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THE IMPORTANCE OF MODERN PHYSIOLOGICAL MONITORING TECHNOLOGIES IN ASSESSING ATHLETES' FUNCTIONAL STATUS

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ABOUT ARTICLE

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Abstract: This article analyzes the significance of modern physiological monitoring technologies used in the assessment of athletes' functional status. Theoretical foundations of sports physiology, mechanisms of adaptation to physical exercise, functional capabilities of the cardiovascular and respiratory systems, heart rate variability (HRV), cardiopulmonary exercise testing (CPET), lactate diagnostics, and methods for evaluating neuromuscular function are discussed. The study demonstrates that comprehensive assessment of functional status enables the individualization of training programs, prevention of excessive physiological strain, optimization of recovery processes, and enhancement of athletic performance.

Introduction. The contemporary development of world sports increasingly emphasizes the necessity of thoroughly understanding and scientifically managing the functional capabilities of the human body in the pursuit of elite athletic performance. The growing intensity of international competition, continuous increases in training volume and intensity, and the narrowing performance gap among elite athletes have created new demands on athlete preparation systems. Under such conditions, achieving high-level sporting success depends not only on increasing training loads but also on the systematic assessment of athletes' functional status, evaluation of adaptive capacities, and individualization of training processes based on objective physiological indicators [1, pp. 10–12].

Sports physiology serves as a fundamental scientific discipline that investigates the functional, morphological, and biochemical changes occurring in the human body under the influence of physical exercise. As a scientific foundation of athletic training theory and practice, sports physiology contributes significantly to understanding adaptation mechanisms, energy supply systems, fatigue development, recovery processes, and methods for assessing functional reserves [2, pp. 18–24].

In recent years, physiological monitoring has become an essential component of athlete management systems. Physiological monitoring refers to the systematic assessment of an athlete's functional condition, adaptation level, and recovery status through specialized diagnostic tools and technologies. Its primary objective is to evaluate physiological responses to training loads, prevent overtraining, and optimize sports performance through evidence-based decision-making [3, pp. 25–31].

The rapid advancement of digital technologies has led to substantial progress in the field of functional diagnostics. While traditional assessment methods were primarily based on heart rate measurements, blood pressure monitoring, and functional exercise tests, contemporary sports science increasingly relies on sophisticated diagnostic approaches such as cardiopulmonary exercise testing (CPET), heart rate variability (HRV) analysis, blood lactate monitoring, electromyography, gas exchange analysis, and wearable technologies [4, pp. 52–60].

According to contemporary scientific concepts, functional reserves play a decisive role in achieving high athletic performance. Functional reserves represent the physiological capacities that can be mobilized in response to external environmental factors and physical exercise. Their magnitude is determined by the functional state of the cardiovascular, respiratory, central nervous, and neuromuscular systems [5, pp. 41–48].

Adaptive responses to physical training are closely associated with the functioning of the autonomic nervous system. Consequently, increasing attention has been devoted to the assessment of heart rate variability (HRV) in sports physiology. HRV is recognized as an important integrative marker reflecting the balance between sympathetic and parasympathetic divisions of the autonomic nervous system. It provides objective information regarding recovery status, physiological stress, training readiness, and the risk of overtraining syndrome [6, pp. 64–70].

Another important method for evaluating athletes' functional condition is cardiopulmonary exercise testing (CPET). This diagnostic approach enables the integrated assessment of cardiovascular, respiratory, and muscular system function during exercise. CPET provides valuable information on maximal oxygen uptake (VO_2max), ventilatory thresholds (VT1 and VT2), oxygen pulse, and gas exchange parameters. Therefore, it is widely regarded as the gold standard for assessing aerobic fitness and functional preparedness in elite athletes [7, pp. 81–90].

Blood lactate monitoring has also become an important component of modern training management. Although lactate was historically considered a primary cause of muscular fatigue, contemporary physiological research has demonstrated its critical role in energy metabolism, cellular signaling, and adaptation processes. Assessment of blood lactate concentration is particularly useful for determining training zones, identifying anaerobic thresholds, and evaluating functional readiness [8, pp. 112–116].

Furthermore, the rapid development of wearable technologies has transformed sports physiology and athlete monitoring. Modern sensor-based devices enable real-time assessment of heart rate, HRV, blood oxygen saturation, sleep quality, physical activity, and recovery status. Such technologies provide coaches and sports scientists with immediate access to physiological data, facilitating individualized training prescription and evidence-based performance optimization [9, pp. 130–138].

Despite substantial advances in physiological monitoring technologies, the comprehensive evaluation of their diagnostic capabilities and practical significance in athlete monitoring remains a relevant scientific challenge. Therefore, the present study aims to analyze the theoretical foundations, diagnostic potential, and practical applications of modern physiological monitoring technologies used in the assessment of athletes' functional status.

Aim of the study

The purpose of this study was to analyze the theoretical and practical significance of modern physiological monitoring technologies used for assessing athletes' functional status and to substantiate their role in the individualization and optimization of the training process.

Materials and methods

The study was based on a comprehensive review and analysis of national and international scientific literature in sports physiology, exercise science, and functional diagnostics. Comparative analysis, systematic review methods, and scientific synthesis approaches were employed to evaluate contemporary physiological monitoring technologies and their application in sports practice.

Physiological adaptation to physical exercise

Physiological adaptation represents one of the fundamental concepts of sports physiology and refers to the process by which the human body adjusts to external stimuli and training loads, resulting in enhanced functional capacity and performance. Adaptation involves complex interactions among the cardiovascular, respiratory, neuromuscular, endocrine, and metabolic systems and serves as the biological basis of athletic development.

The modern scientific understanding of adaptation is largely based on the General Adaptation Syndrome proposed by the Canadian physiologist Hans Selye in 1936. According to this theory, exposure to physical stressors induces three consecutive stages of physiological response: the alarm reaction, the resistance stage, and the exhaustion stage. In sports training, these mechanisms underlie the development of both short-term and long-term adaptations.

Acute adaptation is characterized by immediate physiological responses, including increased heart rate, pulmonary ventilation, cardiac output, oxygen uptake, and hormonal secretion. In contrast, chronic adaptation develops through repeated exposure to training stimuli and results in structural and functional modifications such as increased stroke volume, enhanced capillary density, mitochondrial biogenesis, improved oxidative enzyme activity, and greater maximal oxygen uptake (VO_2max).

Regular training also promotes neuromuscular adaptations, including improved motor unit recruitment, enhanced intermuscular coordination, and increased movement efficiency. From a molecular perspective, exercise-induced adaptation is mediated by signaling pathways involving PGC-1α, AMPK, and mTOR. Endurance training predominantly stimulates mitochondrial biogenesis and oxidative metabolism, whereas resistance training promotes muscle hypertrophy and protein synthesis.

Consequently, physiological adaptation constitutes the primary mechanism through which athletes improve their functional reserves, exercise tolerance, and competitive performance.

Physiological basis of functional status assessment

Functional status is an integrative characteristic reflecting an athlete’s current working capacity, physiological reserves, recovery state, and readiness for training and competition. Assessment of functional status has become an essential component of modern sports science due to its role in optimizing training loads, preventing overtraining, and improving athletic performance.

The concept of functional status assessment has evolved through the contributions of prominent scientists such as Pyotr Anokhin and Nikolai Bernstein, whose theories of functional systems and motor control established the theoretical foundation for understanding the regulation of human performance.

The primary objectives of functional status assessment include:

individualization of training programs;

monitoring of fatigue and recovery processes;

prediction of athletic performance;

identification of maladaptive responses to training;

prevention of overtraining syndrome.

In contemporary sports physiology, functional status is evaluated through a comprehensive analysis of multiple physiological systems. Cardiovascular assessment typically includes heart rate, blood pressure, electrocardiography (ECG), echocardiography, and heart rate variability. Cardiorespiratory evaluation focuses on maximal oxygen uptake, ventilatory thresholds, and cardiopulmonary exercise testing. Neuromuscular assessment incorporates electromyography, reaction time measurements, jumping tests, and motor performance indicators. In addition, biochemical markers such as blood lactate, creatine kinase, ferritin, cortisol, and testosterone provide valuable information regarding metabolic and recovery status.

A multidimensional assessment approach allows for a more accurate evaluation of an athlete's physiological condition and adaptive capacity.

Importance of heart rate variability (HRV) monitoring

Heart Rate Variability (HRV) refers to the natural variation in time intervals between consecutive heartbeats. It is widely recognized as one of the most informative non-invasive indicators of autonomic nervous system function and has become an essential tool in athlete monitoring.

The scientific development of HRV analysis was significantly influenced by the work of Hon and later Matti Malik. In 1996, standardized guidelines for HRV measurement and interpretation were established by the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, providing a foundation for its widespread application in sports science.

HRV reflects the dynamic interaction between sympathetic and parasympathetic branches of the autonomic nervous system. Consequently, HRV analysis provides valuable information regarding recovery status, physiological stress, training readiness, sleep quality, and the risk of overtraining.

The most frequently used HRV parameters include:

RMSSD (Root Mean Square of Successive Differences);

SDNN (Standard Deviation of Normal-to-Normal Intervals);

HF (High-Frequency Power);

LF (Low-Frequency Power);

LF/HF Ratio.

Table 1

Normative HRV ranges across different sports

Sport	**RMSSD (ms)**	**SDNN (ms)**	**HF (ms^2)**	**LF (ms^2)**
Marathon, Cycling, Triathlon	60-120	80-180	1200-5000	800-3000
Rowing	55-110	70-160	1000-4500	700-2800
Swimming	50-100	70-150	900-4000	700-2500
Football	40-90	60-140	700-3500	600-2500
Basketball	35-80	50-130	600-3000	500-2200
Volleyball	35-75	50-120	500-2800	500-2000
Wrestling and Boxing	30-70	40-110	400-2500	500-2200
Weightlifting	25-60	40-100	300-2000	500-2500

Analysis of these values indicates that endurance athletes generally demonstrate higher RMSSD and HF values than strength- and power-oriented athletes. This reflects greater parasympathetic dominance and superior cardiovascular adaptation.

From a practical perspective, HRV monitoring is typically performed daily under standardized morning conditions. A reduction of approximately 15–20% in an athlete's baseline RMSSD may indicate accumulated fatigue, insufficient recovery, or excessive training stress.

Cardiopulmonary exercise testing (CPET)

Cardiopulmonary Exercise Testing (CPET) is widely regarded as the gold standard for evaluating functional capacity in sports physiology and sports cardiology. It provides an integrated assessment of cardiovascular, respiratory, and muscular system responses during exercise.

The modern scientific foundations of CPET were established by Karlman Wasserman, Brian Whipp, and James Hansen, whose pioneering work transformed exercise testing into a comprehensive physiological assessment method.

During CPET, several physiological variables are measured simultaneously:

maximal oxygen uptake (VO_2max);

carbon dioxide production (VCO_2);

minute ventilation (VE);

ventilatory thresholds (VT1 and VT2);

oxygen pulse;

respiratory exchange ratio (RER).

VO_2max represents the maximal capacity of the organism to transport and utilize oxygen during exercise and remains one of the most important indicators of aerobic fitness.

Table 2

Typical CPET values across different sports

Sport	VO_2max (ml·kg^{-1}·min^{-1})	VT1 (% VO_2max)	VT2 (% VO_2max)
Marathon Running	70–85	65–75	85–92
Cycling	68–82	65–75	85–92
Triathlon	65–80	65–75	85–90
Rowing	60–75	60–70	82–88
Cross-Country Skiing	70–90	65–75	85–93
Football	55–70	55–65	75–85
Basketball	50–65	55–65	75–85
Volleyball	45–60	50–60	70–80
Boxing	55–70	55–65	80–88
Wrestling	50–65	55–65	75–85
Weightlifting	35–50	45–55	65–75

Endurance athletes typically exhibit the highest VO_2max values, reflecting superior aerobic capacity and cardiovascular efficiency. Likewise, higher VT1 and VT2 values indicate improved metabolic efficiency and greater tolerance to prolonged exercise intensities.

CPET results are invaluable for determining training zones, evaluating physiological adaptation, monitoring performance development, and reducing the risk of overtraining.

Lactate diagnostics and fatigue monitoring

Lactate diagnostics has become one of the most informative biochemical methods for assessing functional status in athletes. Contemporary physiological research recognizes blood lactate concentration as a valuable biomarker reflecting metabolic activity, adaptation processes, and fatigue development.

For many years, lactate was considered the primary cause of muscular fatigue. However, the Lactate Shuttle Theory proposed by George Brooks fundamentally changed this perspective. According to this theory, lactate functions not merely as a metabolic by-product but also as an important energy substrate and signaling molecule involved in cellular adaptation.

As exercise intensity increases, glycolytic activity accelerates, resulting in greater lactate production. Therefore, blood lactate concentration provides valuable information regarding exercise intensity, anaerobic threshold, and metabolic stress.

Table 3

Physiological characteristics of training zones based on blood lactate concentration

Blood lactate ($mmol \cdot L^{-1}$)	Training zone	Physiological characteristics
0.8–2.0	Recovery aerobic zone	Predominantly fat oxidation
2.0–4.0	Aerobic development zone	Aerobic endurance enhancement
4.0–6.0	Mixed aerobic–anaerobic zone	Balanced lactate production and clearance
6.0–10.0	Anaerobic zone	Predominantly glycolytic energy production
>10.0	Maximal intensity zone	Rapid fatigue development

The onset of blood lactate accumulation (OBLA), commonly identified at approximately 4 $mmol \cdot L^{-1}$, is considered an important physiological threshold for training prescription and performance evaluation.

Lactate threshold is widely regarded as one of the strongest predictors of endurance performance. Elite endurance athletes often reach their lactate threshold at 85–90% of VO_2max, whereas recreational athletes typically reach this point at 60–70% of VO_2max.

Consequently, lactate monitoring plays a crucial role in training individualization, fatigue assessment, recovery management, and performance optimization.

Wearable technologies and digital monitoring

The rapid development of wearable technologies has revolutionized physiological monitoring in sports. Modern wearable devices enable continuous assessment of physiological parameters in both training and competition environments.

Currently, systems such as Polar, Garmin, WHOOP, Oura Ring, and Firstbeat are widely used in elite sports. These technologies provide real-time monitoring of:

heart rate;

heart rate variability;

blood oxygen saturation;

sleep quality;

energy expenditure;

stress levels;

recovery status.

The integration of wearable technologies with artificial intelligence and big-data analytics has significantly enhanced the accuracy of training load management. Continuous monitoring allows coaches and sports scientists to make evidence-based decisions regarding training prescription, recovery strategies, and injury prevention.

As a result, wearable technologies have become an indispensable component of modern athlete monitoring systems and play a central role in the individualization of sports training.

Conclusion. Modern physiological monitoring technologies provide comprehensive and objective information regarding athletes' functional status, adaptive capacity, recovery processes, and readiness for training and competition. HRV analysis, CPET, lactate diagnostics, and wearable technologies represent powerful tools for evidence-based training management. Their integrated application facilitates individualized training prescription, early detection of maladaptation, prevention of overtraining syndrome, and optimization of athletic performance, thereby contributing to sustainable success in high-performance sports.

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