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Heart Rate Variability as a Marker of Training Load, Recovery and Overtraining in Athletes – A Systematic Review

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ABSTRACT

Background and aim

Heart rate variability (HRV) is an indicator of autonomic nervous system activity and a useful tool for monitoring training load, recovery, and adaptation in athletes. It reflects the balance between sympathetic and parasympathetic activity. Decreases in HRV are generally associated with fatigue and increased training load, whereas stable or elevated values may indicate recovery and positive adaptation. However, the relationship is complex and non-linear. This review aims to summarize knowledge about the utility of Heart Rate Variability (HRV) as a parameter for monitoring training load, recovery, and overall athlete readiness.

Review methods

The literature included in this review focused on the use of heart rate variability (HRV) as a tool for athlete monitoring. Particular attention was given to studies examining the relationship

between HRV and training load, recovery processes, overtraining, factors affecting HRV measurements, and the implementation of HRV-guided training approaches. Priority was assigned to original research papers, systematic reviews, meta-analyses, and narrative reviews published within the past decade. Earlier publications were also considered when they constituted foundational research or provided essential context for understanding the topic.

Results and conclusions

HRV is a useful marker of autonomic nervous system activity with considerable relevance in sports science. Its practical value, depends on proper interpretation, an individualized perspective, and its combination with other monitoring methods. Instead of serving as an independent diagnostic measure, HRV should be considered part of a broader framework for assessing training load, recovery, and overall athlete readiness.

Key words

heart rate variability, training load, recovery, overtraining, athletes, autonomic nervous system, sport performance, fatigue monitoring

INTRODUCTION AND OBJECTIVE

Heart Rate Variability (HRV) is defined as the natural variation in time intervals between consecutive heartbeats, expressed as RR intervals on an electrocardiogram. This parameter reflects the continuous interaction between the sympathetic and parasympathetic branches of the autonomic nervous system, which together control the sinoatrial node [1,2]. Contrary to intuitive belief, a healthy heart does not beat at a perfectly constant rate. The presence of minor variations between consecutive RR intervals indicates the efficient functioning of the body's regulatory mechanisms [1]. Cardiac activity is under the constant control of the autonomic nervous system. The parasympathetic branch, acting primarily through the vagus nerve, exerts a rapid inhibitory effect on the heart, slowing the heart rate and increasing RR interval variability. In contrast, the sympathetic system drives heart rate acceleration and mobilizes the body during physical exertion, psychological stress, or other stressors [1,2]. In recent years, there has been a growing interest in the application of HRV in sports. Advances in measurement

technologies, including electrocardiography (ECG), heart rate monitor chest straps, and photoplethysmography-based devices, have enabled regular assessment of autonomic nervous system function in both elite and recreational athletes [1,2]. Owing to its non-invasive nature, ease of measurement, and suitability for daily monitoring, HRV has become one of the most widely used indicators for evaluating an athlete's functional status and physiological adaptation to training [1–3].

Table 1 Main HRV Parameters Applied in Sports Science and Athlete Monitoring.

Parameter	Domain	Physiological Significance	Application in Sports
RMSSD (Root Mean Square of Successive Differences)	Time-Domain	Reflects parasympathetic (vagal) activity and short-term beat-to-beat variability	Most widely used HRV marker in athletes; monitoring recovery, training load, fatigue, and readiness to train
LnRMSSD (Natural Log of RMSSD)	Time-Domain	Log-transformed RMSSD providing a more stable and normally distributed measure of vagal activity	Preferred metric for longitudinal athlete monitoring and HRV-guided training programs
SDNN (Standard Deviation of NN Intervals)	Time-Domain	Represents overall autonomic modulation and total HRV	Assessment of global autonomic function, recovery status, and cardiovascular adaptation
LF/HF	Frequency Domain	Traditionally considered an index of sympathovagal balance, although interpretation remains controversial	Monitoring autonomic responses to training and fatigue; should be interpreted cautiously

The aim of this review is to examine the current literature regarding the use of heart rate variability as a marker of training load, recovery, and overtraining in athletes. The review presents the physiological basis of HRV, discusses the most commonly used methods for its assessment, and analyzes findings from studies investigating the application of HRV in

monitoring physiological responses to exercise and the adaptive processes associated with sports training.

DESCRIPTION OF THE STATE OF KNOWLEDGE

HRV as a marker of training load

Cardiac autonomic activity, quantified through heart rate variability (HRV), provides an objective physiological window into an athlete's internal response to training stress. Unlike subjective measures, HRV reflects the autonomic nervous system's (ANS) adaptation to physical demands, making it a tool for quantifying internal load and recovery status [3,4].

Current evidence emphasizes that HRV parameters—particularly those reflecting parasympathetic activity, such as RMSSD—are highly sensitive to fluctuations in training volume and intensity. A common physiological manifestation of increased fatigue and workload is a suppression of these vagal indices [1,5]. In contrast, the stabilization or rebound of HRV metrics toward baseline values serves as a critical marker of successful physiological adaptation [1].

The practical utility of HRV monitoring is evident across various athletic populations. In adolescent swimmers, for instance, rapid escalations in training volume (exceeding 6 km daily) have been shown to induce significant HRV reductions, acting as an warning system for cumulative fatigue [5]. Similar trends are observed in technical disciplines like artistic gymnastics, where morning HRV values correlate significantly with the previous day's session RPE (sRPE) and the athlete's subjective psychophysiological state [4]. This relationship extends to high-intensity resistance and interval training, where overload microcycles consistently trigger measurable declines in RMSSD, reflecting heightened cardiovascular strain [6].

In elite intermittent sports such as rugby sevens, the stability of HRV may be as informative as its absolute magnitude. A lower coefficient of variation ($\text{LnRMSSD}_{\text{cv}}$) during intensified training periods, when coupled with stable wellness scores, indicates preserved autonomic homeostasis and a positive adaptive response [7]. In contrast, mixed-modality sports like CrossFit exhibit periodization-dependent HRV profiles. While LnRMSSD may remain elevated during competitive phases, it tends to drop sharply only under extreme overload conditions [3].

Beyond performance tracking, HRV serves a vital role in injury prevention. Research by Sanchez et al. indicates that athletes often exhibit lower HRV values in the weeks immediately preceding a musculoskeletal injury. Such autonomic withdrawal may signal a state of systemic stress, impaired recovery, or diminished adaptive capacity, thereby increasing the athlete's vulnerability to trauma [8]. These findings suggest that HRV monitoring may be particularly valuable not only for tracking fatigue but also for distinguishing between functional adaptation and maladaptive training responses.

HRV and recovery monitoring

In athletic populations, Heart Rate Variability (HRV) serves as a tool for tracking recovery, prized for its non-invasive nature and suitability for longitudinal monitoring. According to the literature, HRV reflects the functional state of the organism and can be used to estimate the current level of recovery as well as readiness for subsequent training loads. Generally speaking, high values of indicators associated with parasympathetic activity are typically interpreted as a sign of effective recovery and a predominance of vagal modulation. On the other hand, decrease in these values suggests sympathetic dominance or reduced vagal tone and the accumulation of fatigue [2,9], establishing the metric as a vital gauge of the recovery-fatigue trade-off.

Experimental evidence demonstrates that both endurance and resistance exercise trigger significant alterations in Heart Rate Variability (HRV). A marked post-exercise reduction in HRV indices is typically observed, reflecting a clear sympathetic dominance [5,10,11]. The subsequent recovery of HRV to baseline values is contingent upon training intensity and volume, serving as a pivotal metric for recovery assessment. For instance, while the RMSSD index was found to return to baseline within 30 minutes following strength training, other markers - such as muscle soreness - persisted, indicating incomplete physiological recovery. Similarly, in basketball players, HRV normalized rapidly despite muscle-related parameters (e.g., vertical jump height) suggesting lingering fatigue. Consequently, HRV should not be utilized as a standalone indicator when monitoring athlete recovery [5,11]. In contrast, studies on track and field athletes have shown that reduced HRV may persist for a longer duration compared to resistance training contexts. Moreover, cluster analysis identified three distinct groups of athletes, including a specific subset characterized by a prolonged suppression of HRV. This pattern may signify diminished adaptive capacity or even a higher risk of injury.

While most participants exhibited a swift return to baseline - indicative of healthy adaptation to training loads— these findings point to a less obvious but important role of HRV in identifying individuals who may require additional recovery strategies or potential medical supervision. [10].

There are certain conditions that make the interpretation of HRV in the context of training load and recovery more complex. Although elevated HRV values are typically regarded as a hallmark of athletic readiness, in some cases they may instead reflect maladaptive physiological responses. Evidence from meta-analytical data suggests that athletes suffering from functional overreaching (F-OR) often exhibit a moderate, statistically significant rise in their average HRV—a phenomenon termed parasympathetic hyperactivity—which should be interpreted as a sign of unfavorable adaptation to training stress rather than improved fitness [12]. Lower HRV readings does not always indicate exhaustion or overload. As highlighted by Plews et al., the relationship between parasympathetic activity and HRV is inherently non-linear. At very high levels of vagal tone, particularly when accompanied by a low resting heart rate, the physiological mechanisms responsible for heart rate modulation may reach a saturation point, resulting in a paradoxical decrease in HRV values despite the athlete being in recover state [13].

HRV and overtraining

The phenomenon of overtraining stems from an imbalance between training load and the body's ability to recover. One of its hallmark manifestations is a deterioration in physical performance, which is often accompanied by alterations in physiological and hormonal responses, as well as disruptions in autonomic nervous system regulation [14,15]. In this context, Heart Rate Variability (HRV) can be potentially used to spot early signals of overload.

Looking closer at the data, one might notice that increases in training load can influence HRV; however, the type of effort and training volume matter [6]. For example, studies on training overload have observed both a decrease in HRV (particularly in resistance training) and an increase (in response to HIIT), suggesting different adaptive mechanisms [6]. In practice, this limits its usefulness as a standalone monitoring tool. Supporting this, a review by Lipka et al. argues that although HRV is a valuable metric for tracking daily fatigue and recovery trends, it lacks the specificity required to diagnose a clinical overtraining syndrome [15]. At best, it serves as a "red flag" that must be interpreted alongside other markers of exhaustion [8,15].

An important relationship was identified in a study conducted by Sanchez. Based on the results of that study, it can be concluded that monitoring HRV is instrumental in evaluating the risk of severe musculoskeletal injuries. Although HRV itself did not differ significantly in every week an injury occurred, it was observed that lower lnRMSSD values and specific disturbances in the distribution of this parameter accompanied athletes in the weeks preceding high-severity injuries. These findings suggest that suppressed HRV, particularly when combined with poor sleep quality and decreased subjective well-being, may act as a vital precursor to physical trauma [8].

At the same time, several studies challenge the assumption that HRV reliably reflects overtraining status. For instance, an experiment involving elite canoeists showed that despite a clear reduction in exercise capacity and VO₂max following a period of intensified training, their HRV metrics remained unchanged [14]. Similar results were seen in endurance athletes, whose nocturnal HRV measurements remained unchanged relative to the baseline despite increased training loads [26]. An important point here is that HRV should not be considered a universal or definitive marker of overtraining, particularly when based on isolated measurements or limited monitoring protocols, such as nocturnal recordings alone.

Factors influencing HRV interpretation

When used to monitor training load, HRV alone is not sufficient and its interpretation depends on many physiological and measurement-related factors [16]. Interpreting heart rate variability (HRV) without considering individual context carries a high risk of error. Researchers point out that what really matters is establishing an individual baseline - a personal benchmark that reflects a person's unique physiological state [9]. HRV differs a lot from person to person due to factors like fitness level, age, sex, lifestyle, and even genetics [9,13]. Comparing HRV values between individuals doesn't make much sense. It is far more useful to monitor changes relative to an individual reference level (baseline), which reflects the typical state of autonomic balance in the body [9]. In research and sports practice, the baseline is established based on at least several HRV measurements taken under standardized conditions - ideally performed under resting conditions upon waking. It is sure that a single measurement has limited diagnostic value [9,13]. Sleep, psychological stress, lifestyle, and biological factors are among the most important non-training determinants of HRV and should always be considered when

interpreting HRV data in athletes. Poor sleep quality, elevated psychological stress, unhealthy dietary habits, nicotine and alcohol use, as well as hormonal fluctuations across the menstrual cycle may all alter HRV independently of training load, potentially leading to misinterpretation of recovery status [17–22]. Selected factors influencing heart rate variability are presented in Table 2.

Table 2 Factors influencing HRV interpretation in athletes.

Factor	Effect on HRV	Proposed mechanism
Sleep quality	Higher sleep quality is associated with higher HRV	Improved parasympathetic activity and better physiological recovery
Menstrual cycle	↑ HRV during the follicular phase compared with the luteal phase	Higher estrogen levels enhance vagal modulation
Physiological stress (cortisol)	↑ Cortisol is associated with ↓ HRV	Activation of the hypothalamic-pituitary-adrenal axis and sympathetic nervous system
Smoking	↓ HRV	Nicotine increases sympathetic activity and reduces parasympathetic modulation.
Alcohol consumption	↓ HRV	Alcohol negatively affects autonomic nervous system function and lowers HRV.
Omega-3 fatty acids / fish consumption	↑ HRV	Improve cardiac autonomic regulation, mainly by increasing vagal activity (HF) and reducing resting heart rate.
Hydration	↑ HRV after water intake	Water ingestion increases cardiac vagal activity, whereas dehydration reduces autonomic flexibility.

HRV-guided training interventions

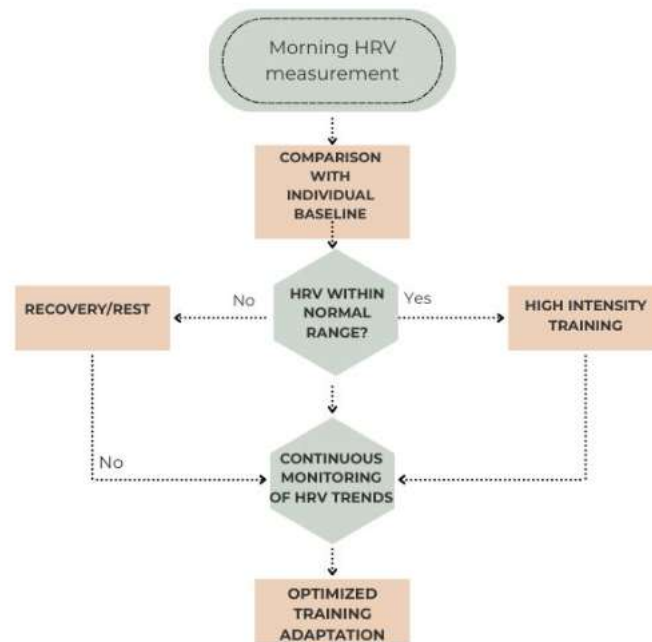
Several studies have demonstrated that HRV-guided training improves athletic performance, particularly in endurance sports. A summary of the main studies and their findings is presented in Table 3. Overall, the available evidence suggests that HRV is most effective when combined with additional markers of recovery and training load [8,12,20,23,24,27]. Based on the

available evidence, a schematic algorithm illustrating the practical application of HRV-guided training is presented in Figure 1.

Table 3 Summary of studies on HRV-guided training interventions in athletes.

Study	Population	Intervention	Main findings	Practical implication
Granero-Gallegos et al. [23]	Meta-analysis of athletes	HRV-guided training	Improved aerobic capacity	Better recovery management and individualized training loads
Bahenský & Grosicki [24]	Young runners	HRV-guided training	Improved cardiovascular adaptations, better performance, lower injury risk	Daily training adjusted according to autonomic status
Alfonso Javaloyes et al. [8]	Endurance athletes	HRV-guided training	Greater effectiveness when HRV combined with subjective measures and resting HR	HRV should not be used alone
Sánchez et al. [27]	Athletes	HRV-guided training	Best results achieved when HRV integrated with wellness indicators	Multivariable monitoring recommended

Figure 1 Author's schematic illustration of the HRV-guided training approach based on the evidence presented in the reviewed literature.



CONCLUSIONS

This review highlights the growing importance of heart rate variability (HRV) as a tool for monitoring training load, recovery, and overtraining in athletes. The analyzed studies confirm that HRV reflects the state of the autonomic nervous system - specifically the balance between the sympathetic and parasympathetic branches [3,4]. Based on current evidence, a decrease in HRV usually indicates sympathetic dominance and serves as a marker of physiological strain, and an increase in HRV suggests parasympathetic dominance and recovery [1,5]. However, this relationship is neither linear nor universal.

The phenomenon of parasympathetic hyperactivity in functionally overtrained athletes, as well as the saturation effect at high levels of vagal tone, suggests that peak HRV values do not always reflect optimal readiness [12,13]. The interpretation of HRV requires contextual consideration and cannot rely on the simplified assumption that “more is better.”

While clear HRV responses to training load are often observed in endurance and interval sports, strength training and mixed disciplines tend to produce much more varied outcomes [3,6]. A similar issue appears in monitoring overtraining—some elite athletes show no changes in HRV despite a decline in performance capacity, suggesting that HRV may not fully reflect all aspects of fatigue [14,26].

One of the key takeaways from this review is that HRV should not be viewed in isolation. When combined with factors such as sleep quality, stress, hormonal changes, and lifestyle, HRV highlights the multifactorial nature of autonomic regulation. These factors can significantly influence HRV independently of training load, which may lead to misinterpretation [18,19,21,22]. The need to establish individual baseline values and to monitor long-term trends rather than relying on single measurements is consistently supported in the literature and should be regarded as the gold standard in both research and practice [9,13].

In practice, HRV-guided training interventions yield promising results. Particularly in endurance sports, they are associated with improvements in aerobic capacity and athletic performance [23,24]. The ability to dynamically adjust training loads based on physiological data marks a move away from more individualized training models. However, evidence suggests that combining HRV with other markers (such as subjective well-being indices or sleep parameters) produces better outcomes than making decisions based solely on HRV [8,27].

Despite a wealth of data, several research gaps remain. Variability in measurement protocols and athlete demographics often complicates the task of drawing universal conclusions [19,20]. Additionally, further research is needed to better understand chronic adaptations and the long-term effects of HRV-guided training. What is more, certain mechanisms that lead to atypical HRV changes (e.g., parasympathetic hyperactivity) require further investigation to clarify their practical significance [12]. Greater attention should also be given to underrepresented groups, including female athletes, in whom hormonal fluctuations may significantly influence HRV patterns [18].

AI

AI was utilized for two specific purposes in this research. Text analysis of clinical reasoning narratives to identify linguistic patterns associated with specific logical fallacies. Assistance in refining the academic English language of the manuscript, ensuring clarity, consistency, and

adherence to scientific writing standards. **AI** were used for additional linguistic refinement of the research manuscript, ensuring proper English grammar, style, and clarity in the presentation of results. It is important to emphasize that all AI tools were used strictly as assistive instruments under human supervision. The final interpretation of results, classification of errors, and conclusions were determined by human experts in clinical medicine and formal logic. The AI tools served primarily to enhance efficiency in data processing, pattern recognition, and linguistic refinement, rather than replacing human judgment in the analytical process.

DISCLOSURES

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