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Article

The role of heart rate variability in the prevention of musculoskeletal injuries in female padel players

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Abstract: The engagement of athletes in competitive Padel is becoming progressively prevalent, and this heightened participation elicits apprehensions regarding the prevalence of overtraining and sports-related injuries. In this framework, the objective of the present investigation was to examine the potential role of Heart Rate Variability (HRV) monitoring in identifying overtraining injuries among female professional Padel athletes. A cohort of 66 elite female Padel players, with ages ranging from 17 to 32 years, was recruited for the study. The duration of the investigation extended over a 13-week period, during which the participants were observed concerning HRV indices and musculoskeletal injuries while adhering to their customary Padel training protocols. The assessment of HRV indices was executed to ascertain the autonomic nervous system's response to a state of overload injury, while the Oslo Sports Trauma Research Center (OSTRC) Overuse Injury Questionnaire was administered to assess the prevalence of musculoskeletal overuse injuries, both at baseline and upon completion of the observational period. Utilizing a Paired Samples *t*-test analysis, the results indicated a statistically significant difference between pre- and post-test assessments, which illustrated that the observational cohort experienced a notable decline in HRV concomitant with an escalation in the incidence of musculoskeletal overuse injuries. Consequently, the findings imply that the monitoring of HRV responses may facilitate the early detection of overuse injuries, inform rehabilitation strategies, and advance return-to-sport protocols, thereby safeguarding and promoting the recovery of injured tissues.

Keywords: autonomic nervous system; overuse injuries; exercise; athletic performance; anatomy; physiology

1. Introduction

Padel currently stands as one of the most widely engaged sports globally, exhibiting a notable increase in the participation of amateur, semi-professional, and professional athletes in recent years [1]. This sport is characterized by its high-intensity nature, necessitating repeated physical actions that include directional changes, sprints, jumps, and variations in speed, thereby demanding considerable physical and technical resilience to meet these challenges [2]. Consequently, as the athlete population has expanded, there has been a corresponding rise in the incidence of injuries, observed not only within professional leagues but also at the semi-professional and amateur tiers [3]. Musculoskeletal injuries constitute a primary factor interrupting athletic participation, affecting both amateur and professional practitioners [4,5]. Among these injuries, those resulting from overtraining represent a significant classification, frequently linked to an excessive physical workload without sufficient recovery periods. Overtraining is characterized as a disjunction between the training load and the body's recuperative capabilities, potentially culminating in an accumulation of physiological and biomechanical strain, thereby amplifying the likelihood of injury [6–8].

Injuries associated with padel predominantly affect two joints: the knees, which are impacted by continuous changes in direction, and the shoulders, which endure the effects of rapid and repetitive ball impacts during gameplay [9]. The principal anatomical structures implicated include muscles, tendons, joints, and bones, with clinical manifestations ranging from minor muscle contractures to more intricate conditions such as tendinopathies, stress fractures, and chronic compartment syndromes [10]. The prevalence and detrimental consequences of overtraining injuries underscore the necessity for a robust monitoring mechanism that can effectively capture the dynamic adaptations of athletes in response to training stimuli [11,12]. Although injuries related to overtraining have been the subject of exhaustive research within specific sports disciplines, there remain significant deficiencies in the comprehension of the underlying pathophysiological mechanisms and predisposing factors, which encompass individual traits, training methodologies, and insufficient preventative measures [13].

The prevalent methodology for monitoring exercise and preventing injuries predominantly relies on physical performance metrics, which exhibit limitations in their capacity to forecast injuries across several critical dimensions [14]. Firstly, these metrics pertain to athletes' absolute strength, functional movement, agility, or speed parameters and fail to capture the longitudinal patterns of alteration in these indices over time [15]. Secondly, physical performance metrics adopt a linear framework that neglects to account for the progressive interplay of intrinsic and extrinsic risk factors as an athlete undergoes recurrent exposure to sports training and competition [16]. Lastly, these evaluative measures primarily center on biomechanics and do not establish a foundational assessment of the athlete's physiological preparedness to engage in the sport or to endure the training load. Consequently, the forecasting of the risk associated with overtraining injuries, when solely reliant on biomechanical evaluations, neglects the contributions of the systems engaged in the remodeling and reparative processes of somatic tissues, notably the Autonomic Nervous System (ANS) [17].

In this framework, extensive research has been conducted on both Heart Rate (HR) and Heart Rate Variability (HRV) in elite athletes to better understand the physiological responses regulated by the autonomic nervous system (ANS) in reaction to increased training loads [18–20]. HRV is recognized as a simple and non-invasive tool for assessing fluctuations in inter-beat intervals and autonomic nervous system activity. It is typically analyzed using linear techniques in time and frequency domains, as well as nonlinear methods [21]. HRV signifies the extent of oscillations surrounding the mean value of the cardiac rhythm, specifically the variability in durations between consecutive heartbeats [22]. This metric encapsulates the capability of the autonomic nervous system to acclimate to diverse stimuli and environmental conditions, being modulated by variables such as physical exertion, respiratory patterns, and emotional states [23]. Numerous studies have indicated that an elevation in parasympathetic dominance, as evidenced by increases in HRV, correlates with enhanced athletic performance [24–28]. Conversely, a reduction in HRV has been correlated with the physiological ramifications of ANS distress, which is evident in athletes exhibiting sustained maladaptive responses to training, commonly referred to as Overtraining Syndrome (OTS) [29–32]. Following a musculoskeletal injury, the inflammatory response represents a key physiological reaction, with the healing process being regulated through the ANS [33,34]. The ANS is pivotal in modulating blood flow, facilitating the transportation of metabolic compounds, and regulating the release of neuro mediators essential for mechanotransduction in injured tissues [35]. Additionally, increased baroreflex activity and the release of inflammatory mediators may contribute to nociceptor activation at the injury site [36]. As a result, an imbalance in the sympathetic and parasympathetic nervous systems may suggest the presence of an injury, typically manifesting as heightened sympathetic activity alongside diminished parasympathetic function, which in turn affects Heart Rate Variability (HRV) metrics [37].

With advancements in sports performance monitoring, HRV has gained recognition as a cost-effective and efficient tool for optimizing training strategies [38]. While some studies suggest that HRV-guided training may help prevent overload injuries, there remains a lack of robust empirical evidence to fully support this claim [39]. Therefore, the present study aims to investigate the potential role of HRV monitoring in detecting overtraining injuries among professional female padel athletes.

2. Materials and methods

2.1. Study design

The research extended over a duration of 13 weeks, during which the subjects were systematically observed concerning HRV indices and musculoskeletal injuries while engaging in their conventional padel training program (comprising 4 sessions per week, each lasting 3 h). This study was executed between February 2024 and May 2024, adhering strictly to the ethical principles outlined in the Helsinki Declaration and its subsequent revisions. The study protocol was reviewed and approved by the Department of Medical, Motor and Wellness Sciences-University of Naples "Parthenope" (DiSMMeB Prot. No. 88592/2024).

2.2. Participants

The study included a total of 66 female athletes, aged between 17 and 32 years (Mean age: 22.42 ± 3.89 SD), recruited from five professional padel clubs located in southern Italy. Eligibility criteria required participants to have at least three years of competitive experience at the national level. Conversely, individuals with a documented history of cardiorespiratory conditions or musculoskeletal injuries sustained within the past three months were excluded from the study. All participants were fully briefed on the study's objectives and provided written informed consent prior to participation. Their involvement was entirely voluntary, and confidentiality of their data was strictly maintained.

The sample size was determined using G*Power 3.1 (Heinrich-Heine-Universität Düsseldorf, Germany). A priori power analysis established that a minimum of 60 participants was necessary to achieve sufficient statistical power ($\alpha = 0.05$, $1-\beta = 0.80$) to detect a moderate effect size ($f = 0.25$ or 0.4) with a correlation coefficient of $p = 0.80$ at 95% power and $\alpha = 0.05$. It was utilized a mixed design that incorporates both within-subject and between-subject factors, where only the between-subject variability is reported after baseline changes are accounted for. To mitigate the impact of potential participant dropout and experimental attrition, a total of 66 individuals were enrolled in the study. All recruited participants met the inclusion criteria and were formally invited to take part in the research. Every selected individual provided informed consent and successfully completed the initial survey. Two weeks prior to the start of the program, participants received an email containing comprehensive details about the study.

2.3. Procedures

All individuals involved in the study were required to endorse an informed consent document to guarantee the privacy, confidentiality, and clarity of the data obtained. Following this, personal information—including name, birth date, and contact details—was gathered, along with the athlete's medical and sports history. At a minimum of two days prior to the intervention, subjects engaged in two evaluative sessions. The initial evaluation concentrated on the detection of overuse injuries, employing The Oslo Sports Trauma Research Center (OSTRC) Overuse Injury Questionnaire. The subsequent evaluation entailed a physiological assessment (HRV) aimed at gauging the autonomic nervous system's reaction to overload injuries. Participants completed both evaluations just before and after the observational period, allowing for the comparison of pre- and post-test results. Both initial and final assessments were conducted simultaneously during a fixed temporal interval while adhering to uniform experimental parameters. Each athlete was evaluated individually, with a thorough explanation of the procedures provided before participation.

2.4. Measures

2.4.1. Hearth rate variability

Heart Rate Variability (HRV) is a critical indicator used to examine variations in the intervals between consecutive heartbeats, also known as R-R intervals [40]. It serves as a valuable biomarker reflecting the functional status of both the physiological and psychological systems [41]. A consistently high HRV suggests a well-adjusted autonomic nervous system (ANS) capable of effectively responding to stressors, correlating with good health and optimal cognitive performance. On the other hand, lower HRV signals reduced ANS flexibility, which is associated with fatigue, stress, and overtraining [42].

In this research, HRV was monitored using the Polar H10 chest strap, chosen for its user-friendly design and practicality [38]. This device is particularly beneficial for field assessments where traditional ECG systems may not be feasible [43]. The accuracy of the Polar H10 was validated by Gilgen-Ammann et al. [44], both at rest and during physical activity. A comparison between the Polar H10 and a three-lead ECG Holter monitor revealed a small average discrepancy of 0.23 ± 26.8 ms in R-R intervals. Notably, the Polar H10 demonstrated excellent data reliability, capturing 99.6% of data, with a strong correlation ($r = 0.997$) between the two devices. Statistical analysis showed no significant difference between the two systems ($p = 0.208$).

Signal fidelity in relation to R-R intervals was assessed by analyzing the frequency of missed or incorrectly detected beats. During low to moderate-intensity exercises, the Polar H10 showed signal quality similar to the Holter monitor. However, at higher intensities, the Polar H10 outperformed the Holter, with only 74 errors in R-R interval detection (99.4% accuracy) compared to the Holter's 1332 errors (89.9% accuracy). Based on these findings, the Polar H10 is considered a reliable tool for measuring R-R intervals in athletic settings.

2.4.2. The oslo sports trauma research center overuse injury questionnaire (OSTRC-OIQ)

The Oslo Sports Trauma Research Center (OSTRC) Overuse Injury Questionnaire, as delineated by Clarsen et al. [45], comprises four inquiries pertinent to each anatomical region of interest, specifically knee, wrist, elbow, lower back, and shoulder, which were selected based on the epidemiological injury data available within Padel populations [46–48]. Each of the responses to the four inquiries was assigned a numerical value ranging from 0 to 25, which was subsequently aggregated to derive a severity score spanning from 0 to 100 for each identified overtraining issue [45]. The response values were structured such that a score of 0 indicates the absence of problems, while a score of 25 signifies the utmost severity for each respective inquiry. The values assigned to intermediate responses were carefully selected to ensure a relatively uniform distribution from 0 to 25, all while employing whole numbers. Consequently, inquiries 1 and 4 utilize a scoring system of 0-8-17-25, whereas inquiries 2 and 3 employ a scoring system of 0-6-13-19-25. The severity score serves as a quantitative measure of the implications associated with an overuse issue and can be employed to chart individual athlete responses, thereby facilitating the monitoring of overuse issues throughout the duration of a research study.

2.4.3. Statistical analysis

A priori power analysis was carried out using G*Power (3.1.9.2) to determine the necessary sample size, with the following parameters: effect size $d = 0.80$, $\alpha = 0.05$, and statistical power = 0.90. The analysis suggested that at least 60 participants were needed; however, to mitigate potential dropout and participant loss, a total of 66 individuals were recruited. The chosen effect size and related parameters were consistent with prior studies investigating changes in HRV during exercise interventions [49].

Descriptive statistics, such as mean and standard deviation, were calculated were derived for each variable subjected to examination. A Shapiro–Wilk test, which is a statistical method employed to evaluate the extent to which a given dataset conforms to a normal distribution, was meticulously utilized to examine the normality of the distribution of the data under consideration, and it is important to note that a p-value exceeding the threshold of 0.05 serves as a robust indicator that the data in question can be reasonably assumed to follow a normal distribution pattern, thereby reinforcing the validity of the assumptions underlying many parametric statistical analyses that may subsequently be performed on this dataset. A Paired Samples *t*-test was then conducted to examine differences between pre-test and post-test measurements, as the Shapiro–Wilk test confirmed normality. Results are presented as mean ± SD for variables with a normal distribution, while median (interquartile range) is reported for those that deviate from normality.

Furthermore, to facilitate the comparison between pre- and post-intervention assessments, Cohen's d was used to calculate the effect size, which is determined by dividing the mean change from baseline by the standard deviation. The interpretation followed these guidelines: < 0.20 (small), 0.20–0.79 (moderate), and > 0.80 (large) [27]. Effect size calculations were based on the eta squared statistic (η^2) and evaluated using the following criteria: small ($\eta^2p < 0.06$), medium ($0.06 \leq \eta^2p < 0.14$), and large ($\eta^2p \geq 0.14$). Furthermore, to assess the strength of the relationship between HRV and OSTRC-OIQ, Pearson's correlation coefficient was calculated.

All statistical analyses were performed using IBM SPSS Statistics 24 (IBM Corp, Armonk, NY, USA). A significance level of $\alpha = 0.05$ was applied to all tests.

3. Results

The two groups did not show any significant differences at baseline in terms of chronological age or anthropometric characteristics ($p > 0.05$), indicating that the groups were comparable at the start of the study. The findings acquired both preceding and following the observational timeframe for all relevant variables are represented in **Table 1**.

Table 1. Changes in HRV and OSTRC-OIQ after 13-weeks of observational study.

	Observational Group (*n* = 66)		
	Baseline	**Post-test**	**Δ**
HRV			
HR	61.92 (1.33)	76.65 (8.91) *	14.72 (9.82)
R-R	1027.58 (118.96)	680.97 (22.94) *	−346.70 (118.42)
OSTRC-OIQ			
Knee	10.81 (14.77)	32.40 (24.41) *	21.59 (22.93)
Wrist	14.69 (18.71)	51.35 (31.86) *	35.87 (32.41)
Elbow	10.80 (18.49)	61.63 (30.91) *	50.83 (29.57)
Lower back	11.24 (17.97)	24.33 (23.36) *	13.09 (14.50)
Shoulder	16.01 (20.91)	63.06 (30.00) *	47.04 (25.53)

Note: values are presented as mean (± SD); Δ: pre- to post-training changes; *Significantly different from pre-test ($p < 0.001$).

3.1. Hearth rate variability (HRV)

Heart Rate Variability (HRV) was evaluated by examining Heart Rate (HR) and the time intervals between consecutive heartbeats, referred to as R-R intervals. These time differences provide valuable information about the autonomic nervous system's control over heart function. The mean heart rate is an indicator of the overall balance between the sympathetic and parasympathetic nervous systems. To assess changes in HR and R-R intervals, a Paired Samples *t*-test was performed to compare the measurements taken before and after the intervention.

The results revealed that the observational group experienced a significant increase in HR ($t = 12.18$, $p < 0.001$, $d = 1.49$, large effect size), indicating a noticeable rise in cardiovascular activity. At the same time, there was a significant decrease in R-R intervals ($t = -23.78$, $p < 0.001$, $d = 2.92$, large effect size), which suggests a shortening of the time between heartbeats, likely reflecting a physiological adjustment to the intervention. These findings demonstrate substantial autonomic nervous system changes, showing the body's response to the intervention.

3.2. The oslo sports trauma research center overuse injury questionnaire (OSTRC-OIQ)

Regarding the incidence of overuse injury, it was calculated through the OSTRC-OIQ questionnaire. In the same way, a significant differences between pre- to post-test was also found for all the five variables of OSTRC-OIQ, specifically we found an increase of Knee injuries ($t = 7.64$, $p < 0.001$, $d = 0.94$, large effect size), Wrist injuries ($t = 9.48$, $p < 0.001$, $d = 1.17$, large effect size), Elbow injuries ($t = 13.96$, $p < 0.001$, $d = 1.71$, large effect size), Lower Back injuries ($t = 7.33$, $p < 0.001$, $d = 0.90$, large effect size), and Shoulder injuries ($t = 14.96$, $p < 0.001$, $d = 1.84$, large effect size).

3.3. Pearson's correlation

Correlation coefficients (Pearson's r) were computed to ascertain the associations between the reduction in HRV indices and the escalation in overuse injuries among female padel athletes. Statistically significant correlations among the examined variables were emphasized (See **Figure 1**).

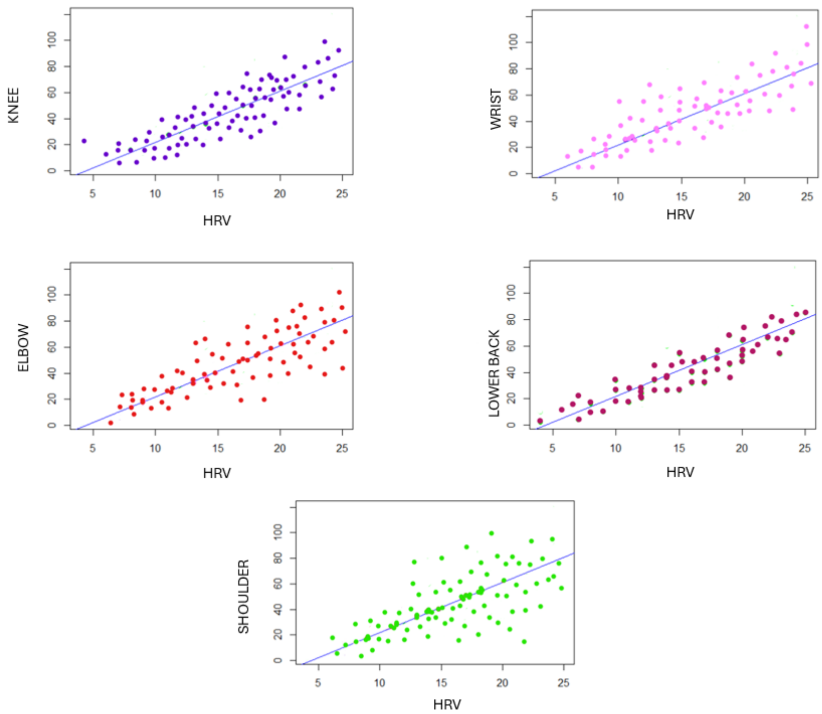

Figure 1. Person's correlation between variables under evaluation.

4. Discussion

The objective of this investigation was to examine the potential role of HRV monitoring in the identification of overtraining-related injuries among female professional padel athletes. Within the parameters of this research, the assessment of the sympathetic and parasympathetic nervous systems, which are two subdivisions of the ANS, through the analysis of HRV facilitates the recognition of potential non-traumatic musculoskeletal injuries at their incipient stages, thereby enabling timely intervention when the severity of the injury remains minimal, thus mitigating the duration of cessation from athletic activities [50].

A pivotal and noteworthy finding that emerged from the comprehensive analysis conducted in this study was the pronounced and substantial disparities that were meticulously observed between the results obtained from the pre-test assessments and those acquired from the subsequent post-test evaluations, indicating a notable decline in physiological markers related to cardiac function, particularly HRV and its components, such as heart rate and R-R intervals. This decline suggests that reduced Heart Rate Variability (HRV) may be linked to autonomic nervous system (ANS) dysregulation in athletes who exhibit prolonged maladaptive responses to training, a condition commonly referred to as overtraining syndrome (OTS) [51–54].

Given that atypical patterns have been documented in athletes who respond negatively to training stimuli, it is proposed that those experiencing cumulative musculoskeletal strain will exhibit HRV alterations at rest, reflecting a shift toward reduced parasympathetic activity and heightened sympathetic nervous system (SNS) activation [55–58]. When compared to an athlete's baseline HRV metrics, fluctuations in parasympathetic nervous system (PNS) and SNS activity may serve as indicators of whether an athlete is engaged in an ongoing physiological recovery process or is effectively adapting to training demands [59–64]. Moreover, when an athlete returns to training following an overuse injury, HRV assessment can provide insight into how external factors such as fatigue, nutrition, and stress influence recovery and the protection of affected tissues.

Numerous investigations have previously elucidated the significance of the ANS in the physiological response to musculoskeletal traumas [65–71]. When the equilibrium between the degradation of somatic tissues and the processes of repair is perturbed, resulting in an aberrant inflammatory response under conditions of mechanical loading, an escalation in ANS activity at the locus of injury may be necessitated [72–74]. Through complex communication networks involving the central nervous system (CNS) and the hypothalamic–pituitary–adrenal (HPA) axis, changes in autonomic nervous system (ANS) activity within peripheral tissues may be reflected in the modulation of Heart Rate Variability (HRV) indices. Afferent vagal neurons transmit information regarding somatic tissue injury to the cerebral cortex, which, in turn, activates efferent vagal fibers. This activation enhances blood circulation, supports the transport of metabolic substrates, and promotes the release of proinflammatory cytokines [75–78].

HRV serves as a highly effective and noninvasive methodology that is utilized for the comprehensive evaluation of the imbalances that can occur between the sympathetic and parasympathetic branches of the autonomic nervous system ANS

[79–81]. A noticeable reduction in HRV has been scientifically linked to the initial signs and symptoms of somatic tissue damage, which frequently manifests prior to the emergence of pain or the progression towards more significant injuries that may require medical intervention [82]. These significant findings are consistent with the research conducted by Jewson et al. [83], who established a correlation between fluctuations in HRV and the preliminary stages of tendinopathy, thereby suggesting that alterations in heart rate patterns may serve as an early warning signal for potential musculoskeletal disorders. This decrement was similarly documented by Lima-Borges et al. [84] in elite swimmers subjected to overtraining stimuli. Damage to somatic tissues incites activation of the ANS, characterized by heightened sympathetic engagement that governs the healing trajectory, which, in turn, results in diminished parasympathetic activity. In a comparable vein, Williams et al. [85] examined the interplay between HRV, training loads, and the susceptibility to overtraining phenomena among competitive CrossFit™ athletes. Daily resting HRV and and training intensities (session duration multiplied by rate of perceived exertion) were systematically documented over a 16-week period within a sample of six competitive CrossFit™ athletes.

Furthermore, Flores et al. [86] conducted a study examining the modifications within the autonomic nervous system following musculoskeletal injuries, employing Heart Rate Variability metrics derived from football players. The investigators proposed that a modification in Heart Rate Variability transpires after a musculoskeletal injury. They scrutinized the low-frequency/high-frequency ratio (LF/HF ratio), which acts as a measure of the overall sympathetic-vagal balance; in particular, an increase in the LF/HF ratio indicates heightened sympathetic activity alongside diminished parasympathetic activity, while a decrease in this ratio reflects an enhancement in parasympathetic activity coupled with a reduction in sympathetic activity. During their evaluation of the LF/HF ratio, the authors discerned statistically significant distinctions between the two temporal evaluations, noting reduced LF/HF ratio values following the injury, which subsequently tend to rise upon complete recovery. The findings of this investigation enabled the authors to assert that the longitudinal monitoring of Heart Rate Variability trends, in conjunction with workload assessments, can offer valuable insights into an athlete’s overarching loading patterns. Consequently, Heart Rate Variability monitoring may serve as an essential tool for professionals in tailoring and personalizing training load prescriptions, thereby mitigating the potential risk of injury resulting from overtraining.

The findings of the current investigation also facilitate the identification of a substantial correlation between Heart Rate Variability (HRV) and injuries to the elbow, shoulder, and wrist, which, in addition to being the most frequently occurring injuries in both professional and amateur padel athletes, exhibit the strongest associations with HRV modulation indices. The anatomical regions most frequently reported for overuse injuries in this investigation (elbow, shoulder, and wrist) align with established injury epidemiology literature in the context of padel [9,87–90]. The heightened response rate, alongside the recognition of injuries that did not impede the athletes’ training effectiveness (i.e., non-critical overuse injuries), suggests that the OSTRC-OIQ overuse injury questionnaire is a valuable tool for obtaining a comprehensive and nuanced insight into overuse injuries within this population.

However, further investigation involving larger sample sizes is essential before drawing definitive conclusions concerning the characteristics of overuse injuries in competitive padel.

HRV is affected by a variety of factors, including physiological and pathological conditions, neuropsychological components, non-modifiable traits, lifestyle behaviors, and environmental factors [91–94]. In the same way, the origin of injury is complex, multifactorial, and context-dependent, often shaped by a web of interconnected determinants [95–97]. For example, an increase in workload might lead to greater neuromuscular exhaustion, but the extent of this relationship could be influenced by lifestyle factors like occupational stress and sleep quality, as well as physical parameters such as aerobic fitness [98–100]. Consequently, the observation of trends in HRV may yield valuable insights into an athlete's developing overall pattern of injury or adaptation [101–103], which, when considered collectively, can be employed to optimally calibrate training regimens [104–107].

Although the current investigation augments our comprehension of HRV dynamics in the context of musculoskeletal injuries, several limitations were apparent within the framework of this study. The foremost limitation was associated with the relatively small sample size (N = 66), which stemmed from the difficulties faced in enlisting adequately motivated female padel players for participation. Additionally, the sample was exclusively derived from a population of athletes affiliated with five padel clubs located within a singular geographic area. As a result, the findings may exhibit restricted generalizability to athletes from diverse demographic backgrounds. Furthermore, another notable limitation of the present research was the absence of male participants, which hindered the exploration of gender differences and potentially diminished the applicability of these results to other athletic cohorts. A secondary limitation was linked to the failure to conduct a longitudinal analysis of HRV and other factors associated with musculoskeletal injuries. Moreover, certain conditions, such as stress and pain, remained beyond our control. Future research initiatives would be essential to investigate these aspects to clarify the intricacies of these variables. Finally, the incorporation of a control group would be beneficial to enhance the understanding of the relationship between HRV and overuse injuries. Nevertheless, the results obtained could provide valuable insights for subsequent studies. Indeed, the advantages of this research were to expand our understanding of HRV and to utilize this knowledge to identify early indicators of somatic tissue distress, thereby minimizing the downtime of athletes. Consequently, we advocate for future investigations (both longitudinal and/or experimental) that encompass a broader spectrum of musculoskeletal injuries and athletic disciplines.

5. Conclusion

The ANS constitutes one of the principal physiological systems engaged in the body's response to trauma and disease, with its byproducts exerting significant influence over hemodynamics, the transport of metabolic constituents, and the secretion of neuromodulators implicated in mechanotransduction. Consequently, if the emergence of somatic tissue damage or the active repair of tissue necessitates a heightened ANS response characterized by augmented blood flow and an increase in inflammatory neuromodulators, such alterations in ANS activity may be discernible through HRV indices. HRV possesses the capacity to yield a more precise representation of the physiological condition of healing tissues and their preparedness for the acceptance of mechanical loads. Analogous to the manner in which HRV has been effectively employed to formulate training regimens aimed at optimizing athletic performance while mitigating excessive fatigue, insights garnered from HRV indices may facilitate the early identification of overuse injuries, inform rehabilitation strategies, and guide the progression of return-to-sport protocols, thereby safeguarding and enhancing the recuperation of injured tissues. This proposed scenario would augment the precision of 'reloading' strategies within rehabilitation protocols, potentially enabling clinicians and coaches to ameliorate the adverse effects associated with previous injury risk factors on an athlete's reintegration into competitive play or training. Hence, the ongoing assessment of HRV responses may bolster practitioners' endeavors to achieve an optimal equilibrium between the risk of overuse injuries and ideal training trajectories. Future investigations should delve into the efficacy of "HRV-guided training" in alleviating the incidence of injuries, while larger-scale studies are essential to examine the prevalence and characteristics of overuse injuries among Padel athletes.

Author contributions: Conceptualization FL; methodology, FL and FT; software, FL and FT; validation, FL; formal analysis, FL; investigation, FL; resources, PL and FPC; data curation, FL and RMR; Bibliographical research, AP; writing—original draft preparation, FL; writing—review and editing, FL; supervision, PL and FPC; funding acquisition, FT. All authors have read and agreed to the published version of the manuscript.

Ethical approval: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Department of Department of Medical, Motor and Wellness Sciences-University of Naples "Parthenope" (DiSMMeB Prot. No. 88592/2024). Informed consent was obtained from all subjects involved in the study.

Conflict of interest: The authors declare no conflict of interest.

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