International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Scholarly Publisher
RS Global Sp. z O.O.
ISNI: 0000 0004 8495 2390

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ARTICLE TITLE	HEART RATE VARIABILITY IN ATHLETES: INDICATOR OF TRAINING LOAD, RECOVERY AND CARDIOVASCULAR HEALTH
DOI	https://doi.org/10.31435/ijitss.3(47).2025.3889
RECEIVED	22 August 2025
ACCEPTED	25 September 2025
PUBLISHED	30 September 2025
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HEART RATE VARIABILITY IN ATHLETES: INDICATOR OF TRAINING LOAD, RECOVERY AND CARDIOVASCULAR HEALTH

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ABSTRACT

Introduction: Heart rate variability (HRV) is a non-invasive biomarker reflecting autonomic nervous system activity. In recent years, its use in sports medicine has increased significantly due to its usefulness in monitoring training load, recovery, and cardiovascular health in athletes.
Material and methods: This review summarizes the current state of knowledge on the physiological basis of HRV, measurement methods, and practical applications in athlete populations. This study is a literature review based on data from PubMed and Google Scholar.
Results: HRV parameters, particularly RMSSD (the square root of the mean of the squares of differences between successive RR intervals) and SDNN (the standard deviation of NN intervals), show a clear sensitivity to training intensity and recovery status. Studies show that HRV-guided training can improve performance measures such as VO_2max (maximal oxygen consumption) and reduce the risk of overtraining. HRV also responds to changes related to sleep quality, supplementation, and biofeedback interventions. Despite technological advances, there are still challenges related to standardizing measurement protocols and accuracy across devices. Low HRV is also associated with increased cardiovascular risk, which additionally creates a potential role in early detection of arrhythmia or autonomic imbalance in athletes.
Conclusions: HRV is a valuable tool in personalized training management and monitoring cardiovascular health. The use of similar measurement protocols and interpretation of trends rather than single values increases its utility in both competitive and recreational sports. Future research should seek to integrate HRV with other physiological measures and validate wearable technologies in diverse athlete populations.

KEYWORDS

Heart Rate Variability, Athletes, Recovery, Training Load, Cardiovascular Risk, Wearable Devices

CITATION

Katarzyna Urbańska, Anna Hawryluk, Adam Żuczek, Kinga Dyndał, Marcelina Broda, Olga Żuczek, Izabela Szczap, Kamil Marzec, Aleksandra Mokrzycka, Patrycja Jędrzejewska-Rzezak. (2025) Heart Rate Variability in Athletes: Indicator of Training Load, Recovery and Cardiovascular Health. *International Journal of Innovative Technologies in Social Science*. 3(47). doi: 10.31435/ijitss.3(47).2025.3889

1. Introduction:

Heart rate variability (HRV) has emerged as a widely recognized, non-invasive biomarker reflecting the dynamic interplay between the sympathetic and parasympathetic branches of the autonomic nervous system. is a measure of the variability of beat-to-beat interval (R-R interval), by the combined effects of the sympathetic (SNS) and parasympathetic (PNS) nervous systems on the sino-atrial node [1,2]. It provides valuable insights into physiological adaptation, stress responses, and overcall cardiovascular regulation. In recent years, HRV has gained particular attention in the context of sports science and medicine, where it is increasingly used to monitor training load, assess recovery status, and evaluate cardiovascular health among athletes.

The importance of individualized monitoring in athletic training is well established. Overtraining inadequate recovery and chronic stress can lead to decreased performance and elevated risk of injury or cardiovascular complications [3]. HRV offers a promising solution to this challenge by enabling real- time assessment of the automatic balance, which is closely related to an athlete's readiness to train and recover [4]. Moreover, technological advances, including wearable devices and mobile applications have made HRV measurements more accessible in both elite and recreational sport settings [5].

The aim of this review is to provide an overview of the physiological basis of HRV, describe its measurement techniques and explore its applications in training load monitoring, recovery assessment and cardiovascular risk evaluation in athletes. Particular attention will be given to recent findings from the scientific literature and the practical implications of HRV monitoring in sport and exercise settings.

2. Material and methods:

This review summarizes the current state of knowledge on the physiological basis of HRV, measurement methods, and practical applications in athlete populations. This study is a literature review based on data from PubMed and Google Scholar.

3. Physiological basis of heart rate variability:

3.1 Mechanisms of the Autonomic Nervous System (ANS)

Heart rate variability (HRV) reflects the physiological modulation of the sinus rhythm by the autonomic nervous system (ANS), which controls cardiovascular function through a dynamic balance between its two main branches: the parasympathetic and sympathetic systems. The parasympathetic system, acting mainly through the vagus nerve, has a fast and precise slowing effect on heart rate, especially during rest and recovery. In contrast, the sympathetic system acts more slowly, but broadly stimulates the cardiovascular system in response to stress or physical activity [6,7].

3.2 HRV as a Biomarker of Autonomic Balance

HRV is considered a sensitive non-invasive biomarker of autonomic balance and physiological adaptation. High values - especially RMSSD (the square root of the mean of the squares of differences between successive RR intervals) and SDNN (the standard deviation of NN intervals)- are typical of people with good fitness and recovery capacity. Low HRV, on the other hand, can suggest physical or emotional stress or overtraining [2]. Interestingly, HRV can also increase in a non-beneficial way for example, in cases of parasympathetic hyperactivity, which is sometimes seen in athletes experiencing functional overreaching [8].

3.3 HRV Parameters method:

In practice, HRV can be analyzed using three main types of measurements: time-domain, frequency-domain, and nonlinear parameters. The most commonly used time-domain measures are SDNN and RMSSD, with RMSSD being the most specific and sensitive indicator of vagal (parasympathetic) activity [6,7]. Frequency-domain analysis includes low-frequency (LF, 0.04–0.15 Hz) and high-frequency (HF, 0.15–0.4 Hz) components. HF mainly reflects parasympathetic activity, while LF represents a mix of sympathetic and parasympathetic input [9]. The LF/HF ratio, once used as a balance index, is now often criticized for being unreliable [10].

Modern approaches also include nonlinear HRV analyses, such as Poincaré plots, entropy measures, and detrended fluctuation analysis (DFA $\alpha 1$). These methods help to capture the complex, fractal nature of heart rate patterns. For example, during recovery from viral infections (like COVID-19), HRV has been shown to be a useful indicator of autonomic dysfunction, as highlighted by Zacher and Branahl [11].

4. Methods of measuring HRV in Athletes

HRV (Heart Rate Variability) measurement in athletes relies primarily on two main methods: electrocardiography (ECG) and 24-hour Holter monitoring, both considered the gold standard due to their high precision. Study has shown that athletes demonstrate significantly higher HRV values (e.g., SDNN ~225 ms) compared to non-athletes (~159 ms), reflecting greater parasympathetic tone [12].

In training settings, wearable devices such as Polar H10, Garmin, Whoop, and Oura are becoming increasingly popular. The Polar H10 chest strap has shown very high agreement with ECG in analyzing RMSSD and RR intervals at rest, and moderate accuracy during movement [13]. On the other hand, devices based on photoplethysmography (PPG) are more prone to errors during physical activity and when peripheral blood flow is low [14].

To ensure reliable HRV data, measurements should be standardized- preferably taken in the morning, in a supine or seated position, and for a duration of at least 1–5 minutes. Eliminating artifacts and maintaining consistent conditions are essential [15]. Nighttime HRV recordings (e.g. from Oura or Whoop) may also be reliable, although they rely on different algorithms.

Limitations include variability in HRV algorithms across manufacturers, lower measurement accuracy during movement, and the risk of misinterpretation. For example, in athletes with very low resting heart rates, the phenomenon of "parasympathetic saturation" may occur, leading to artificially low HRV values despite adequate recovery [10,16]

4.1 Measurement protocols & standardization

A critical aspect of heart rate variability (HRV) assessment in athletes is having highly consistent measurement protocols, which ensures reliable and comparable data. The best practice guidelines recommend that recordings be performed in the morning immediately upon awakening, using supine or standing positions, or both, to assess autonomic flexibility through posture changes. Recordings ranging from 1 to 10 minutes have been validated: ultra-short protocols show that as little as 1 minute, following a brief 30–60 second stabilization, can reliably capture RMSSD and other time-domain HRV measures. More comprehensive protocols typically involve 5–10 minutes supine and 5–6 minutes standing, especially when spectral (frequency-domain) components are analyzed [17].

During recordings, participants should breathe naturally and spontaneously, since paced or metronomic breathing can artificially elevate parasympathetic indices—particularly HF power and RMSSD- distorting true autonomic activity [18,19]. Consistency in environmental and contextual factors is equally important: athletes should record HRV under similar conditions each morning with an empty bladder, steady ambient temperature, and without recent caffeine intake, meals, or emotional stress, as these variables significantly influence HRV readings [17,19].

To mitigate day-to-day variability and improve trend detection, it's recommended to use rolling 7-day averages rather than single-day values. This method greatly reduces noise and enhances reliability in longitudinal monitoring [20].

4.2 Technical limitations & interpretation challenges

Photoplethysmography (PPG)-based devices—like wristbands and smart rings—have become popular for HRV tracking, but they come with important problems. Firstly, sensor accuracy can be compromised by motion artifacts and the use of proprietary algorithms. A study developing an end-to-end PPG pipeline noted that real-world signals often contain noise that can severely distort HRV estimates if not properly handled. In noisy conditions, wrist-worn devices struggle to match ECG precision, especially during movement [21,22].

Secondly, device variability poses a challenge. Differences in hardware and processing techniques across manufacturers mean that some wearables may underestimate HRV by up to 200 ms compared to ECG standards- a gap that could significantly impact longitudinal monitoring accuracy [23].

Thirdly, protocol inconsistencies threaten data integrity. Variations in measurement posture (e.g., supine vs. standing), recording duration, and breathing practices can all skew results. Researchers stress the need for strict standardization- without it, subtle trends in HRV reliability may be masked [21,24].

That only about 35% consistently adhered to daily morning HRV measurements. This low agreement confirms the need for multi-day measurements, which will provide more reliable results. [25].

5. The Use of HRV in Monitoring Training Load

Heart rate variability (HRV) is a useful tool for tracking how an athlete's body responds to training. When training is very intense, HRV usually goes down. When resting, HRV goes up. Because of this, HRV helps us understand whether the body is handling training well or needs more recovery.

Recent studies show that planning workouts based on daily HRV readings (such as RMSSD) gives better results than sticking to a fixed training plan. For example, Granero-Gallegos et al. found that athletes who adjusted their training according to HRV improved their VO_2max more than those who followed a standard schedule [25].

Similar results were seen in swimmers. During heavy training phases, HRV dropped – showing signs of fatigue. During tapering phases (when training is reduced before a competition), HRV went up, showing the body was recovering and getting ready to perform. Kamandulis et al. showed that with young swimmers after just a few days of heavy training (over 6 km swimming daily), HRV clearly dropped. This kind of change can be an early warning sign of overtraining [26].

HRV can also help in strength training. After intense sessions, HRV usually decreases. When tapering is used, HRV returns to normal. This helps coaches better plan rest and recovery [27].

Thanks to this kind of information, coaches can adjust training day by day. If HRV is stable or increasing, training can continue or be made harder. But if HRV drops for several days, it may be a sign to reduce training or rest more – to avoid overtraining.

6. HRV as a Tool for Recovery Assessment

Heart rate variability (HRV) is not just useful for tracking training stress — it's also a great way to check how well the body is recovering. Research shows that morning HRV, especially RMSSD measured right after waking up, is a good sign of how well someone recovered during the night [28]. Studies using smartwatches and ECG apps show that better sleep usually means higher HRV, which suggests the nervous system had time to rest and reset [29].

Some supplements like melatonin and magnesium can help improve sleep and, in turn, boost HRV. For example, a study by Ronan Doherty and his team found that taking a mix of melatonin, magnesium, and zinc helped people sleep better and longer ($p < 0.05$), which may also improve HRV [30]. Besides supplements, eating foods high in magnesium for example many vegetables also help the body relax and sleep better, which supports HRV [31].

HRV biofeedback (HRV-BFB) is another helpful tool. It teaches athletes how to breathe slowly and calmly to activate the parasympathetic nervous system. A review of studies showed that this kind of breathing training improved HRV and helped the body recover faster [32, 33]. Perez-Gaido et al. showed that participants did HRV-BFB during tough training periods lowered their mental stress and made the workouts feel easier [32].

In short, HRV can be a powerful tool for checking recovery. Tracking morning HRV helps athletes know when they're ready to train again. Using tools like sleep monitoring, smart supplementation, and HRV-BFB can speed up recovery and reduce the risk of overtraining. This allows coaches and athletes to adjust training based on real data - for better performance and less burnout.

7. HRV and Cardiovascular Health in Athletes

In athletes, heart rate variability (HRV) is an important marker of autonomic nervous system function and cardiovascular health. Low HRV - especially a reduction in parasympathetic-related components (such as RMSSD or HF)- indicates a dominance of the sympathetic system and is often associated with a higher risk of complications, including arrhythmias or sudden cardiac events [34].

A study involving amateur cyclists found that an increased LF/HF ratio during deep sleep after intense multi-day exertion was a strong predictor of supraventricular arrhythmias [34]. This suggests that early HRV monitoring- especially during recovery sleep- may help detect heart rhythm disturbances before clinical symptoms appear.

Extreme fatigue caused by intense training or competition leads to a sharp drop in HRV right after exercise. Markers such as SDNN, RMSSD, and pNN50 typically decrease, while the HF component declines, resulting in a higher LF/HF ratio and increased sympathetic dominance [35]. This reduction can last for 24–48 hours or even longer after highly exhausting activity.

It's important to note that endurance athletes such as runners or cyclists often experience seasonal changes in HRV, reflecting the intensity of their training. Daily HRV monitoring can help fine-tune recovery plans and reduce the risk of overtraining [36].

Additionally, research involving middle-aged competitive athletes showed that immediately after maximal exertion, both time-domain and frequency-domain HRV values worsened. However, in better-trained individuals, HRV returned to baseline levels faster [37]. This shows that HRV can be used as an indicator of fitness and recovery- greater athletic conditioning leads to faster autonomic recovery.

Together, these findings show that:

1. Low HRV and sympathetic dominance are signs of elevated cardiovascular risk, including arrhythmias.
2. Extreme physical effort leads to reduced HRV, often lasting 24–48 hours.
3. Monitoring HRV during sleep and recovery may help detect early warning signs of arrhythmias, although more clinical research is needed.
4. Well-trained athletes recover HRV more quickly, indicating better autonomic adaptation.

In conclusion, HRV is a practical tool for monitoring cardiovascular health and preventing complications in athletes. Daily measurement, especially during rest and sleep, may help detect potential issues like arrhythmias before they become serious. However, despite promising results, large-scale clinical studies are still needed to confirm the effectiveness of HRV monitoring as a method of preventing sudden cardiac events in sports. Further research involving larger athlete populations will be essential to make HRV a standard in sports cardiology.

8. HRV and Cardiovascular Health in Athletes

Heart rate variability (HRV) is a simple, non-invasive way to check how well the heart is working. It shows how balanced the nervous system is- especially the two parts that control heart rate: the sympathetic ("fight or flight") and parasympathetic ("rest and recover") systems. In athletes, HRV is often used as a sign of how healthy the heart is. A higher HRV usually means the heart is recovering well and the body is in good shape. A low HRV can sometimes be a warning sign- showing stress, overtraining, or possible health problems.

Sessa et al. have found that low HRV can be linked to a higher risk of heart issues like heart attacks, heart failure, or even sudden cardiac death [38]. In patients with heart disease, low HRV values like SDNN or RMSSD are connected to worse outcomes and more complications [39].

Even though sudden cardiac death in athletes is rare (about 1–3 cases per 100,000 athletes per year), using HRV for regular monitoring could help spot those at higher risk- especially athletes with undiagnosed heart conditions or those under heavy training load [34].

Tracking HRV during rest or sleep has also helped researchers notice abnormal heart rhythms (like atrial fibrillation) after intense training [40]. Some patterns - such as high LF/HF ratios or low RMSSD- may appear before heart problems and give an early warning.

In sports, HRV is used to:

- Check general heart health and spot unusual values,
- Monitor how well the body recovers after hard training, helping prevent overtraining,
- Support prevention by giving extra information alongside tests like ECG or heart ultrasound.

To get good results, HRV should be measured while resting (for example, in the morning or during sleep), and without any movement or distractions. While HRV isn't a full heart test on its own, it's a helpful tool for coaches, doctors, and athletes to monitor heart and training health.

9. Future Directions and Recommendations for HRV Research in Sports Medicine

Heart rate variability (HRV) research in sports medicine is on the brink of transformation, driven by technological advances and a strong emphasis on personalized athlete care. Here's how the landscape is evolving:

First, the need for standardized reference values across diverse athletic groups is becoming clear. Rabia Tugba Tekin et al. involving male soccer players found meaningful correlations between resting HRV and metrics like VO_2max, agility, neuromuscular coordination, sleep quality, and body awareness. The authors recommend establishing sport- and sex-specific HRV norms, along with testing HRV-based interventions for performance enhancement [41]. Additionally Amida Sundas et al. highlighted significant methodological inconsistencies- such as variations in protocols and device types- calling for consensus in measurement practices to enable reliable cross-study comparisons [42].

Second, there is growing interest in integrative monitoring- combining HRV with physiological and biomechanical indicators to obtain a richer, more accurate picture of athlete readiness. Neves et al. emphasized the value of linking HRV with lactate thresholds, ventilatory thresholds, and load metrics to better prescribe training intensity [43]. The focus was also on exploring how HRV can be combined with body composition data (e.g. BMI, fat percentage) to optimize training load [44].

Third, artificial intelligence and machine learning are now being used to extract actionable insights from complex HRV datasets. Materko et al. using machine learning distinguished between sympathetic and parasympathetic components of HRV in soccer players- demonstrating how HRV could eventually help identify athletes within teams and monitor training adaptation at the individual level [45].

Fourth, many researchers have stress-tested the gap between lab research and real-world application. A clinical review Gronwald et al.along with publication's Lundstrom et al emphasize the necessity for applied research that connects HRV monitoring to athlete training, recovery, and injury prevention. [36,22].

Finally, there's a recognized need for technological refinement. A 2025 scoping review examined decades of HRV research and concluded that while wearables hold promise, inconsistent protocols and significant device variability especially in PPG-based wearables undermine accurate and comparable data collection. The review recommends future work to focus on validating consumer-grade devices across sports and environments [42].

10. Summary

HRV is a useful and versatile tool for athletes. It helps track how the body is handling training, how well it's recovering, and gives insight into heart health.

Using HRV to guide training plans can improve endurance and support better physical adaptation. It helps athletes train smarter, not just harder.

Wearable devices have made it easier than ever to measure HRV every day. But not all wearables are the same- so it's important to understand the differences and follow a consistent routine to get reliable results.

Here are some practical tips:

- Measure your HRV daily, ideally in the morning while at rest.
- Pay attention to drops in HRV of more than 20–30%- this can be a sign to reduce training and focus on recovery.
- Support your recovery with good sleep, relaxation techniques, or biofeedback.
- In the future, research should focus on combining HRV with other body signals, looking at how recovery methods affect athletes, and exploring how HRV can help predict injuries and support long-term health in sport.

Disclosure

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

Funding Statement: This article received no external funding.
Institutional Review Board Statement: Not applicable
Informed Consent Statement: Not applicable
Data Availability Statement: Not applicable
Acknowledgments: Not applicable
Ethical Approval: Not applicable
Conflict of Interest Statement: The authors declare no conflict of interest.

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