process, such systems enable effective monitoring of rhythm and conduction disturbances and timely detection of signs of myocardial overload or ischemia.

Thus, a multi-level approach encompassing the investigation of psychophysiological and psychological characteristics, assessment of current functional state, and physical work capacity of the organism represents the most rational pathway for optimizing the training process and achieving the highest athletic results.

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