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Investigating the Acute Effect of Different Training Protocols on Heart Rate Variability

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Abstract

Purpose: This study examined the acute effects of High-Intensity Interval Training (HIIT) and prolonged endurance training (ET) on heart rate variability (HRV) in elite Greco-Roman wrestlers. A secondary aim was to assess the usefulness of HRV in optimizing recovery strategies by monitoring post-exercise changes. Methods: Using a longitudinal crossover design, 13 elite male wrestlers completed two training protocols separated by a 15-day washout period. HRV variables were recorded at baseline, pre-exercise, during training, and 24 hours post-exercise. Data were analyzed with a linear mixed model (LMM) and Bonferroni-adjusted post hoc comparisons. Results: A significant main effect of Timepoint was found for all HRV parameters (SDNN, RMSSD, LF/HF ratio, and overall HRV), indicating marked reductions during exercise followed by partial recovery after 24 hours. A significant effect of Training Type was observed for SDNN. Post hoc analysis showed a significantly greater suppression of overall HRV during HIIT compared to ET ($p = .012$, Cohen's $d = 0.82$). Despite these differences, both protocols demonstrated similar recovery patterns at 24 hours. Conclusion: Both HIIT and ET induced acute decreases in HRV, with HIIT causing a more pronounced decline. Nevertheless, HRV recovery after 24 hours was comparable between the two training modalities.

Keywords: autonomic nervous system; greco-Roman wrestling; interval training; athlete monitoring

1. Introduction

Heart rate variability (HRV) refers to the fluctuations in the intervals between successive heartbeats, representing dynamic adjustments of the autonomic nervous system (ANS). Rather than being constant, the time between R-R intervals varies slightly, offering a non-invasive index of cardiac autonomic regulation. HRV analysis includes time-domain and frequency-domain measures, each providing insights into sympathetic and parasympathetic modulation. Among these, the standard deviation of normal R-R intervals (SDNN) and the root mean square of successive differences (RMSSD) are key time-domain indices, while high-frequency (HF) power represents parasympathetic activity in the frequency domain. Elevated SDNN values generally indicate enhanced autonomic function and cardiovascular adaptability [1,2].

The ANS plays a central role in regulating involuntary physiological processes such as heart rate, blood pressure, respiration, and digestion. HRV is therefore recognized as a marker of autonomic balance. The sympathetic branch, responsible for the "fight-or-flight" response, increases cardiovascular activity during stress, whereas the parasympathetic branch, associated with the "rest-and-digest" response, promotes recovery and energy conservation. A dynamic balance between these branches is essential for physiological homeostasis and athletic performance [3,4].

Numerous intrinsic and extrinsic factors modulate HRV, with physical exercise being a primary external influence. The autonomic response to exercise differs depending on the intensity, type, and duration of the activity. Low-intensity aerobic exercise typically enhances parasympathetic activity, thereby increasing HRV [5,6]. In contrast, high-intensity exercise induces sympathetic dominance, temporarily reducing HRV due to increased cardiovascular and metabolic demands. However, post-exercise parasympathetic reactivation can promote long-term autonomic adaptation and improved cardiovascular efficiency [7].

However, this temporary reduction in HRV can contribute to improved cardiovascular endurance and autonomic balance over the long term. The post-exercise increase in HRV is likely associated with reduced sympathetic dominance and enhanced parasympathetic reactivation. HRV markers indicating high parasympathetic activity, which can be evaluated after exercise, provide valuable insights into recovery status. Previous studies have reported that elite athletes exhibit pronounced parasympathetic reactivation and adaptive changes in cardiac autonomic control, serving as indicators of efficient recovery following exercise. [8–10]. The magnitude and duration of exercise-induced sympathetic activation—and the degree of subsequent HRV suppression—are typically modulated by the individual's fitness level, stress resilience, and training experience [11,12].

While acute HRV suppression during exercise is expected, elite athletes often exhibit attenuated reductions in parameters such as SDNN and RMSSD during high training loads (e.g., HIIT or endurance exercise), in contrast to recreational athletes. This suggests a more efficient sympathetic response and greater physiological adaptability [13,14] Moreover, HRV analysis during and after exercise provides valuable insights into training load, fatigue, and recovery dynamics, and has therefore gained prominence as a practical performance monitoring tool in elite sport [15,16].

However, despite HRV's growing use, its interpretation in elite athletes remains complex and sometimes contradictory. While increases in vagal-mediated HRV indices are generally associated with positive adaptations (e.g., improved fitness, autonomic balance), elite athletes often show inconsistent patterns. Studies have reported both increases and decreases in HRV accompanying signs of maladaptation, such as overreaching or stagnation in performance [17]. Paradoxically, improvements in cardiorespiratory fitness have also been observed alongside reductions in HRV—possibly due to "HRV saturation," a phenomenon in highly trained individuals where further improvements in autonomic efficiency no longer translate to higher HRV values [16].

This indicates that elite athletes possess a unique HRV fingerprint requiring individualized, longitudinal monitoring rather than reliance on isolated values. Daily or weekly fluctuations in HRV should be interpreted with caution, and meaningful trends should be extracted using appropriate statistical techniques such as rolling averages or baseline-corrected changes [13,16]. In this context, HRV becomes most useful not as a standalone diagnostic, but as part of a comprehensive athlete monitoring system tailored to each athlete's physiological baseline and competitive demands [17].

Recent work with Olympic and World Champion athletes has shown that strategic use of HRV metrics—particularly indices less prone to saturation—can effectively track fitness (chronic adaptation) and freshness (acute readiness). This nuanced interpretation allows coaches and practitioners to align training load with recovery capacity, thereby reducing injury risk and optimizing performance outcomes during critical periods such as tapering or competition phases [13,16,18].

Despite its growing application, limited research has examined the acute effects of HIIT and ET on HRV in elite-level wrestlers.

To address this gap, the present study investigates the immediate effects of HIIT and endurance exercise protocols on HRV in elite Greco-Roman wrestlers. A secondary aim is to evaluate HRV responses during the 24-hour post-exercise recovery period. Ultimately, this study aims to contribute to the literature by exploring the potential of HRV as a physiological biomarker for guiding training load, assessing performance capacity, and enhancing recovery strategies in elite athletes.

2. Materials and Methods

2.1. Experimental Approach to the Problem

This longitudinal study employed a short-term repeated-measures design to investigate changes in HRV among elite Greco-Roman wrestlers from the Danish National Team, in response to different training modalities. Data collection took place in Nykøbing, Denmark, at the national training camp held two months prior to international competitions.

Anthropometric assessments—including body mass, height, and age—were recorded on the first day of the camp. No dietary interventions were implemented, and as wrestling is a weight-classified sport, athletes' weight fluctuations were closely monitored throughout the study. According to both athletes and coaches, no weight loss occurred during the camp or training sessions.

The study incorporated two distinct exercise protocols—HIIT and ET—separated by a 15-day washout period to prevent carryover effects. All training sessions were part of the regular preparation program designed by the national coaching staff, and no modifications were made to their content or intensity.

To assess autonomic nervous system (ANS) modulation, HRV data were collected using validated parameters: the standard deviation of normal-to-normal RR intervals (SDNN), the root mean square of successive RR interval differences (RMSSD), and the low-frequency to high-frequency power ratio (LF/HF).

Measurements were performed under resting conditions for 5 minutes each morning, in a supine position immediately after waking up, to reduce the influence of confounding variables. HRV data were averaged over multiple time points:

- Baseline (BASE): At least one week prior to each training protocol
- Pre-exercise (PRE): On the day of each training session, before exercise
- During Exercise (TRAINING): Average HRV during the session
- Post 24 h (POST): 24 hours after each training session

Heart rate data, including maximal heart rate (HRmax), were also recorded. HRV values obtained during the training sessions were averaged to represent general training HRV response. Figure 1 illustrates the overall study design and timeline.

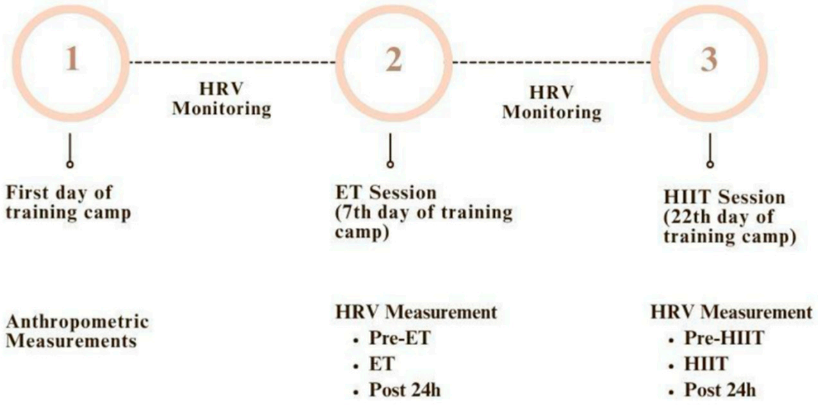

Figure 1. Overview of the Study Design and Timeline. Schematic representation of the experimental protocol used to evaluate acute heart rate variability (HRV) responses to endurance training (ET) and high-intensity interval training (HIIT) in elite Greco-Roman wrestlers. Daily HRV monitoring was conducted throughout the training camp. Key measurements were taken at four time points: baseline (BASE), immediately before training (PRE), during training (TRAINING), and 24 hours post-exercise (POST 24h). The timeline reflects the sequence of training interventions and HRV assessments used to compare autonomic responses and recovery profiles across training modalities.

2.2. Subjects

Thirteen elite male wrestlers (mean age: 21.26 ± 1.34 years; body mass: 74.82 ± 8.01 kg; height: 177.07 ± 6.56 cm) from the Danish National Greco-Roman Wrestling Team voluntarily participated in this study. All athletes had a minimum of 10 years of competitive training experience at the national and international levels. Among the participants, one was a bronze medalist at the Paris 2024

Olympics, while three others held European and continental championship titles across different age categories. In the year of data collection, four athletes competed in the Junior Greco-Roman European Championships.

All participants provided written informed consent prior to the study. The research protocol adhered to the ethical principles outlined in the Declaration of Helsinki and was approved by the Akdeniz University, Clinical Research Ethics Committee (TBAEK-194 / 30.01.2025). Additionally, institutional permission for data collection was obtained from the Danish Wrestling Federation.

A priori power analysis was conducted using G*Power (version 3.1.9.7) to determine the required sample size for detecting a medium-to-large interaction effect ($f = 0.30$) in a 2 (Training Type: ET vs. HIIT) × 4 (Timepoint: BASE, PRE, TRAINING, POST 24h) repeated measures ANOVA, with $\alpha = 0.05$ and power $(1–\beta) = 0.80$. The analysis indicated that a minimum of 12 participants would be sufficient to detect statistically significant effects. The final sample of 13 elite wrestlers exceeded this requirement, ensuring adequate statistical power for the within-subject crossover design employed in this study.

2.3. Training Protocol

The training sessions were integrated into the pre-planned program designed by the national team coaches. HRV measurements were conducted on Day 7 (ET) and Day 22 (HIIT) of the preparatory camp for international competitions. Both the endurance and interval training sessions were implemented at 10:00 AM on the final day of a one-week training block.

The ET session was performed on an intercity cycling path in Denmark. During the session, athletes were followed by coaches in vehicles and received verbal instructions to either maintain or increase their cycling pace. The session concluded with athletes cycling at their maximal effort until exhaustion.

Both endurance training (ET) and high-intensity interval training (HIIT) sessions were preceded by a standardized 15-minute traditional warm-up consisting of dynamic mobility drills and light aerobic activity.

The ET protocol included a continuous 2-hour cycling session performed at 70–85% of the participants' maximum heart rate (HR), immediately followed by a cycling bout at maximum HR until volitional exhaustion. The session concluded with a 5-minute cool-down phase consisting of low-intensity cycling at 30–40% of HR and static stretching exercises.

The HIIT protocol consisted of two consecutive high-intensity segments:

1. 10x 1-min. bouts of cycling at 70% HR, each followed by 1-min. rest periods.
2. 10x 45-sec. running bouts performed at 80% to maximal HR, interspersed with 20-sec. passive recovery intervals.

The HIIT session also ended with a 5-minute cool-down including jogging at 30–40% of HR and stretching.

All sessions were supervised, and heart rate was continuously monitored to ensure adherence to the target intensities.

The HIIT session was structured into two distinct phases based on intensity. The first phase involved moderate intensity, while the second phase, as instructed by the coaches, required maximum exertion.

2.4. Anthropometric Measurements

All anthropometric assessments were conducted by the same researcher on the first day of the national team training camp, prior to breakfast. Body weight was measured using a calibrated electronic scale and recorded in kilograms. Stature was measured in meters using a wall-mounted stadiometer, with participants standing barefoot and in an upright posture.

2.5. Heart Rate Variability Measurements

HRV was assessed at multiple time points: daily for one week prior to each exercise protocol (baseline), on the morning of the exercise session (pre), during the exercise (training), and 24 hours post-exercise (post 24h). Morning measurements were taken in the supine position in bed immediately after waking, using 5-minute recordings. During exercise, HRV data were continuously recorded throughout the training session to compute average values.

Each participant was equipped with a Polar H10 chest strap heart rate monitor (Polar Electro Oy, Kempele, Finland), capable of sampling at 1000 Hz. HRV data were recorded and exported via the Elite HRV mobile application. Before data collection, participants were trained on how to use both the chest strap and the app.

Resting HRV measurements were obtained over a 5-minute period each morning, immediately after waking and while lying in bed. For exercise measurements, the chest strap was securely positioned on the chest so as not to interfere with physical movement, and real-time monitoring was conducted.

The HRV analysis included both time-domain (e.g., SDNN, RMSSD) and frequency-domain (e.g., LF/HF ratio) parameters. Mean HRV values were calculated for each time point (BASE, PRE, TRAINING, POST 24h), separately for the ET and HIIT protocols.

2.6. Statistical Analyses

HRV parameters -including SDNN, RMSSD, general HRV index, LF/HF ratio, and heart rate- were analyzed using a Linear Mixed Model to assess the main effects of Training Type (ET vs. HIIT), Timepoint (BASE, PRE, TRAINING, POST 24h), and their interaction (Timepoint × Training Type). Participant ID was included as a random effect with random intercepts to account for within-subject variability due to the repeated-measures crossover design.

Estimated Marginal Means (EMMs) were calculated for each level of the fixed factors, and Bonferroni-adjusted post hoc pairwise comparisons were conducted to explore significant differences across timepoints and between training types.

Statistical significance was set at $p < .05$. Effect sizes were reported using partial eta squared (η^2) for main and interaction effects, and Cohen's d was calculated for relevant pairwise comparisons to interpret the magnitude of between-group differences at each timepoint (interpreted as: small ≥ 0.20, medium ≥ 0.50, large ≥ 0.80).

All statistical analyses were conducted using Jamovi software (version 2.6.19.0).

3. Results

A total of 13 elite male Greco-Roman wrestlers participated in this randomized crossover study. Each participant underwent both exercise conditions -ET and HIIT- with an adequate washout period between sessions to minimize potential carryover effects.

The athletes had a mean age of 23.0 ± 3.47 years, mean body mass of 76.61 ± 9.08 kg, and mean height of 1.76 ± 0.07 m. Since the study followed a within-subject crossover design, no between-group comparisons were required for baseline characteristics, as each athlete served as their own control.

3.1. SDNN (Standard Deviation of NN Intervals)

The linear mixed model revealed a significant main effect of Timepoint on SDNN values ($F(3, 84) = 45.065$, $p < .001$, $\eta^2 = .616$), indicating substantial fluctuations across the measurement phases (Fig. 2). Both training conditions (ET and HIIT) showed a pronounced decrease in SDNN during the TRAINING phase compared to BASE and PRE, followed by partial recovery at POST 24h.

Additionally, a significant main effect of Training Type was found ($F(1, 84) = 6.807$, $p = .011$, $\eta^2 = .075$), suggesting that overall SDNN values differed between endurance and interval training modalities. However, the Timepoint × Training Type interaction was not statistically significant ($F(3, 84) = 0.312$, $p = .833$), indicating that the temporal response pattern was similar for both exercise types.

Post hoc comparisons did not reveal any statistically significant differences between the ET and HIIT groups at individual time points. The largest between-group difference occurred during the TRAINING phase (Cohen's d = 0.41), though this was not statistically significant, suggesting a small to moderate effect size.

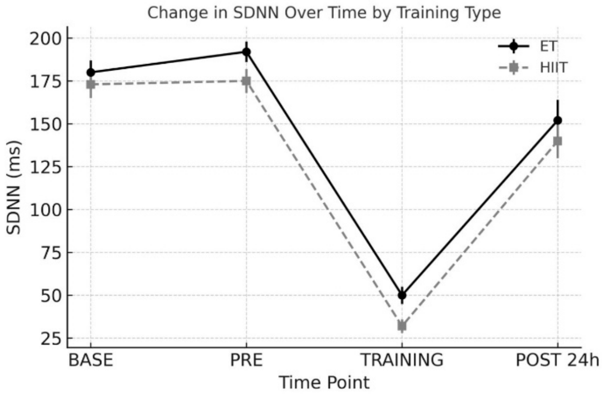

Figure 2. Change in SDNN Over Time by Training Type. Mean ± SD values of SDNN (ms) are shown across four time points (BASE, PRE, TRAINING, POST 24h) for endurance training (ET) and high-intensity interval training (HIIT). A significant main effect of timepoint was observed ($p < .001$), indicating a marked reduction in SDNN during exercise for both protocols, followed by partial recovery 24 hours later. Additionally, a significant main effect of training type ($p = .011$) revealed higher overall SDNN values in the ET group. These results suggest that HIIT induces greater acute autonomic stress compared to ET.

3.2. RMSSD (Root Mean Square of Successive Differences)

The linear mixed model revealed a significant main effect of Timepoint on RMSSD values ($F(3, 84) = 95.949$, $p < .001$, $\eta^2 = .774$), indicating a substantial reduction in parasympathetic activity during the TRAINING phase in both exercise modalities (Fig. 3). RMSSD decreased markedly during training compared to BASE and PRE, followed by partial recovery at POST 24h.

However, the main effect of Training Type was not significant ($F(1, 84) = 1.717$, $p = .194$), nor was the Timepoint × Training interaction ($F(3, 84) = 0.905$, $p = .446$), suggesting that both groups exhibited similar temporal HRV responses.

Post hoc analysis showed no significant differences between ET and HIIT at any timepoint. The between-group effect size at the TRAINING phase was small (Cohen's d = 0.27, ns).

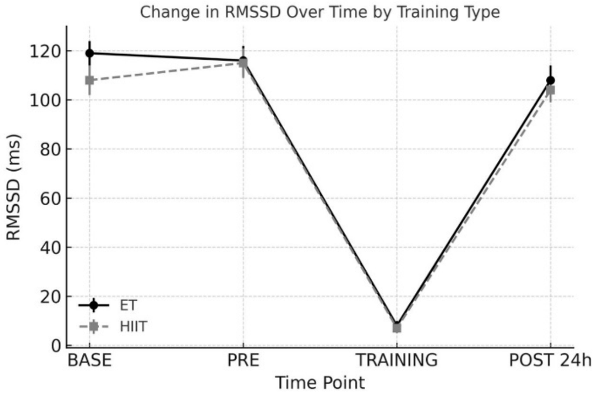

Figure 3. Change in RMSSD Over Time by Training Type. Mean ± SD values of RMSSD (ms) are shown across four time points (BASE, PRE, TRAINING, POST 24h) for ET and HIIT. RMSSD, a time-domain marker of parasympathetic activity, declined sharply during the training phase in both groups ($p < .001$) and partially

recovered by 24 hours post-exercise. There were no significant differences between ET and HIIT. This pattern reflects transient vagal withdrawal during exercise, with similar recovery dynamics across both protocols.

3.3. LF/HF Ratio

A significant main effect of Timepoint was observed for the LF/HF ratio (F(3, 84) = 14.264, p < .001, η^2 = .378), reflecting increased sympathetic dominance during the TRAINING phase in both groups (Fig. 4). This elevation is consistent with a typical autonomic response to acute physical stress.

However, no significant main effect of Training Type was found (F(1, 84) = 0.131, p = .719), and the Timepoint × Training interaction was also not significant (F(3, 84) = 0.222, p = .877).

These results indicate that ET and HIIT produced comparable shifts in autonomic balance over time. The effect size during TRAINING was small (Cohen’s d = 0.19) and not statistically significant.

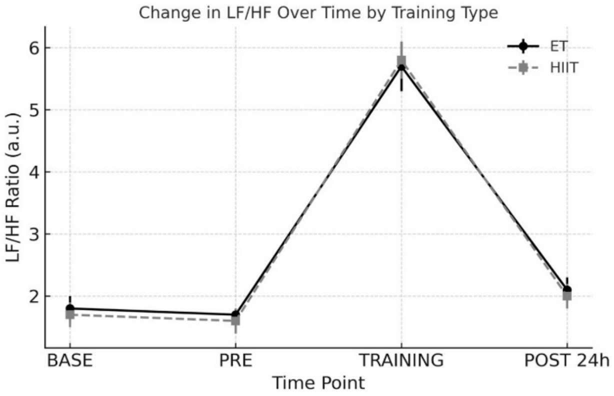

Figure 4. Change in LF/HF Ratio Over Time by Training Type. Mean ± SD values of LF/HF ratio are shown across four time points (BASE, PRE, TRAINING, POST 24h) for ET and HIIT. The ratio increased substantially during the training phase (p < .001), reflecting sympathetic dominance during exertion. Although a decline was observed by POST 24h, baseline levels were not fully restored. No significant differences were found between protocols, suggesting comparable autonomic strain in terms of sympathovagal balance. .

3.4. HRV (General Heart Rate Variability Index)

The linear mixed model revealed a robust main effect of Timepoint on general HRV (F(3, 84) = 166.370, p < .001, η^2 = .856), indicating substantial temporal fluctuations across conditions (Fig. 5). A significant Timepoint × Training Type interaction was also observed (F(3, 84) = 4.369, p = .008, η^2 = .135), suggesting that changes in HRV over time varied between the ET and HIIT protocols. Although the main effect of Training Type was not significant (F(1, 84) = 0.561, p = .456), post hoc comparisons revealed that HRV was significantly more suppressed during the TRAINING phase in the HIIT group compared to the ET group (p = .012), with a large effect size (Cohen’s d = 0.82). This finding reflects a more pronounced acute autonomic disruption in response to high-intensity interval loading.

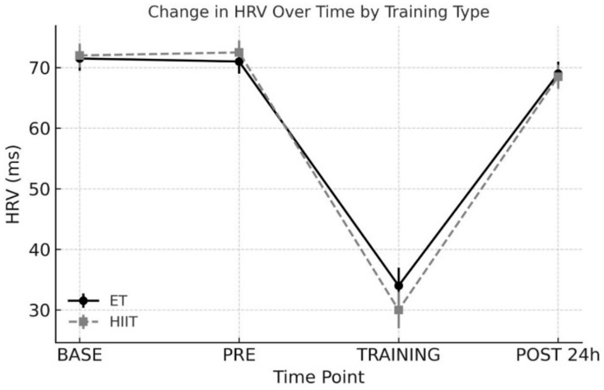

Figure 5. Change in HRV Over Time by Training Type. Mean ± SD values of general HRV (ms) are shown across four time points (BASE, PRE, TRAINING, POST 24h) for ET and HIIT. HRV declined significantly during training ($p < .001$) in both protocols, with HIIT showing a significantly greater suppression (interaction effect: $p = .008$; post hoc $p = .012$, $d = 0.82$). Although partial recovery occurred by POST 24h, the HIIT group maintained lower HRV values, suggesting prolonged autonomic disturbance.

3.5. Heart Rate

Linear mixed model analysis demonstrated a highly significant main effect of Timepoint on heart rate ($F(3, 84) = 290.323$, $p < .001$, $\eta^2 = .912$), indicating a substantial increase in HR during the TRAINING phase, followed by a return toward baseline values at POST 24h (Fig. 6). In contrast, neither the main effect of Training Type ($F(1, 84) = 2.396$, $p = .127$) nor the Timepoint × Training interaction ($F(3, 84) = 0.218$, $p = .872$) reached statistical significance, suggesting that both ET and HIIT protocols elicited similar heart rate responses over time. The between-group effect size during TRAINING was small (Cohen's $d = 0.33$, not significant), implying only minimal differences in cardiovascular load during the exercise sessions.

Figure 6. Change in Heart Rate Over Time by Training Type. Mean ± SD values of heart rate (bpm) are shown across four time points (BASE, PRE, TRAINING, POST 24h) for ET and HIIT. Heart rate increased significantly during the training session ($p < .001$), returning toward baseline 24 hours later. No significant differences were detected between groups. These results demonstrate robust cardiovascular activation during exercise, though HR alone may not differentiate training stress between protocols as clearly as HRV indices.

4. Discussion

The present study investigated acute HRV responses to two different training modalities -cycling-based ET and HIIT- in elite Greco-Roman wrestlers. The primary aim was to evaluate the autonomic responses during exercise and to assess the extent of recovery 24 hours post-exercise by analyzing multiple HRV indices. Given the importance of HRV as a non-invasive marker of ANS function, this study also sought to determine the potential utility of HRV for monitoring training load and recovery status in elite athletes.

Our findings revealed that baseline HRV values (BASE and PRE) were comparable between the two training conditions, indicating a similar autonomic state prior to exercise regardless of training type. However, both ET and HIIT elicited significant reductions in HRV indices -particularly SDNN, RMSSD, and general HRV- during the TRAINING phase, accompanied by an increase in the LF/HF ratio and heart rate. These changes reflect a shift toward sympathetic dominance and parasympathetic withdrawal, which is consistent with the physiological stress response observed during acute physical exertion. This phenomenon has been well-documented in the literature, with acute exercise known to decrease HRV through mechanisms including increased heart rate, respiratory frequency, and blood pressure, all of which amplify cardiovascular and metabolic demand [19–21]. Such autonomic adjustments are indicative of the body's effort to maintain homeostasis under physical load and are mediated primarily through the sympathetic branch of the ANS [22].

Despite similar overall trends, between-group comparisons revealed that the suppression in general HRV during the training session was significantly greater in the HIIT condition compared to ET, with a large effect size (Cohen's d = 0.82). This suggests that although both training methods impose substantial physiological stress, HIIT may provoke a more pronounced acute autonomic disturbance. The greater sympathetic activation and vagal withdrawal observed in the HIIT group may be attributed to the higher intensity and intermittent nature of the protocol, which likely imposed greater cardiovascular and neuromuscular strain within a shorter duration. This finding supports previous studies demonstrating that high-intensity interval protocols can induce stronger autonomic responses than continuous moderate-intensity efforts, even when total exercise volume is lower [19,23].

These results have practical implications for coaches and sport scientists, as they underscore the physiological demands of HIIT and its utility as a time-efficient training strategy. The comparable or even greater autonomic load induced by HIIT supports its inclusion in high-performance training programs where time constraints exist, but physiological adaptation is critical. Importantly, these findings also contribute to the broader discussion of whether HRV monitoring can serve as a real-time tool for quantifying training stress and informing recovery strategies in elite populations.

Overall, the acute decrease in HRV during both exercise conditions highlights the responsiveness of the ANS to physical load, while the magnitude of suppression -more pronounced in HIIT- reflects the intensity-specific nature of autonomic regulation. While both modalities led to partial recovery at the 24-hour post-exercise mark, the utility of HRV for tracking these patterns suggests its value not only in physiological monitoring but also in personalized training design for elite athletes.

Although changes in HRV during exercise are primarily driven by the imposed training load and the athlete's fitness level, post-exercise HRV fluctuations -especially those measured at rest- are modulated by a broader range of physiological and psychological factors, including sleep quality, nutritional status, emotional stress, and circadian influences [24]. In the present study, given that all participants were residing in the same training camp under standardized living conditions with uniform training loads and schedules, it is reasonable to assume that extraneous factors influencing HRV (e.g., sleep, diet, and environmental stressors) were minimized. This controlled setting enhances the reliability of the 24-hour post-exercise HRV assessments in reflecting true autonomic recovery following exercise.

The analysis of HRV values obtained 24 hours after the training sessions revealed significant differences between the two protocols. Both SDNN and RMSSD values remained lower following HIIT compared to endurance training. This finding highlights the sensitivity of these time-domain indices to post-exercise parasympathetic activity and supports their use as markers of recovery. Elevated post-exercise SDNN values are typically associated with increased vagal tone and reduced sympathetic dominance, both of which are recognized as indicators of favorable recovery status and cardiovascular fitness [15,24]. Therefore, the higher SDNN values observed after endurance training in our study suggest a more complete autonomic recovery compared to the HIIT condition.

The attenuated recovery seen following HIIT may reflect the greater physiological stress induced by high-intensity efforts, which is consistent with prior studies reporting reduced HRV values in the hours and even days following strenuous training sessions [25,26]. These findings reinforce the notion that training intensity plays a critical role in shaping post-exercise autonomic recovery trajectories. Taken together, our results underscore the potential utility of SDNN and RMSSD as objective tools for evaluating short-term recovery and guiding training decisions in elite athletic settings.

Finally, regardless of the fluctuations in HRV observed during and after exercise sessions, the athletes in this study consistently demonstrated high resting HRV and SDNN values throughout the daily monitoring period. Sustained elevations in daily SDNN are widely considered a marker of

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optimal autonomic balance and physiological readiness, indicating that an athlete is well-prepared for subsequent training or competition [27,28]. Elevated resting SDNN values -commonly observed in elite endurance and high-performance athletes- reflect a highly adaptable ANS, capable of efficiently responding to and recovering from physical stressors such as intensive training loads.

More specifically, high SDNN values suggest enhanced flexibility in both the sympathetic and parasympathetic branches of the ANS, contributing to robust cardiovascular health and superior aerobic fitness. This autonomic efficiency facilitates rapid post-exercise recovery by promoting effective parasympathetic reactivation (the "rest-and-digest" response), which accelerates physiological repair processes. Accordingly, the elevated resting HRV and SDNN values observed in the athletes of this study likely reflect their elite performance status and may serve as reliable biomarkers of training readiness and overall physiological resilience in the lead-up to competition.

Conversely this study has several limitations that should be considered. First, the small and homogeneous sample—limited to 13 elite male Greco-Roman wrestlers—restricts the generalizability of the findings to other populations, such as female athletes or competitors from different sports. Second, while the camp environment ensured similar training and living conditions, individual factors known to influence HRV—such as sleep quality, nutrition, and psychological stress—were not objectively controlled or measured. Third, post-exercise recovery was only assessed at a single time point (24 hours), which may not fully capture the autonomic recovery process, particularly after high-intensity training. Lastly, although HRV is a valuable indicator of autonomic function, the absence of additional physiological or biochemical recovery markers (e.g., hormonal or neuromuscular indicators) limits the interpretation of recovery dynamics. Future studies should aim to include larger and more diverse samples, extend recovery monitoring beyond 24 hours, and incorporate multimodal recovery assessments to provide a more comprehensive understanding.

5. Conclusions

This study examined the acute autonomic responses and subsequent recovery following two distinct training modalities -cycling-based ET and HIIT- in elite Greco-Roman wrestlers preparing for international competition. By employing continuous HRV monitoring across key time points (baseline, during exercise, and 24 hours post-exercise), the study provided detailed insights into how different exercise intensities impact ANS dynamics.

The findings clearly indicate that HIIT imposes a greater acute physiological stress compared to ET, as evidenced by a more substantial suppression in HRV parameters such as SDNN, rMSSD, and general HRV during the exercise bout. Moreover, although partial recovery was observed in both protocols 24 hours post-exercise, HRV indices remained lower in the HIIT condition. This suggests that the recovery period following high-intensity efforts may require closer monitoring and potentially longer durations to ensure full autonomic restoration, even in well-trained athletes.

Importantly, athletes demonstrated consistently high baseline HRV and SDNN values throughout the study, highlighting their elite conditioning and efficient autonomic regulation. This also reinforces the utility of HRV as a sensitive biomarker for detecting training readiness, stress accumulation, and recovery trends in high-performance environments.

These results offer several practical implications. First, they confirm that HIIT can serve as an effective and time-efficient training strategy capable of eliciting comparable, if not greater, physiological adaptations relative to traditional endurance training. Second, the observed HRV dynamics emphasize the value of individualized monitoring approaches -particularly in elite sport settings where fine-tuning of training loads and recovery windows can make a substantial difference in performance outcomes. Lastly, this research underscores the role of HRV-based tools as non-invasive, real-time indicators for guiding periodization, avoiding overreaching, and enhancing athlete resilience.

In conclusion, the integration of HRV monitoring into training programs provides coaches and sports scientists with a powerful method for evaluating autonomic stress and tailoring recovery strategies. By recognizing the nuanced responses elicited by different training modalities, practitioners can make more informed decisions to optimize performance, reduce injury risk, and support long-term athlete development.

6. Practical Applications

The findings of this study offer valuable insights for coaches, sport scientists, and performance staff aiming to optimize training load management and recovery strategies in elite athletes. The significantly greater suppression of general HRV observed during HIIT compared to ET supports the use of HRV monitoring—particularly during and immediately after sessions—as a practical, non-invasive tool for quantifying acute physiological stress. These real-time autonomic markers can be integrated into daily training routines to objectively assess training intensity, enabling informed adjustments in load distribution.

Additionally, the results advocate for a personalized approach to training design, whereby each athlete's individual HRV response guides the progression and recovery of future sessions. This approach can help mitigate the risk of overreaching or maladaptation, especially during periods of intensified training. Although both HIIT and ET elicited partial recovery by 24 hours post-exercise, ongoing HRV tracking may help identify subtle differences in recovery dynamics and support more tailored recovery strategies.

To further enhance athlete monitoring, future applications should incorporate long-term HRV surveillance in conjunction with other physiological or perceptual metrics. This would allow practitioners to more precisely identify the cumulative effects of training load, recovery quality, and adaptation capacity—ultimately contributing to sustained performance and reduced injury risk in high-performance sport.

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