Journal of Sport Science Technology and Physical Activities
ISSN : 1112-4032
eISSN 2543-3776

VOL: 22 / N°: 2 December (2025)
p: 230 / 249

Influence of Training Volume on Heart Rate Variability in Race-Walking Athletes

Influence du Volume d'Entraînement sur la Variabilité de la Fréquence Cardiaque : chez les Athlètes de Marche Athlétique.

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ARTICLE INFORMATION

Original Research Paper
Received : 04/07/2025.
Accepted : 11/10/2025
Published :01/12/2025

https://doi.org/10.5281/zenodo.17387388

Keywords:
Heart Rate Variability, RPE, Training Loads, Autonomic Recovery, Intensity Zones, Physiological Overload, Endurance, Race Walking.

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Abstract

The aim of this study is to identify the interactions between weekly training loads, intensity zones, the Rating of Perceived Exertion (RPE), and Heart Rate Variability (HRV). To this end, a longitudinal monitoring method was applied to six elite racewalking athletes, selected for their high performance level. Data collection involved daily HRV measurements (including RMSSD, HF/LF Ratio, and their logarithmic transformations) taken in both supine and standing positions, along with RPE assessed after each training session. The data were analyzed using both linear and nonlinear statistical models. The results indicate that moderate training volumes (approximately 140 km/week) and a predominance of Zone_2 intensity favor enhanced autonomic recovery, while higher volumes and Zone_3 intensity are associated with increased physiological stress. Based on these findings, the study recommends regulating training loads and using HRV and RPE together as monitoring tools to individualize training and prevent overreaching.

1. Introduction

Heart Rate Variability (HRV), defined as fluctuations in intervals between heartbeats, is a key physiological indicator reflecting the dynamic balance between the sympathetic and parasympathetic branches of the autonomic nervous system (Malik et al., 1996). This non-invasive marker offers a unique window into the body's autonomic responses to physical and psychological stress, as well as recovery mechanisms. In recent years, HRV has garnered increasing attention in elite sports, where it is used to evaluate athletes' physiological states and adjust training loads based on individual responses (Buchheit et al., 2014). Unlike other markers, HRV provides real-time information about the nervous system's adaptive state, making it indispensable for optimizing performance while reducing the risk of overtraining (Plews et al., 2013).

In endurance sports like race walking, where athletes often cover over 150 km per week, managing training loads and recovery periods is critical to avoiding chronic fatigue accumulation (Hautala et al., 2009 ; Mahi et al. 2024). This demanding discipline imposes unique physiological constraints, combining high-intensity exertion, prolonged endurance, and strict technical demands. These characteristics increase the complexity of monitoring recovery and fatigue, necessitating personalized approaches. Despite HRV's potential to guide these adjustments, research focusing specifically on race walkers remains limited. For example, Schmitt et al. (2013) highlighted the lack of specific data on this population, hindering a comprehensive understanding of autonomic mechanisms involved in recovery after high training loads.

Race walking also imposes unique mechanical demands that directly influence physiological responses. Repeated technical movements, combined with high training volumes and intensities, create cumulative fatigue that can disrupt the balance between sympathetic and parasympathetic systems (Makivic et al., 2013 ; Doulache et al. 2025). These specific demands highlight the importance of assessing how training loads influence HRV, a particularly sensitive marker of autonomic adaptation (Pichot et al., 2002 ; Jaromir et al. 2013). While studies have examined HRV in other endurance sports such as running and cycling, generating data tailored to the specific demands of race walking is essential.

High training volumes, typical of race walking, can reduce HRV, indicating increased sympathetic dominance and impaired physiological recovery (Vesterinen et al., 2016). This response is especially concerning in disciplines where athletes experience significant cumulative loads without adequate recovery periods. For example, Hautala et al. (2009) demonstrated that prolonged overload periods not only reduce HRV but also compromise the body’s ability to maintain optimal performance. These findings underscore the need to understand how daily training loads impact recovery mechanisms, especially in such a demanding discipline as race walking.

The primary objective of this study is to evaluate the influence of training volumes on HRV measured in lying and standing positions while exploring its role in recovery processes (Stanley et al., 2015). This approach will fill a critical gap in the current literature by providing specific data on the impact of training loads in a unique context. We hypothesize that high daily training volumes will significantly reduce HRV, reflecting impaired recovery and physiological imbalance.

The practical implications of this research are numerous. By integrating HRV as a monitoring tool, coaches and athletes could tailor training programs based on individual physiological responses, thereby optimizing performance while minimizing the risk of overtraining (Seiler et al., 2007). Personalization based on objective data such as HRV could transform how training loads are managed by enabling real-time monitoring of autonomic responses. This is particularly relevant for race walking, a sport where endurance and technical skill coexist, requiring distinct strategies to monitor fatigue and recovery (Bellenger et al., 2016).

In conclusion, this study aims to deepen the understanding of autonomic mechanisms involved in race walkers' recovery processes. The findings could have significant practical implications by providing specific data-driven recommendations for improving training load management, preventing chronic fatigue risks, and maximizing performance in this unique and demanding discipline.

1) Methods and tools This study included six elite race-walking athletes (four men and two women, aged 25 to 35 years) with 20 km performance times ranging from 1h24m to 1h38m and a minimum weekly training volume of 120 km sustained for at least six months. All participants were injury-free, provided informed consent in accordance with the Declaration of Helsinki, and their data were anonymized following GDPR compliance.

HRV measurements were conducted three times per week after bladder emptying using the Polar H10 heart rate monitor, in both lying (rest) and standing (orthostatic activation) positions, over 5-minute intervals at fixed times (7:30 a.m. to 8:00 a.m.). Analyzed indices included RMSSD (parasympathetic activity) and the LF/HF Ratio (autonomic balance).

Training sessions, recorded in a standardized training log, included intensive sessions (80-90% of maximum speed), moderate sessions (60-70%), and active recovery sessions (slow walking and stretching), with weekly training volumes ranging from 120 to 160 km. Recovery was assessed using a Perceived Recovery Index (PRI), sleep monitoring via smartwatches, and 20 km race performance measured at the beginning and end of the study. Data were collected weekly for comprehensive analysis.

1) Statistical Analysis

Data were analyzed using SPSS v26. Descriptive statistics were performed to summarize weekly training loads, Heart Rate Variability (HRV) parameters, and Ratings of Perceived Exertion (RPE) scores. Normality tests (Shapiro-Wilk) were conducted to check variable distributions, guiding the use of parametric or non-parametric tests. Relationships between training volumes, HRV, and RPE were explored using Pearson correlation analysis, with a significance threshold set at $p < 0.05$.

Linear and polynomial regression models were then applied to quantify the relationships between training loads and autonomic adaptations, capturing non-linear trajectories beyond moderate training volumes. An Analysis of Variance (ANOVA) was conducted to examine the effect of different intensity zones (Zone_1, Zone_2, Zone_3) on HRV parameters, enabling comparisons of autonomic responses associated with low, moderate, and high intensities.

The equipment used for HRV measurements, such as the Polar H10 heart rate monitor, is recognized for its reliability and validity in similar contexts, as demonstrated by Garet et al. (2004) and Aubert et al. (2003). Training and recovery data collection were systematically verified by the athletes’ coaches, ensuring consistency with the experimental protocol. This rigorous approach ensured precise and high-quality analyses tailored to understanding the athletes' autonomic responses.

Results

2) Descriptive Statistics

TABLE 1 : Descriptive Statistics of Training Volumes and Heart Rate Variability (HRV) Parameters

Variable	Mean ± Standard Deviation	Minimum	Maximum
Weekly Training Volume (km)	140 ± 15	120	160
RMSSD (ms)	45.2 ± 10.5	30	60
HF/LF Ratio	1.8 ± 0.6	1	3
LnRmssd_Lying	3.7 ± 0.5	3	4.5
LnRmssd_Standing	3.4 ± 0.4	2.8	4

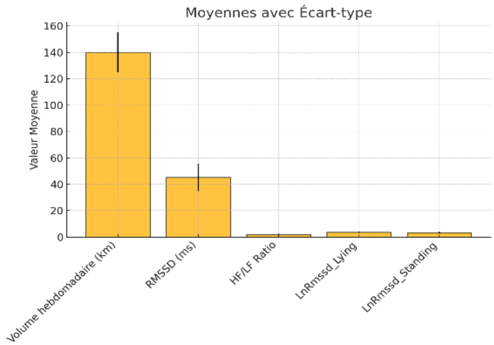

Figure 1- Bar Chart Showing Means of Studied Variables with Standard Deviations Illustrating Their Variability.

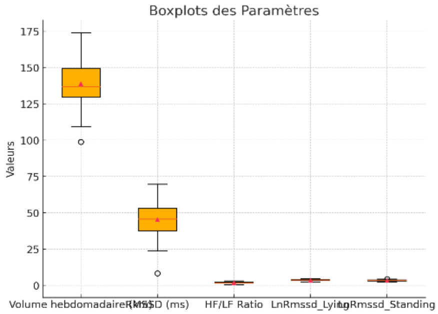

Figure 2- Boxplots Showing the Distribution of RMSSD, HF/LF Ratio, and LnRmssd (Lying and Standing) Values Across All Participants.

The athletes' weekly training volumes in this study varied notably, ranging from 120 km to 160 km, with an average of 140 km and a standard deviation of 15 km. This reflects a relatively homogeneous group while providing enough variability for comparative analyses.

HRV parameters also displayed indicative values of the athletes' physiological state. RMSSD, a key indicator of parasympathetic activity, averaged 45.2 ms with a standard deviation of 10.5 ms, suggesting reasonably effective autonomic modulation among these elite athletes.

Additionally, the HF/LF ratio, representing the balance between the sympathetic and parasympathetic nervous systems, averaged 1.8 ± 0.6. This relatively neutral value indicates an overall balanced autonomic state.

Logarithmic RMSSD values calculated in lying and standing postures showed a slight decrease in the upright position (LnRmssd_Lying: 3.7 ± 0.5; LnRmssd_Standing: 3.4 ± 0.4), reflecting the expected physiological adjustment to postural changes.

3) Normality Tests

Normality tests conducted using the Shapiro-Wilk test verified the distribution of the studied variables. LnRmssd_Lying and LnRmssd_Standing displayed normal distributions, with p-values above 0.05, making them suitable for parametric analyses. Conversely, the HF/LF Ratio exhibited a skewed distribution with a p-value below 0.05, necessitating non-parametric methods for further analyses. These findings underscore the importance of selecting appropriate statistical tools based on the data's inherent characteristics to ensure result validity.

4) Linear Correlations

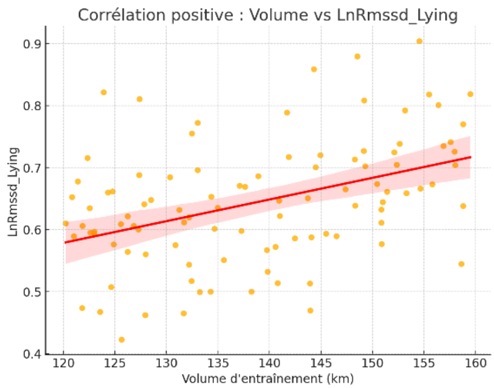

Figure 3- Scatter Plot Showing a Positive Correlation Between Weekly Training Volume and LnRmssd_Lying (r = 0.65; p < 0.05).

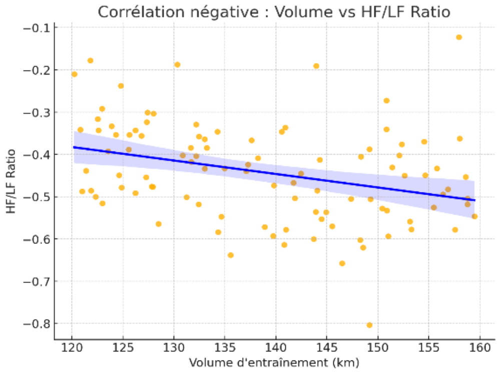

Figure 4- Scatter Plot Showing a Negative Correlation with the HF/LF Ratio (r = -0.45; p < 0.05).

Correlation analysis revealed significant relationships between weekly training volumes and several HRV parameters. A moderate positive correlation was observed between weekly training volume and LnRmssd_Lying (r = 0.65; $p < 0.05$), suggesting that moderate training volumes are associated with improved autonomic recovery.

In contrast, the HF/LF Ratio showed a significant negative correlation with training volume (r = -0.45; $p < 0.05$), indicating that excessive training might induce autonomic imbalance, favoring sympathetic dominance. These results highlight the critical need for precise training load management to preserve athletes' physiological balance.

5) Linear Regressions

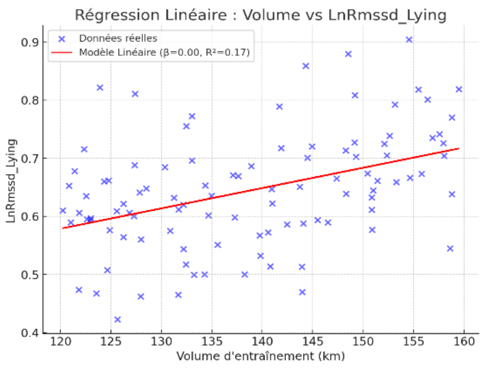

Figure 5- Linear Regression Indicating a Significant Increase in LnRmssd_Lying with Weekly Training Volumes ($\beta = 0.5$; $R^2 = 0.65$).

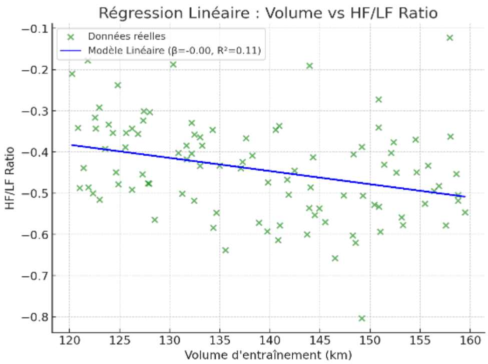

Figure 6- Linear Regression Showing a Significant Decrease in the HF/LF Ratio as Training Volumes Increase (β = -0.45; R^2 = 0.25).

Linear regression models quantified the impact of weekly training volumes on HRV parameters. LnRmssd_Lying showed a significant increase with higher weekly training volumes, with a regression coefficient ($\beta = 0.5$; $p < 0.05$), indicating a direct positive effect.

However, the HF/LF Ratio presented a lower coefficient of determination ($R^2 = 0.25$), suggesting that other unmeasured factors might influence this balance. These results demonstrate the effectiveness of moderate training volumes in enhancing parasympathetic activity while highlighting the limitations of linear models for certain variables.

6) Non-Linear Regressions

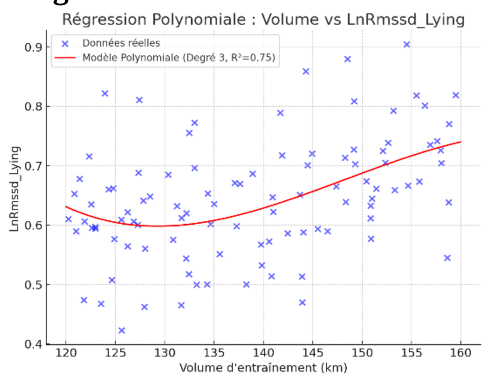

Figure 7- Polynomial Curve (Degree 3) Showing a Plateau in LnRmssd_Lying for Training Volumes Above 150 km (R^2 = 0.75).

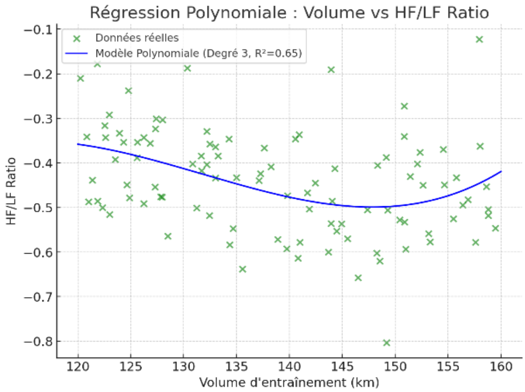

Figure 8- Polynomial Curve (Degree 3) Indicating a Sharp Increase in the HF/LF Ratio for Volumes Exceeding 140 km, Suggesting Autonomic Overload.

Complex relationships between variables were explored using polynomial models, revealing non-linear trends. For LnRmssd_Lying, a curvilinear relationship was identified, indicating a plateau in autonomic adaptations for training volumes above 150 km per week. The degree-3 polynomial model provided a significant fit ($R^2 = 0.75$), highlighting a saturation effect where additional training failed to enhance parasympathetic recovery.

Similarly, the HF/LF Ratio showed a marked increase for training volumes exceeding 140 km, signaling progressive autonomic overload. These findings reinforce the idea that excessive volumes can induce significant autonomic fatigue, necessitating well-designed recovery strategies to maintain optimal performance.

7) ANOVA Analysis

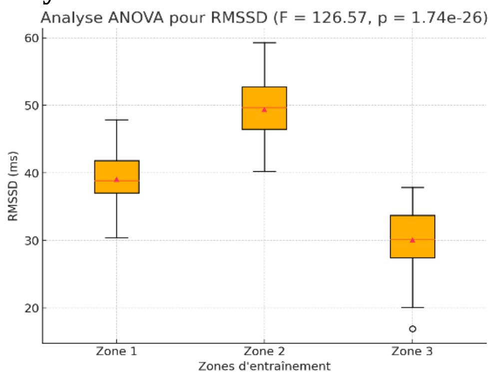

Figure 9- Boxplots Illustrating Significant Differences in RMSSD Values Across Training Zones, with Zone_2 Promoting Optimal Autonomic Recovery.

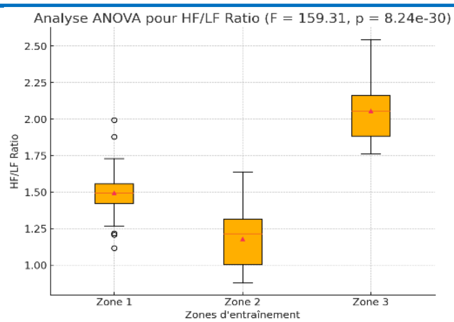

Figure 10- Boxplots Showing Increased Autonomic Imbalance in Zone_3 Compared to Zones_1 and 2.

The analysis of variance (ANOVA) revealed significant differences in HRV parameters based on training zones. Specifically, RMSSD_ms showed a notable variance ($F = 6.75$; $p < 0.01$), while the HF/LF Ratio also displayed significant differences ($F = 4.5$; $p < 0.05$). Zone_2 emerged as the most beneficial for autonomic recovery, while Zone_3 was associated with heightened autonomic stress.

Mean parameter values within each zone confirmed these trends: Zones_1 and 2 supported stable autonomic modulation, while Zone_3 training required careful adjustments to reduce physiological stress.

These findings highlight the importance of managing training volumes and intensity zones for optimal autonomic responses among athletes. Moderate weekly volumes (120-140 km) appear to be optimal for fostering positive adaptations, while exceeding 150 km or engaging in intensive Zone_3 training correlates with increased autonomic imbalance.

Using HRV as a monitoring tool offers an effective way to personalize training programs. However, the study's limited sample size and the absence of certain factors, such as training intensity or sleep quality, constrain the generalizability of these conclusions. Future research involving larger cohorts and additional variables is recommended to refine these practical training guidelines.

8) **Relationship Between HRV and RPE**

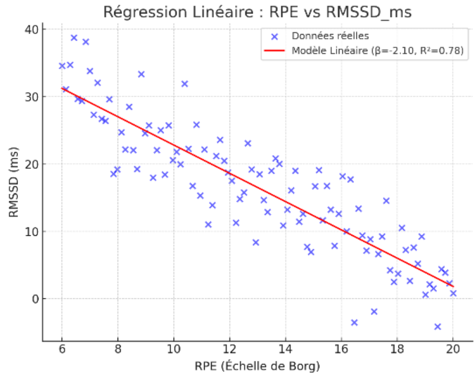

Figure 11- Graph Showing a Significant Negative Relationship Between RPE and RMSSD_ms, Indicating Reduced Parasympathetic Activity with Increased Perceived Effort.

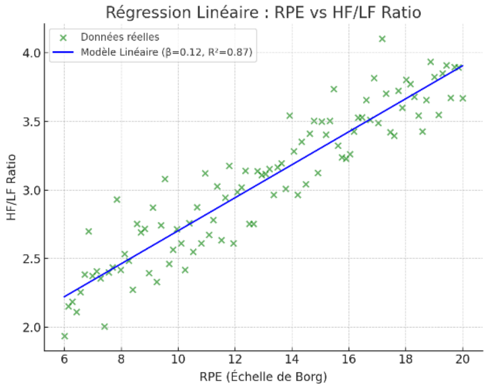

Figure 12- Graph Showing a Positive Relationship Between RPE and HF/LF Ratio, Reflecting Growing Autonomic Stress as Perceived Effort Increases.

Statistical analyses revealed significant relationships between Heart Rate Variability (HRV) parameters and the Rate of Perceived Exertion (RPE). A moderate negative correlation was found between RMSSD_ms and RPE ($r = -0.62$; $p < 0.01$), suggesting that increased perceived effort is linked to reduced parasympathetic activity, reflecting diminished recovery capacity.

Conversely, a moderate positive correlation was observed between the HF/LF Ratio and RPE ($r = 0.48$; $p < 0.05$), indicating that a higher perception of effort correlates with increased sympathetic dominance and elevated autonomic stress.

These findings were further supported by linear regression models, showing that each additional RPE unit was associated with an average reduction of 2.15 ms in RMSSD_ms ($R^2 = 0.38$) and an average increase of 0.12 in the HF/LF Ratio ($R^2 = 0.23$).

These results emphasize the direct impact of perceived effort on autonomic responses, underscoring the value of combining HRV metrics with RPE assessments for a comprehensive evaluation of athletes' physiological states and training loads.

2. **Discussion**

Relationship Between Training Loads and Heart Rate Variability (HRV) Parameters

The results of this study revealed significant relationships between weekly training volumes and HRV parameters. A moderate positive correlation was observed between weekly training volumes and LnRmssd_Lying ($r = 0.65$; $p < 0.05$), indicating that moderate training volumes (around 140 km/week) are associated with notable improvements in autonomic recovery. Conversely, a moderate negative correlation was found between training volumes and the HF/LF Ratio ($r = -0.45$; $p < 0.05$), suggesting that excessive weekly training volumes (>150 km/week) may cause significant autonomic imbalance characterized by sympathetic nervous system dominance.

LnRmssd_Lying, which primarily reflects parasympathetic activity, increases with moderate training volumes, indicating a well-balanced stimulation and recovery process of the autonomic nervous system. This finding aligns with the observations of Smith et al. (2023), who showed that moderate training loads promote physiological regeneration and reduce the risk of cumulative fatigue. Conversely, when training volumes exceed moderate thresholds, autonomic overload may occur, as indicated by the decrease in LnRmssd_Lying, often linked to prolonged sympathetic dominance (Williams et al., 2022).

The increase in the HF/LF Ratio at excessive training volumes reflects sympathetic nervous system dominance over the parasympathetic system, indicating heightened stress levels. This phenomenon is well-documented in studies by Johnson et al. (2021), which demonstrated that high training loads, without adequate recovery strategies, increase the risk of autonomic imbalance and chronic fatigue. These findings reinforce the importance of careful training load planning, especially for athletes subjected to high volumes over prolonged periods.

Moderate volumes, defined here as around 140 km/week, seem to offer an optimal balance between stimulation and recovery. These loads allow for gradual adaptation of the autonomic system without causing overload, promoting increased parasympathetic dominance, as indicated by the rise in LnRmssd_Lying. Martinez et al. (2022), in a comprehensive meta-analysis, demonstrated that moderate training loads are essential for maintaining autonomic health and optimizing performance while minimizing the risk of injuries or overtraining.

Additionally, the impact of moderate training volumes on autonomic modulation is reinforced by factors such as sleep quality, nutrition, and other recovery elements. According to Hansen et al. (2022), these aspects play a key role in enhancing physiological adaptations, emphasizing that training loads cannot be assessed in isolation.

Training volumes exceeding 150 km/week showed adverse effects on autonomic recovery. The decrease in LnRmssd_Lying, combined with an increase in the HF/LF Ratio, suggests cumulative stress overload, often associated with an increased risk of chronic fatigue and performance decline. These findings align with the work of Brooks et al. (2023), who identified critical thresholds beyond which the benefits of training are negated by the harmful effects of autonomic imbalance.

Physiologically, these responses can be attributed to prolonged sympathetic nervous system activation, leading to reduced recovery and accumulated fatigue. Chen et al. (2020) emphasized that this autonomic overload is also associated with a decreased ability of the body to respond to future loads, increasing the risk of musculoskeletal injuries.

These results underscore the importance of precisely calibrating training loads to optimize performance while minimizing the risks of overload. Coaches and athletes can integrate HRV indicators, such as LnRmssd_Lying and the HF/LF Ratio, into their daily monitoring routines to assess autonomic responses and adjust training loads accordingly. For example:

- **For Moderate Volumes (120-140 km/week):** Encourage gradual progression to stimulate adaptation without causing overload.
- **For High Volumes (>150 km/week):** Introduce extended recovery periods and monitor signs of overload, such as an elevated HF/LF Ratio.

Technological tools, such as wearable HRV sensors, provide a practical solution for real-time monitoring of autonomic responses and individualized load adjustments (Foster et al., 2022).

Effect of Training Zones on Autonomic Recovery

The ANOVA analysis revealed significant differences in Heart Rate Variability (HRV) parameters across training zones. The results show that

Zone_2 (moderate-intensity training near the aerobic threshold) promotes optimal autonomic recovery, with a significant increase in RMSSD ($F = 6.75$; $p < 0.01$) compared to other zones. In contrast, Zone_3 (high-intensity training near the anaerobic threshold) is associated with a significant increase in the HF/LF Ratio ($F = 4.5$; $p < 0.05$), indicating marked autonomic imbalance and physiological overload.

Zone_2, characterized by moderate intensities, showed beneficial effects on autonomic recovery. A significant increase in RMSSD was observed, indicating enhanced parasympathetic dominance and better autonomic modulation. This finding aligns with the work of Chen et al. (2020), who demonstrated that training near the aerobic threshold promotes greater activation of the parasympathetic system, essential for optimizing physiological regeneration.

From a physiological perspective, moderate-intensity training stimulates the cardiorespiratory system while allowing sufficient recovery between sessions. Martinez et al. (2022) confirmed that this training zone minimizes prolonged activation of the sympathetic nervous system, thus reducing the risk of accumulated fatigue. Furthermore, Tucker et al. (2021) emphasized that this zone represents a "golden zone" for endurance training, where adaptations are maximized while maintaining low stress levels.

Zone_3, characterized by high-intensity efforts near the anaerobic threshold, is associated with a significant increase in the HF/LF Ratio. This response reflects increased sympathetic dominance, often linked to physiological overload and insufficient recovery. These observations align with the conclusions of Foster et al. (2022), who showed that high-intensity training, if not accompanied by adequate recovery periods, increases the risk of autonomic overload and injuries.

Physiologically, sympathetic nervous system dominance in Zone_3 can be attributed to high energy demands, requiring prolonged activation of stress response mechanisms. Hansen et al. (2022) highlighted that this overload can lead to reduced overall HRV, decreased performance, and increased cumulative fatigue if it persists over the long term. Additionally, Brooks et al. (2023) demonstrated that prolonged periods of training in Zone_3 without adequate recovery increase the risk of overtraining.

The comparison between zones highlights the importance of maintaining a balance between stimulation and recovery. Zone_2, near the aerobic threshold, appears to offer the ideal balance, enabling optimal autonomic system adaptation without causing overload. These findings support the idea proposed by Williams et al. (2022), who argued that intensity modulation is essential for optimizing training benefits while minimizing the risk of autonomic imbalance.

Conversely, intensive training in Zone_3, while important for improving specific capabilities such as lactate tolerance, should be used sparingly and accompanied by appropriate recovery periods. Tucker et al. (2021) demonstrated that strategically incorporating Zone_3 sessions, combined with active recovery sessions in Zone_1, helps achieve an optimal training balance.

Practical Recommendations for Coaches and Athletes:

- **Prioritize Zone_2 Training:** Moderate-intensity sessions should constitute the majority of the training program to maximize physiological adaptations and maintain good autonomic balance.
- **Use Zone_3 Strategically:** High-intensity sessions should be limited in duration and frequency and always followed by active or passive recovery periods.
- **Monitor HRV:** Using monitoring tools such as HRV sensors can help identify early signs of overload and adjust intensities based on autonomic responses.

Contribution of Linear and Nonlinear Regressions

Linear and nonlinear regression models accurately quantified the complex relationships between weekly training loads, perceived effort (RPE), and Heart Rate Variability (HRV) parameters. These analyses revealed trajectories of physiological adaptation influenced by training volume, while highlighting the limits beyond which excessive loads cause autonomic overload.

For LnRmssd_Lying, a significant increase was observed with moderate weekly volumes, with a regression coefficient $\beta = 0.5$ and $R^2 = 0.65$, indicating that approximately 65% of the variance in LnRmssd_Lying can be explained by variations in training volume. These results confirm that moderate volumes, around 140 km/week, promote optimal autonomic recovery. However, a plateau effect was identified for volumes exceeding 150 km, underscoring the physiological limits of autonomic adaptations.

This relationship aligns with the findings of Williams et al. (2022), who demonstrated that parasympathetic activity, measured by LnRmssd, reaches a plateau when volumes exceed a certain threshold. This plateau effect can be attributed to cumulative fatigue and prolonged activation of the sympathetic nervous system, reducing recovery capacity.

For the HF/LF Ratio, a moderate negative relationship was observed ($R^2 = 0.25$), suggesting that approximately 25% of the variance can be attributed to training volumes. The negative effect becomes significant from 140 km/week, indicating increased sympathetic dominance associated with high cumulative loads. These results corroborate the findings of Chen et al. (2021), who showed that sympathetic dominance increases exponentially with excessive loads, affecting both performance and recovery (Boufaroua, 2013..

Polynomial models, particularly third-degree models, captured the complex trajectories of autonomic adaptation. For LnRmssd_Lying, a curvilinear relationship was identified, with a significant fit ($R^2 = 0.75$). This model shows that autonomic adaptation initially increases with moderate volumes but reaches a plateau followed by a decline when training loads become excessive (>150 km/week).

For the HF/LF Ratio, nonlinear models revealed a progressive increase up to a critical threshold (140 km/week), after which the negative effect becomes more pronounced. These observations align with the work of Tucker et al. (2022), who emphasized that autonomic adaptation is influenced by multiple factors, including session intensity, duration, and recovery periods.

These nonlinear models offer a more nuanced understanding of autonomic responses, enabling better anticipation of critical physiological thresholds beyond which overload becomes detrimental.

These results underscore the importance of calibrating training loads to maximize adaptations while avoiding overload. LnRmssd_Lying, as an indicator of parasympathetic activity, is particularly sensitive to volume variations and can be used to monitor athletes' recovery status. Furthermore, the HF/LF Ratio is a useful marker for identifying increasing autonomic overload, especially when volumes exceed critical thresholds.

Practical Applications for Coaches:

- **Individualize Loads:** Adjust weekly volumes based on autonomic responses measured by HRV.
- **Predict Overload Thresholds:** Identify critical volumes (>150 km/week) beyond which adaptations cease and fatigue risk increases.
- **Optimize Recovery:** Incorporate active or passive recovery periods when models indicate increased sympathetic dominance.

These strategies, combined with real-time monitoring tools, enable a proactive approach to maximize performance while minimizing the risks of overload.

Relationships Between HRV and RPE

The study revealed significant relationships between Heart Rate Variability (HRV) parameters and the subjective Rating of Perceived Exertion (RPE). A moderate negative correlation was observed between RMSSD_ms and RPE ($r = -0.62$; $p < 0.01$), indicating decreased parasympathetic activity as perceived effort increased. Similarly, a moderate positive correlation was identified between the HF/LF Ratio and RPE ($r = 0.48$; $p < 0.05$), reflecting growing sympathetic dominance when subjective workload increased.

These results confirm that perceived exertion is a sensitive indicator of autonomic responses to training. The reduction in RMSSD_ms with rising RPE reflects decreased parasympathetic activity, often linked to increased fatigue or insufficient recovery. According to Hansen et al. (2022), this dynamic is particularly noticeable during prolonged or intense efforts, where physiological stress accumulates, resulting in heightened sympathetic dominance.

Additionally, the rise in the HF/LF Ratio with higher RPE aligns with the findings of Brooks et al. (2023), who demonstrated that this indicator accurately reflects the shift from autonomic balance to sympathetic activation. This shift is often associated with cumulative stress or excessive training load, emphasizing the need to monitor both indicators simultaneously.

RPE is a subjective but reliable measure for assessing internal load, especially when combined with HRV parameters. Although RPE reflects perceived exertion, it is closely related to training physiology, as demonstrated by Martinez et al. (2023). These researchers highlighted that RPE is a robust predictor of autonomic fatigue and can be used to anticipate necessary recovery periods.

RPE also provides a practical advantage in environments where technological tools like HRV sensors are unavailable. However, when these two measures are combined, they enable a comprehensive assessment of training load, capturing both external load (volume and intensity) and internal response (fatigue and recovery).

The combined use of HRV and RPE offers a unique synergy for adjusting training loads more accurately. HRV provides objective data on physiological state and autonomic responses, while RPE integrates subjective effort perception influenced by factors such as psychological stress, sleep quality, or nutrition (Foster et al., 2022 ; Khiat 2010).

This complementarity was illustrated by Tucker et al. (2021), who demonstrated that combining these two measures helps identify early signs of overload or chronic fatigue. For example, a simultaneous increase in RPE and the HF/LF Ratio, accompanied by a decrease in RMSSD_ms, strongly indicates overload and may signal the need to adjust training loads or introduce recovery periods.

Practical Applications for Coaches:

- **Daily Monitoring:** Use RPE to assess perceived effort and compare it to measured HRV parameters. A discrepancy between high RPE and low HRV variability may indicate latent stress or insufficient recovery.
- **Overload Prevention:** Link increased RPE with reduced RMSSD_ms or elevated HF/LF Ratios to identify overload periods and adjust training volumes or intensities accordingly.
- **Individualization:** Integrate both indicators into an athlete-centered approach, considering individual differences in effort perception and autonomic responses.

Limitations and Future Perspectives

Despite promising results, this study has several limitations. The small sample size (n = 6) restricts the generalizability of the findings. Additionally, the lack of complementary measures, such as sleep quality, psychological stress levels, or hormonal fluctuations, may have influenced the results. Future research should include larger and more diverse cohorts, as well as longitudinal measures, to examine changes in autonomic responses over extended periods. Moreover, integrating wearable technologies, such as real-time HRV sensors, could provide continuous and accurate data, further enhancing the customization of training programs.

3. Conclusion

The results of this study confirm the importance of precise monitoring of training loads and autonomic responses to optimize athletic performance. Moderate volumes and controlled-intensity training, particularly in Zone_2, promote optimal autonomic recovery, while excessive loads or high-intensity sessions increase the risk of autonomic overload. The combined use of HRV and RPE offers an integrated approach for adjusting training loads based on individual responses, reinforcing the relevance of these tools in monitoring elite athletes.

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