Quality in Sport. 2026;52:69422. eISSN 2450-3118.

https://doi.org/10.12775/QS.2026.52.69422

Quality in Sport. eISSN 2450-3118

Journal Home Page
https://apcz.umk.pl/QS/index

JAKLIK, Dominik, CHOLEWA, Dominik, GUZIK, Natalia, STARZYK, Radosław, ŚMIAŁEK, Sara, FLOREK, Julia, SŁABY, Wiktor, GROELE, Adrian, DĘBSKA, Patrycja, and MICZEK, Marcin. Heart Rate Variability (HRV) as a Marker for Overtraining Syndrome Prevention in Endurance Athletes: A Systematic Review. Quality in Sport. 2026;52:69422. eISSN 2450-3118. https://doi.org/10.12775/QS.2026.52.69422

The journal has been awarded 20 points in the parametric evaluation by the Ministry of Higher Education and Science of Poland. This is according to the Annex to the announcement of the Minister of Higher Education and Science dated 05.01.2024, No. 32553. The journal has a Unique Identifier: 201398. Scientific disciplines assigned: Economics and Finance (Field of Social Sciences); Management and Quality Sciences (Field of Social Sciences).
Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).

The authors declare that there is no conflict of interest regarding the publication of this paper.
Received: 01.03.2026. Revised: 08.03.2026. Accepted: 9.03.2026. Published: 13.03.2026.

Heart Rate Variability (HRV) as a Marker for Overtraining Syndrome Prevention in Endurance Athletes: A Systematic Review

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Abstract

Background. The autonomic nervous system (ANS) regulates physiological recovery. In sports medicine, distinguishing Functional Overreaching (FOR) from Overtraining Syndrome (OTS) remains difficult due to the absence of a gold-standard biomarker. Heart Rate Variability (HRV) has emerged as a non-invasive indicator of vagal withdrawal and sympathetic activation.

Aim. To critically evaluate daily HRV monitoring as an early-warning biomarker for Non-Functional Overreaching (NFO) and OTS, and to assess the reliability of consumer-grade wearables versus clinical ECG.

Materials and Methods. A systematic review of clinical trials and longitudinal studies (2020–2026) was conducted using PubMed/MEDLINE, Scopus, and the Cochrane Library. Following PRISMA and PICO criteria, 14 high-quality studies involving competitive endurance and elite athletes were included. Study quality was assessed with the Cochrane RoB 2 tool and the Newcastle-Ottawa Scale.

Results. RMSSD and the non-linear index DFA alpha 1 were the most sensitive markers of acute autonomic fatigue and organismic stress. Evidence indicates that HRV-guided training (HRV-GT), using the Smallest Worthwhile Change (SWC) threshold, significantly improves VO_2max and peak power output compared with fixed periodization. High-end chest straps (e.g., Polar H10) demonstrate strong agreement with ECG, whereas wrist-based PPG sensors are more prone to motion artifacts.

Conclusions. HRV is a sensitive leading indicator of autonomic maladaptation but should not serve as a standalone diagnostic tool for OTS. For clinical relevance, HRV monitoring should be integrated with subjective wellness scales and performance metrics. Individualized 7-day rolling averages and gender-specific protocols are recommended to reduce overtraining risk in elite athletes.

Keywords: Heart Rate Variability, Overtraining Syndrome, Athletic Performance, Endurance Training, Autonomic Nervous System, Sports Medicine

1. Introduction

1.1 Physiology of the Autonomic Nervous System (ANS): The R-R Interval Dynamics

The autonomic nervous system (ANS) is the primary regulator of the body's involuntary physiological responses to internal and external stressors. In the context of sports physiology, the ANS maintains a delicate equilibrium between the sympathetic nervous system (SNS)—often termed the "fight or flight" branch—and the parasympathetic nervous system (PNS), responsible for "rest and digest" functions. This interplay is exquisitely reflected in the timing of successive heartbeats, known as R-R intervals on an electrocardiogram (ECG).

Heart Rate Variability (HRV) serves as a non-invasive, proxy measure of this autonomic regulation. A healthy, well-recovered organism exhibits high complexity in these intervals, signifying a dominant parasympathetic (vagal) tone that allows for rapid adaptation to changing demands [1]. Conversely, physical exertion and systemic stress trigger a withdrawal of vagal activity and an increase in sympathetic outflow, resulting in more rhythmic, less variable heartbeats. Recent clinical trials have emphasized that monitoring the "vagal reactivation" phase post-exercise is crucial for understanding an athlete's recovery capacity. Advanced metrics, such as the Root Mean Square of Successive Differences (RMSSD) and non-linear indices like DFA alpha 1, have been shown to be particularly sensitive to acute changes in training load, providing a more granular view of the ANS than resting heart rate alone [2, 3].

1.2 Overtraining Syndrome (OTS): The Diagnostic Quagmire

Overtraining Syndrome (OTS) represents the maladaptive end of the training spectrum. While progressive overload is essential for athletic improvement, an imbalance between high-intensity training and inadequate recovery can lead to a cascade of physiological and psychological failures. The progression is typically categorized from Functional Overreaching (FOR)—a temporary state of fatigue followed by a "supercompensation" effect—to Non-Functional Overreaching (NFO), and finally to OTS.

Despite decades of research, OTS remains a clinical challenge because it lacks a definitive "gold standard" diagnostic biomarker. It is often described as a multisystemic disorder involving the hypothalamic-pituitary-adrenal (HPA) axis, the immune system, and the ANS [5]. Clinical trials frequently highlight that by the time an athlete presents with the hallmark symptoms of OTS—such as persistent performance decrement, chronic fatigue, and sleep disturbances—the condition is already well-advanced. The absence of a single, reliable blood marker or imaging technique means that diagnosis is largely based on the exclusion of other pathologies (e.g., anemia, thyroid dysfunction, or infections). This diagnostic delay underscores the urgent need for proactive, daily monitoring tools that can identify the transition from FOR to NFO before it reaches the irreversible stage of OTS [6, 7].

1.3 The Role of Technology: From Clinical ECG to Consumer Wearables

The evolution of HRV monitoring has been revolutionized by the transition from laboratory-based ECG systems to consumer-grade wearables. For years, the requirement for multi-lead ECGs and specialized software confined HRV analysis to elite clinical settings. Today, the democratization of this technology through chest straps (e.g., Polar H10), smart rings (e.g., Oura), and high-precision optical sensors in watches has made daily longitudinal tracking feasible for both elite and recreational athletes [8].

These devices utilize photoplethysmography (PPG) or micro-ECG sensors to capture R-R intervals, often during sleep or in the early morning, to minimize the influence of external noise (such as caffeine or daily stressors). Mobile applications then process these raw data points using proprietary algorithms to provide "readiness scores." However, the rapid proliferation of these tools has outpaced the scientific validation required for clinical decision-making. Recent randomized controlled trials have begun to address this gap, comparing wearable data to clinical ECGs and evaluating whether "HRV-guided training" - where training intensity is adjusted daily based on autonomic status is superior to traditional, pre-planned training blocks [9, 10]. This technological shift offers a promising pathway for real-time fatigue management, provided the data is interpreted within a rigorous physiological framework.

1.4 Objective of the Review

The objective of this article is to critically evaluate the efficacy of daily HRV monitoring as an early-warning biomarker for Non-Functional Overreaching (NFO) and Overtraining Syndrome (OTS). By synthesizing the latest evidence from clinical trials and longitudinal studies involving endurance athletes and elite players, this review aims to:

1. Determine the sensitivity and specificity of various HRV indices (RMSSD, SDNN, DFAa1) in detecting early signs of autonomic maladaptation.
2. Assess the reliability of consumer-grade wearables compared to the gold-standard ECG in the context of overtraining detection.
3. Propose a practical framework for integrating HRV-guided training into athletic programs to mitigate the risk of OTS.

2. Methodology

This review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure a transparent, objective, and reproducible synthesis of current evidence regarding Heart Rate Variability (HRV) and overtraining in athletes.

2.1 Search Strategy

A systematic, comprehensive search was performed across three primary electronic databases: PubMed/MEDLINE, Scopus, and the Cochrane Library. To ensure the inclusion of the most recent technological advancements and clinical findings, the search was limited to articles published between 2020 and 2026.

The search string utilized a combination of Boolean operators and MeSH terms. For the PubMed search (as specified in the source material), the following logic was applied:

> *(HRV OR "heart rate variability") AND (overtraining OR overreaching OR fatigue OR recovery) AND (athletes OR endurance OR "elite players")*

The search was further refined using filters for Clinical Trials, Randomized Controlled Trials (RCTs), and studies involving human adult (19+ years) populations published in English.

2.2 PICO Framework

To define the eligibility criteria and focus the research question, the PICO (Population, Intervention, Comparison, Outcome) framework was employed as follows:

Table 1. Eligibility criteria based on the PICO framework.

Component	Criteria
P (Population)	Competitive endurance athletes (e.g., runners, cyclists, triathletes) and elite professional players.
I (Intervention)	Daily or longitudinal monitoring of HRV (using ECG or consumer-grade wearables) to guide training or monitor recovery.
C (Comparison)	Traditional monitoring methods, including Ratings of Perceived Exertion (RPE), mood/wellness questionnaires (e.g., POMS), and resting heart rate (RHR).
O (Outcome)	Detection/prevention of Non-Functional Overreaching (NFO) and OTS, optimization of training load, and improvements in performance metrics.

2.3 Study Selection and Data Extraction

Titles and abstracts were screened by the authors to exclude duplicates and irrelevant studies. The remaining articles underwent a full-text review based on the following inclusion criteria:

1. Original research published in peer-reviewed journals.
2. Studies reporting at least one specific HRV metric (e.g., RMSSD, SDNN, or LF/HF ratio).
3. Protocols involving structured training loads where recovery or fatigue was a primary endpoint.

Exclusion criteria included studies focusing on sedentary populations, animal models, or those lacking a clear longitudinal training intervention.

2.4 Quality Assessment

To ensure the robustness of the synthesized data, the included studies were subjected to a rigorous quality assessment:

- **Randomized Controlled Trials (RCTs):** Evaluated using the Cochrane Risk of Bias (RoB 2) tool, focusing on randomization process, deviations from intended interventions, missing outcome data, and measurement of the outcome.
- **Non-Randomized/Observational Studies:** Assessed via the Newcastle-Ottawa Scale (NOS), evaluating the selection of cohorts, comparability of groups, and the adequacy of follow-up.

Studies were categorized as having a "low," "moderate," or "high" risk of bias, and these ratings were factored into the final discussion of the evidence's reliability.

3. Results

3.1 Study Selection (PRISMA Flow)

The systematic search across PubMed, Scopus, and the Cochrane Library yielded a total of 82 records. After removing duplicates and records published prior to 2015, 57 articles were screened by title and abstract. A total of 25 full-text articles were assessed for eligibility. Following the application of strict inclusion criteria specifically focusing on randomized clinical trials (RCTs) involving competitive endurance athletes and longitudinal HRV monitoring 14 studies were included in this qualitative synthesis.

3.2 Key HRV Indices: The Primacy of RMSSD and DFA Alpha 1

The systematic review confirms that the Root Mean Square of Successive Differences (RMSSD) is the most robust time-domain parameter for assessing short-term autonomic fatigue [1, 2]. RMSSD reflects parasympathetic (vagal) activity.

Clinical data indicate that RMSSD is effective for daily monitoring because it can be captured in 60-second "ultra-short-term" recordings [2, 10]. Additionally, the non-linear index DFA alpha 1 (α_1) has emerged as a sensitive marker of "organismic stress" during and after high-intensity exercise. A decline in $\boldsymbol{\alpha_1}$ values is strongly correlated with acute performance decrements in runners, providing an early warning sign of non-functional overreaching (NFO) [2, 3].

Table 2. Summary of primary HRV indices, their physiological significance, and clinical applications in athletic monitoring.

Metric	**Domain**	**Physiological Significance**	**Clinical Application**	**Sensitivity**
RMSSD	Time	Reflects parasympathetic (vagal) activity; primary marker of short-term recovery.	Daily "readiness" monitoring; foundation for HRV-Guided Training (HRV-GT).	**High** (Acute fatigue)

DFA alpha 1	Non-linear	Measures correlation properties of R-R intervals; reflects "organismic stress."	Identifying biological tipping points during/after high-intensity exercise.	**High** (Intensity/Stress)
SDNN	Time	Reflects total variability (both sympathetic and parasympathetic influences).	Longitudinal assessment of overall ANS health and adaptation to training blocks.	**Moderate**
LF/HF Ratio	Frequency	Traditionally viewed as "sympathovagal balance" (now scientifically debated).	Assessing systemic stress; however, clinical utility is decreasing in favor of RMSSD.	**Low/Moderate**
SWC (Smallest Worthwhile Change)	Statistical	Not a metric, but a threshold calculated from an individual's baseline.	Determining if a drop in HRV is a meaningful sign of fatigue or normal fluctuation.	**Essential for Context**

3.3 HRV-Guided Training: Real-Time Load Optimization

The review identifies HRV-guided training (HRV-GT) as a superior method for training prescription compared to traditional fixed-periodization models. In several randomized controlled trials (RCTs), athletes who adjusted their training daily based on their RMSSD scores showed significantly greater improvements in maximal oxygen consumption (VO_2max) and peak power output [9, 11].

The integration of Smallest Worthwhile Change (SWC) thresholds allows coaches to determine if a drop in HRV is a meaningful sign of fatigue or a normal daily fluctuation. By reducing intensity when RMSSD falls below the SWC, athletes can avoid the accumulation of chronic stress that leads to Overtraining Syndrome (OTS) [11].

3.4 Biological Variables: Correlation with Sleep and Systemic Recovery

HRV acts as a "leading indicator" that reflects broader physiological and environmental stress:

Sleep and Hypoxia: Clinical trials from 2025 demonstrate that nocturnal hypoxia or poor sleep quality significantly suppresses morning RMSSD. This drop often precedes a measurable decline in exercise performance, making it a critical early-warning tool [12].

Metabolic Factors: Exogenous factors such as the consumption of energy drinks or alcohol post-exercise can mask or delay the return of parasympathetic tone, potentially providing false "readiness" signals [13, 14].

Central Nervous System (CNS) Fatigue: Chronic suppression of HRV indices is closely linked to biomarkers of CNS fatigue and altered cortical arousal, reinforcing HRV's role as a holistic marker of homeostatic balance [7].

4. Discussion

The synthesis of recent clinical trials and longitudinal data reinforces the position of Heart Rate Variability (HRV) as a pivotal tool in the modern athletic monitoring toolkit. As endurance sports move toward highly individualized programming, the transition from reactive diagnosis to proactive fatigue management—centered on autonomic regulation—becomes essential for preventing the transition from functional overreaching (FOR) to the more debilitating non-functional overreaching (NFO) and Overtraining Syndrome (OTS).

4.1 Clinical Utility: Non-invasive and Cost-effective Monitoring

The primary strength of HRV lies in its non-invasive nature and physiological sensitivity. Unlike invasive biomarkers such as cortisol or creatine kinase, which require blood sampling and laboratory analysis, HRV parameters like RMSSD provide a real-time window into the athlete's homeostatic state [1, 10]. Our results highlight that ultra-short-term (60-second) recordings are sufficient to capture valid vagal indices, making daily compliance far more achievable for elite players [2]. Furthermore, the application of the Smallest Worthwhile Change (SWC) allows for a statistically grounded approach to training prescription. By identifying meaningful deviations from an athlete's baseline, coaches can implement "HRV-guided training" (HRV-GT), which has been shown to yield superior gains in VO_2max and peak power compared to rigid, pre-planned blocks [11, 15].

4.2 Confounding Factors: The Complexity of the Autonomic Signal

While HRV is a powerful marker, its high sensitivity is also its greatest challenge. The autonomic nervous system responds to a myriad of non-training stressors that can confound the interpretation of recovery.

- **Lifestyle and Substances:** Clinical trials indicate that acute intake of energy drinks or alcohol can delay parasympathetic reactivation, potentially masking the true recovery status of the cardiovascular system [13, 14].
- **Circadian Rhythms and Sleep:** The suppression of morning RMSSD following a single night of hypoxia or poor sleep quality underscores the need for standardized measurement conditions [12]. Recent studies (2024) further emphasize that nocturnal HRV tracking might provide a more stable baseline than morning measurements by eliminating the "awakening response" and environmental noise [18].
- **Psychological Load:** Because HRV reflects systemic "organismic stress," high cognitive load or emotional anxiety can lower HRV even in the absence of physical training. Longitudinal trials (2025) have shown that perceived stress scores (PSS) are inversely correlated with RMSSD, requiring practitioners to distinguish between physical fatigue and mental burnout [7, 19].

4.3 Technological Validity: Medical-Grade vs. Consumer Wearables

The democratization of HRV technology through apps like Elite HRV and wearables such as Whoop, Oura, and Polar H10 has bridged the gap between the lab and the field. Current evidence suggests high levels of agreement between medical-grade ECGs and top-tier chest straps for R-R interval detection [8]. However, caution is advised with wrist-based optical sensors (PPG) during high-intensity movement, where motion artifacts remain a significant limitation. While "readiness scores" provided by consumer apps offer a user-friendly interface, validation studies (2023) caution that they often rely on proprietary algorithms that may aggregate multiple data points (sleep, activity, HRV), potentially obscuring the specific vagal signal (RMSSD) necessary for precise training adjustments [16, 20].

4.4 Research Gaps and Future Perspectives

A significant limitation identified in this review is the lack of gender-specific frameworks for HRV interpretation. The majority of clinical trials in our synthesis utilized male-dominant cohorts. Emerging evidence (2024) suggests that the menstrual cycle significantly influences autonomic tone, with fluctuations in estrogen and progesterone impacting RMSSD and resting heart rate [17, 21]. Future research must establish whether the thresholds for NFO detection need to be adjusted based on hormonal phases to avoid "false-positive" fatigue signals in female athletes. Furthermore, more longitudinal studies are required to validate non-linear indices like DFA alpha 1 across different sports modalities to see if they offer a more sensitive "early warning" than traditional time-domain metrics [2, 3, 22].

5. Conclusions

The systematic review of clinical evidence from 2020–2026 confirms that Heart Rate Variability (HRV), specifically the RMSSD and DFA alpha 1 indices, is an exceptionally sensitive marker for the early detection of autonomic maladaptation. However, its role in the prevention of Overtraining Syndrome (OTS) must be clearly defined to ensure clinical efficacy.

Final Verdict: Standalone Tool vs. Multi-modal Approach

The clinical data suggest that while HRV is a superior leading indicator of "organismic stress," it cannot stand alone as a definitive diagnostic tool for Overtraining Syndrome. OTS is a multisystemic disorder involving metabolic, hormonal, and psychological pathways that may not always be fully captured by cardiac autonomic tone alone.

- **Sensitivity vs. Specificity:** HRV is highly sensitive to acute fatigue, but it lacks the specificity to distinguish between Functional Overreaching (FOR) and the onset of clinical OTS without context.
- **The "Multi-modal" Necessity:** To move from "monitoring" to "diagnosis," HRV must be integrated into a broader framework. A drop in RMSSD should be cross-referenced with subjective wellness scales (e.g., sleep quality, muscle soreness) and performance-based metrics (e.g., submaximal heart rate or peak power). Only when autonomic suppression aligns with persistent performance decrements and mood disturbances can a transition toward Non-Functional Overreaching (NFO) be confirmed [5, 6, 20].

Practical Recommendations for Practitioners and Coaches

To successfully mitigate the risk of OTS, sports medicine practitioners and coaches should adopt the following evidence-based framework:

1. **Establish an Individualized Baseline:** Use a 7-day rolling average to determine an athlete's "normal range." Static, one-off measurements are insufficient for clinical decision-making [10, 18].
2. **Implement HRV-Guided Training (HRV-GT):** Adjust training intensity based on the Smallest Worthwhile Change (SWC). If RMSSD falls below the individual threshold, high-intensity sessions should be replaced with low-intensity recovery or complete rest to prevent the accumulation of chronic stress [11, 15].
3. **Standardize Measurement Conditions:** To minimize the impact of confounding factors (caffeine, circadian shifts), measurements should be taken consistently in the morning (60-second ultra-short-term) or during the entire nocturnal period using validated wearables [8, 12, 18].
4. **Adopt Gender-Specific Protocols:** Practitioners must account for the menstrual cycle when interpreting HRV in female athletes, recognizing that a decrease in vagal tone during the luteal phase may be physiological rather than a sign of overreaching [17, 21].

5. **Utilize Non-linear Indices for High-Intensity Monitoring:** Incorporate DFA alpha 1 tracking during or after high-intensity bouts to identify "biological tipping points" where the organism's ability to maintain homeostatic balance is compromised [2, 22].

In summary, HRV provides a non-invasive, cost-effective, and highly responsive "early warning system." When integrated into a multi-modal monitoring strategy, it allows for a shift from a fixed training philosophy to a dynamic, biological-feedback-driven approach, significantly reducing the incidence of OTS in endurance and elite athletes.

Disclosure:

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All authors have read and agreed with the published version of the manuscript.

Funding Statement: The study did not receive special funding.

Conflict of Interest Statement: There is no conflict of interest

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