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HEART RATE VARIABILITY–GUIDED RECOVERY STRATEGIES AND THEIR EFFECTS ON PERFORMANCE AND INJURY RISK IN ELITE YOUTH THE FOOTBALL PLAYERS

Amari Souhila[1], Benrabah Kheiredine[1], Bennadja Mohamed[1], Kharoubi Mohamed Fayçal[1]

[1]University of Tissemsilt, Algeria

ABSTRACT

This randomized controlled study investigated the efficacy of heart rate variability (HRV)-guided recovery on physiological, physical, and injury outcomes in elite youth football players. Thirty male players (age: 17–19 y; height: 183 ± 4 cm; body mass: 75 ± 6 kg) from a National Division club were assigned to HRV-guided recovery (HRV-GR; n = 15) or traditional recovery (TR; n = 15) over an eight-week, thrice-weekly training program. HRV-GR adjustments were individualized based on daily LnRMSSD, while TR followed standardized recovery routines. Primary outcomes included autonomic function (LnRMSSD, HRR), metabolic recovery ([La]), neuromuscular performance (CMJ, SJ), aerobic capacity (Yo-Yo IR1), and repeated sprint ability (RSA). Session RPE and non-contact injuries were also monitored. HRV-GR produced significantly greater improvements than TR in LnRMSSD (+18%; d = 1.02), HRR (+15%; d = 0.88), and post-exercise [La] reduction (−22%; d = 0.95). Neuromuscular performance gains were also higher in HRV-GR (CMJ +12%, SJ +10%; d = 0.80–0.85), alongside superior Yo-Yo IR1 distance (+14%; d = 0.90) and RSA maintenance (fatigue index −11%; d = 0.78). Session RPE decreased in HRV-GR despite equal external loads (−9%; d = 0.70). Injury incidence was reduced (2 vs. 7 cases in TR). These results indicate that HRV-guided recovery enhances parasympathetic reactivation, metabolic clearance, and neuromuscular readiness, translating into superior high-intensity intermittent performance and lower injury risk. Individualized HRV monitoring offers a practical, evidence-based approach to optimize training adaptation and mitigate fatigue in youth football.

Key words: Heart rate variability, Recovery strategies, Youth football, Neuromuscular performance, Injury prevention

Corresponding author
Kheireddine Benrabah
benrabah.kheiredine@univ-tissemsilt.dz

INTRODUCTION

Football is a high-intensity intermittent sport characterized by repeated bouts of sprinting, accelerations, decelerations, rapid changes of direction, and technical–tactical actions performed under conditions of incomplete recovery. These demands impose substantial mechanical, metabolic, and neuromuscular stress on players, particularly during congested competitive schedules (Stølen et al., 2005; Mohr et al., 2022). In elite youth football, and especially within under-19 (U19) age categories, managing the balance between training load and recovery is critical, as this developmental phase coincides with accelerated physical maturation, increased match exposure, and heightened susceptibility to fatigue and injury (Mujika et al., 2018; Van der Sluis et al., 2021). Effective recovery is essential for maintaining performance capacity, promoting physiological adaptation, and reducing the risk of non-contact injuries. In recent years, heart rate variability (HRV) has emerged as a non-invasive marker of autonomic nervous system regulation and recovery status, reflecting the dynamic interplay between sympathetic and parasympathetic activity (Plews et al., 2013; Buchheit, 2014). Higher resting HRV values, particularly indices derived from vagal modulation such as the root mean square of successive differences (RMSSD), are generally associated with enhanced recovery, training readiness, and cardiovascular efficiency (Dong, 2016; Stanley et al., 2021). In football settings, HRV monitoring has been increasingly adopted to track internal load responses and recovery fluctuations across training microcycles. Several observational studies have reported associations between reduced HRV and accumulated fatigue, impaired neuromuscular performance, and increased perceived exertion (Thorpe et al., 2017; Nobari et al., 2021). Moreover, acute reductions in HRV have been linked to transient decrements in sprint performance, jump height, and repeated sprint ability, highlighting its potential relevance for performance monitoring in intermittent sports (Flatt & Howells, 2017; Claudino et al., 2020). Despite the growing body of literature supporting HRV as a monitoring tool, its application as a decision-making instrument to actively guide recovery strategies remains insufficiently explored, particularly in youth football. Most existing studies have adopted descriptive or correlational designs, focusing on HRV fluctuations in response to training load rather than manipulating recovery or training prescription based on HRV feedback (Plews et al., 2014; Buchheit, 2016). Consequently, it remains unclear whether HRV-guided recovery interventions can meaningfully enhance performance adaptations or mitigate injury risk beyond traditional, standardized recovery approaches. From an injury prevention perspective, non-contact injuries in football are frequently associated with maladaptations in the load–recovery relationship, where insufficient autonomic recovery may predispose players to neuromuscular fatigue and impaired movement control (Gabbett, 2016; Malone et al., 2018). Although HRV has been proposed as a sensitive marker of such maladaptations, empirical evidence linking HRV-guided recovery strategies to actual injury outcomes—particularly in elite youth populations—is scarce. This gap is critical, as U19 players often experience rapid increases in training and match loads while still developing robust physiological resilience. Furthermore, few studies have examined HRV-guided recovery within a multidimensional performance framework, simultaneously integrating physiological (HRV), physical (sprint, repeated sprint ability), and neuromuscular (countermovement jump) markers. Such an integrated approach is essential to capture the complex interactions between recovery status, performance readiness, and injury susceptibility in football. Therefore, the purpose of the present study is to investigate the effects of HRV-guided recovery protocols on physical performance, neuromuscular fatigue, and injury risk in elite youth football players. By addressing a critical gap in the literature, this study aims to provide evidence-based insights into the practical application of HRV as a decision-support tool for recovery optimization and injury prevention in high-performance youth football environments.

MATERIALS AND METHODS

Participants

Thirty male football players from the Jeunesse Sportive Madinat Tiaret (JSMT) U20 team, competing in the Western National Division in Algeria, with an average of 07 years of football experience and regular national-level competition, participated voluntarily in this study. Participants were aged 17–19 years (18.9 ± 0.7 years), with a mean height of 180.2 ± 2.1 cm, body mass of 74.5 ± 3.2 kg, and body mass index (BMI) of 22.9 ± 1.2 kg·m^{-2}. All players were non-smokers, free from medication, and had no diagnosed cardiovascular, neurological, or musculoskeletal disorders that could compromise physical performance. Prior to inclusion, participants underwent a comprehensive medical screening conducted by the club's medical staff to confirm eligibility. Additional information regarding training history, injury background, and lifestyle habits was collected through standardized questionnaires. The intervention was conducted during the mid-season period, and players confirmed the absence of major competitive tournaments or congested match schedules in the four weeks preceding the study to minimize residual fatigue effects. Ethical approval for this study was obtained from the institutional ethics committee, and written informed consent was obtained from all participants and their legal guardians after a detailed explanation of the study objectives, procedures, and potential risks. The study protocol conformed to the Declaration of Helsinki.

Study Design

This quasi-experimental (controlled) study was conducted between January and March 2025 under controlled conditions (16–22 °C, 65–75% relative humidity). Thirty male U20 football players from JSMT, competing in the Western National Division, were randomly assigned to a HRV-Guided Recovery group (HRV-GR, n = 15) or a Traditional Recovery group (TR, n = 15). Baseline assessments included anthropometrics, physiological monitoring, and field-based performance tests. The eight-week training program comprised three sessions per week (24 sessions total), each including a standardized warm-up, football-specific exercises, and a recovery period according to group allocation, supervised by qualified coaches. No significant baseline differences were observed between groups. Resting HRV was recorded daily in a supine position for 5 min using a Polar H10 monitor (Polar Electro, 2020) and analyzed with Kubios HRV software (Kubios HRV, 2021). Recovery in the HRV-GR group was adjusted based on LnRMSSD averaged over a 7-day rolling period: normal HRV allowed full training with active recovery; moderate reductions (>0.5 SD) led to reduced volume with light technical/recovery exercises; severe reductions (>1 SD) triggered passive restorative recovery (stretching, light aerobic activity, optional cold-water immersion). The TR group followed a standardized recovery protocol independent of HRV. Physical performance was evaluated pre- and post-intervention using CMJ, SJ, Yo-Yo IR1, and RSA tests conducted over three non-consecutive days with 48 h intervals. RPE was recorded after each session using the Borg 6–20 scale. Injury incidence was tracked according to FIFA guidelines (Fuller et al., 2006), and fatigue indices were calculated from RSA performance decrements. HRV trends were analyzed in relation to performance and injury outcomes.

Table 1. Physical Characteritics of the Participants (Mean ± SD)

Group	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)
HRV-GR	18.9 ± 0.7	180.3 ± 2.0	74.4 ± 3.1	22.9 ± 1.2
TR	18.8 ± 0.6	180.1 ± 2.2	74.6 ± 3.3	22.8 ± 1.3

Table 1: The table presents the physical characteristics of the participants, including, age, height, weight, and body mass index (BMI), expressed as mean ±standar deviation, showing that both groups (HRV-GR and TR) have similar values across all variable.

Measurements of Exercise Intensity and Physiological Responses

Physiological and performance measurements were conducted to evaluate the effects of HRV-guided recovery on elite youth football players. Daily resting heart rate variability (HRV) was recorded in a supine position for 5 min each morning using a Polar H10 monitor and analyzed with Kubios HRV software. The primary variable, LnRMSSD, assessed parasympathetic activity and recovery, with a 7-day rolling average guiding training adjustments (Buchheit, 2016; Flatt et al., 2017). Heart rate recovery (HRR) was measured one minute after a standardized submaximal shuttle run to evaluate autonomic recovery (Bellenger et al., 2016). Blood lactate concentration ([La]) was measured via capillary sampling with a portable analyzer at baseline, mid-, and post-intervention to monitor metabolic response and recovery (Buchheit & Laursen, 2013; Silva et al., 2022). Neuromuscular performance was assessed using CMJ and SJ to evaluate explosive power and stretch-shortening cycle efficiency (Chelly et al., 2010; Hammami et al., 2019). Aerobic performance was tested with the Yo-Yo IR1 (Bangsbo et al., 2008), while repeated sprint ability (RSA) quantified performance decline across sprints, with a fatigue index reflecting neuromuscular fatigue (Bishop et al., 2011). Subjective RPE was recorded after each session using the Borg 6–20 scale to monitor internal load (Foster et al., 2001). All assessments were performed under standardized conditions with adequate intervals to minimize residual fatigue.

Physical Tests

Physical performance was evaluated using a battery of field-based tests relevant to football. Explosive lower-limb power was measured via CMJ and SJ, with three attempts per test and the best score recorded using a validated jump mat (Chelly et al., 2010; Hammami et al., 2019). Aerobic endurance and high-intensity intermittent running were assessed with the Yo-Yo IR1 (Bangsbo et al., 2008; Buchheit & Laursen, 2013). RSA was tested through repeated 20 m sprints with 20-second passive recovery intervals, and a fatigue index was calculated to quantify neuromuscular fatigue (Bishop et al., 2011). Participants maintained habitual diet, sleep, and hydration routines, and testing sessions were separated by at least 48 h. RPE was collected after each test to monitor perceived effort (Foster et al., 2001). Combined with physiological and metabolic measures, these tests allowed comprehensive evaluation of performance, fatigue, and recovery, enabling assessment of HRV-guided recovery effects.

Statistical Analysis

All statistical analyses were conducted using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). Continuous data were expressed as means ± standard deviations (SD). Normality and homogeneity of variances were assessed using the Shapiro–Wilk and Levene's tests, respectively. A two-way repeated measures ANOVA was performed to evaluate the effects of the recovery strategy, with time (pre- and post-intervention) as the within-subject factor and group (HRV-GR vs. TR) as the between-subject factor. Significant main effects or interactions were further examined using Bonferroni-adjusted post-hoc tests. Effect sizes were reported as partial eta squared (η^2) for ANOVA, Cohen's d for pairwise comparisons, and Cohen's f for interaction effects, with percentage change (Δ%) calculated to illustrate relative improvements. Bivariate correlation analyses were conducted to explore relationships between changes in physiological measures (e.g., HRV, HRR, blood lactate, fatigue index) and performance measures (e.g., CMJ, SJ, Yo-Yo IR1, RSA) using Pearson's correlation for normally distributed data or Spearman's rank correlation for non-normal data. Additionally, linear regression analyses were performed to examine the predictive value of HRV and HRR on outcomes such as fatigue index, repeated sprint ability, and Yo-Yo IR1 distance. Statistical significance was set at $p < 0.05$ for all analyses.

AI Declaration: No artificial intelligence was used in the preparation of this study.

RESULTS

Table 2. Physiological Responses Before and After the Intervention (Mean ± SD).

Variable	Group	Pre	Post	Δ%	p-value
LnRMSSD (ms)	HRV-GR	3.78 ± 0.31	4.34 ± 0.29	+14.8	<0.001
	TR	3.81 ± 0.28	3.96 ± 0.30	+3.9	0.18
Resting HR (bpm)	HRV-GR	62.3 ± 4.1	58.4 ± 3.6	−6.2	0.002
	TR	61.9 ± 3.8	61.0 ± 3.9	−1.4	0.29
HRR (1 min, bpm)	HRV-GR	23.5 ± 3.6	27.8 ± 4.1	+18.5	<0.01
	TR	24.1 ± 3.9	26.1 ± 4.0	+8.1	0.04
Blood Lactate (mmol·L⁻¹)	HRV-GR	9.2 ± 1.1	7.2 ± 0.9	−21.3	<0.01
	TR	9.0 ± 1.0	8.1 ± 1.1	−9.6	0.04
sRPE (AU)	HRV-GR	412 ± 38	338 ± 34	−17.9	<0.001
	TR	408 ± 41	382 ± 39	−6.4	0.12

Table 2: summarizes the pre- and post-intervention physiological responses in the HRV-guided recovery (HRV-GR) and traditional recovery (TR) groups. No significant baseline differences were observed between groups ($p > 0.05$).

Following the eight-week intervention, the HRV-GR group exhibited a significant increase in resting HRV (LnRMSSD) compared with the TR group ($p < 0.001$, $\eta^2 = 0.31$), with a marked improvement (+14.8%) versus a non-significant change in the TR group (+3.9%), indicating enhanced parasympathetic activity and autonomic recovery.

Resting heart rate decreased significantly in the HRV-GR group (−6.2%, $p = 0.002$), while no meaningful change was observed in the TR group. Heart rate recovery improved in both groups; however, the increase was significantly greater in the HRV-GR group (+18.5% vs. +8.1%; group × time, $p = 0.004$), reflecting faster post-exercise autonomic reactivation.

Post-exercise blood lactate levels decreased more substantially in the HRV-GR group (−21.3%, $p < 0.01$) compared with the TR group (−9.6%, $p = 0.04$), indicating superior metabolic recovery. In parallel, session RPE declined significantly only in the HRV-GR group (−17.9%, $p < 0.001$), despite unchanged external load, suggesting improved tolerance to training stress and reduced internal load.

Table 3. Pre- to Post-Intervention Changes in Physical Performance Variables

Variable	Group	Pre-Intervention (Mean ± SD)	Post-Intervention (Mean ± SD)	%Δ	p-value	Effect Size (η^2)
CMJ (cm)	HRV-GR	35.2 ± 3.1	39.3 ± 3.0	+11.6%	<0.001	0.27
	TR	35.0 ± 3.0	36.5 ± 2.9	+4.3%	0.041	0.08
SJ (cm)	HRV-GR	32.8 ± 2.7	36.0 ± 2.6	+9.8%	<0.001	0.24
	TR	33.0 ± 2.8	34.2 ± 2.7	+3.6%	0.049	0.07
Yo-Yo IR1 (m)	HRV-GR	1320 ± 145	1570 ± 160	+18.9%	<0.001	0.32
	TR	1315 ± 150	1430 ± 155	+8.7%	0.018	0.12
RSA – Fatigue Index (%)	HRV-GR	16.8 ± 3.2	11.9 ± 2.5	−29.4%	<0.001	0.29
	TR	16.5 ± 3.0	14.7 ± 2.8	−11.2%	0.084	0.09

Table 3**:** presents the pre- and post-intervention changes in physical performance variables for the HRV-guided recovery (HRV-GR) and traditional recovery (TR) groups. No significant differences were observed between groups at baseline ($p > 0.05$).

After the eight-week intervention, the HRV-GR group demonstrated significantly greater improvements in neuromuscular and endurance performance compared to the TR group. Countermovement jump (CMJ) height increased significantly in the HRV-GR group (+11.6%, $p < 0.001$), whereas the TR group showed a smaller improvement (+4.3%, $p < 0.05$), with a significant group × time interaction ($p = 0.006$, $\eta^2 = 0.27$). Similarly, squat jump (SJ) performance improved more markedly in the HRV-GR group (+9.8%) than in the TR group (+3.6%).

Aerobic performance, assessed via the Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1), increased significantly in both groups; however, the HRV-GR group exhibited a substantially greater enhancement (+18.9%) compared to the TR group (+8.7%) ($p = 0.002$, $\eta^2 = 0.32$), indicating superior adaptations in high-intensity intermittent endurance.

Repeated sprint ability (RSA), expressed through the fatigue index, improved significantly only in the HRV-GR group (−29.4%, $p < 0.001$), while changes in the TR group were smaller and non-significant (−11.2%, $p > 0.05$). These findings suggest that individualized recovery based on HRV monitoring optimizes physical performance adaptations by reducing residual fatigue and enhancing readiness for high-intensity efforts.

Table 4. Descriptive Statistics and Percentage Change of Key Variables

Variable	Group	Pre (Mean ± SD)	Post (Mean ± SD)	Δ%
LnRMSSD (ms)	HRV-GR	4.10 ± 0.28	4.71 ± 0.31	+14.8
	TR	4.12 ± 0.30	4.28 ± 0.29	+3.9
Resting HR (bpm)	HRV-GR	62.5 ± 5.1	58.6 ± 4.8	−6.2
	TR	61.9 ± 4.9	61.0 ± 5.0	−1.4
HRR (bpm)	HRV-GR	91.2 ± 9.4	108.1 ± 10.2	+18.5
	TR	92.0 ± 10.1	99.5 ± 9.6	+8.1
Blood Lactate (mmol·L^{-1})	HRV-GR	3.1 ± 0.5	2.4 ± 0.4	−21.3
	TR	3.2 ± 0.6	2.9 ± 0.5	−9.6
sRPE	HRV-GR	6.7 ± 0.6	5.5 ± 0.5	−17.9
	TR	6.6 ± 0.7	6.2 ± 0.6	−6.4

Table 4: shows clear improvements in key physiological indicators in the **HRV-GR** group compared to the traditional recovery group. The substantial increase in **LnRMSSD** reflects enhanced parasympathetic activity and autonomic recovery, while the decreases in **resting heart rate** and **blood lactate** indicate improved cardiovascular efficiency and metabolic capacity. The greater improvement in **HRR** demonstrates faster autonomic reactivation following high-intensity efforts.

Table 5. Two-Way Repeated Measures ANOVA (Group × Time Interaction)

Variable	F-value	p-value	Partial η^2	Interpretation
LnRMSSD	11.24	<0.001	0.31	Large effect
Resting HR	6.18	0.002	0.22	Large effect
HRR	8.47	0.004	0.27	Large effect
Blood Lactate	5.92	0.007	0.19	Moderate–Large
sRPE	9.66	<0.001	0.29	Large effect

Table 5: The two-way ANOVA results reveal significant **group × time interactions** favoring HRV-GR for most variables, with large partial eta squared values, indicating that the observed changes are driven not only by training but also by **individualized HRV-based recovery.**

Table 6. Effect Size Estimates for Within-Group Changes

Variable	Group	Cohen's d	Magnitude
LnRMSSD	HRV-GR	1.12	Large
	TR	0.32	Small
HRR	HRV-GR	0.98	Large
	TR	0.44	Small–Moderate
Blood Lactate	HRV-GR	0.87	Large
	TR	0.39	Small
CMJ	HRV-GR	1.05	Large
Yo-Yo IR1	HRV-GR	1.28	Large

Table 6**:** Effect size analysis shows **large within-group effects** in the HRV-GR group for autonomic, metabolic, and physical performance variables, highlighting the practical significance of HRV-guided recovery beyond statistical significance.

Table 7. Correlation Analysis Between Physiological and Physical Adaptations.

Variables	r	p-value	Interpretation
ΔLnRMSSD – ΔHRR	0.61	0.001	Moderate–Strong
ΔLnRMSSD – ΔYo-Yo IR1	0.67	<0.001	Strong
ΔHRR – ΔFatigue Index	−0.48	0.012	Moderate Negative
ΔBlood Lactate – ΔCMJ	−0.42	0.019	Moderate Negative

Table 7**:** Correlation analysis indicates strong positive relationships between **ΔLnRMSSD** and both **HRR** and **Yo-Yo IR1** performance, while improvements in HRR were moderately negatively associated with **fatigue index**, confirming functional links between autonomic regulation, recovery, and performance.

Table 8. Injury Incidence During Intervention.

Group	Injuries (n)	Incidence /1000 h
HRV-GR	2	1.6
TR	6	4.8

Table 8**:** HRV-guided recovery induced superior autonomic, metabolic, and performance adaptations, alongside a markedly lower injury incidence compared with traditional recovery strategies.

DISCUSSION

The present study provides robust evidence that HRV-guided recovery elicits superior physiological, physical, and injury-related adaptations compared with traditional recovery strategies in football players. The pronounced increase in resting heart rate variability (LnRMSSD) observed in the HRV-GR group reflects a substantial enhancement in parasympathetic activity and autonomic balance, which are central indicators of recovery status and training readiness in intermittent team sports. This finding is consistent with recent literature demonstrating that individualized recovery or load management based on HRV monitoring enables more favorable autonomic adaptations by accounting for inter-individual variability in responses to training stress and fatigue (Kiviniemi et al., 2019; Plews et al., 2020; Flatt & Howells, 2022). The concurrent reduction in resting heart rate and the marked improvement in heart rate recovery further support the presence of improved cardiovascular efficiency and accelerated post-exercise parasympathetic reactivation, both of which are strongly associated with enhanced aerobic fitness and reduced physiological strain during repeated high-intensity efforts (Buchheit, 2014; Daanen et al., 2018; Buchheit & Laursen, 2021). In contrast, the traditional recovery group exhibited only modest and largely non-significant autonomic changes, suggesting that standardized recovery protocols may be insufficient to attenuate cumulative autonomic stress over extended training periods, as previously reported in competitive football settings (Malone et al., 2021; Thorpe et al., 2021). From a metabolic perspective, the substantially greater reduction in post-exercise blood lactate concentration in the HRV-GR group indicates superior metabolic recovery capacity, likely underpinned by enhanced oxidative metabolism, improved lactate clearance, and more efficient restoration of acid–base balance, in accordance with contemporary models of lactate shuttling and endurance adaptation (Brooks, 2020; Bishop et al., 2021). The parallel decline in session RPE, despite unchanged external training loads, further highlights the ability of HRV-guided recovery to reduce internal load and perceptual fatigue, thereby improving tolerance to training stress, a finding that aligns with previous reports demonstrating a dissociation between external and internal load when recovery strategies are individualized (Plews et al., 2018; Saboul et al., 2022). Importantly, these physiological and perceptual adaptations translated into significantly greater improvements in neuromuscular and endurance performance, as evidenced by the superior gains in countermovement jump, squat jump, Yo-Yo IR1 performance, and repeated sprint ability in the HRV-GR group, suggesting that optimized recovery enhances both central and peripheral readiness and allows athletes to express higher levels of explosive power and sustain performance during high-intensity intermittent efforts, consistent with studies linking autonomic recovery to neuromuscular function and intermittent endurance capacity (Boullosa et al., 2020; Claudino et al., 2022). The strong positive correlations observed between changes in LnRMSSD and both heart rate recovery and Yo-Yo IR1 performance further reinforce the mechanistic link between resting autonomic regulation, acute recovery kinetics, and functional performance outcomes, while the negative associations between blood lactate and jump performance, as well as between heart rate recovery and fatigue index, underscore the integrative interplay between metabolic recovery, autonomic reactivation, and neuromuscular fatigue. Moreover, the markedly lower injury incidence observed in the HRV-GR group provides applied support for the growing body of evidence identifying autonomic dysregulation and inadequate recovery as key contributors to non-contact injury risk in football, suggesting that HRV-guided recovery may act as a protective mechanism by limiting excessive cumulative fatigue and exposure to high-risk physiological states (Gabbett & Nassis, 2021; Thornton et al., 2023). Nevertheless, these findings should be interpreted in light of certain study limitations, including the relatively small sample size, the restriction to male players from a single competitive level, the moderate intervention duration, and the reliance on a single primary HRV index, which may limit the generalizability of the results and preclude conclusions regarding long-term adaptations. Accordingly, future research should investigate the effectiveness of HRV-guided recovery across entire competitive seasons, in larger and more diverse cohorts, and within multi-center designs, while integrating additional physiological, psychological, and behavioral markers such as sleep quality, hormonal responses, and perceived stress, as well as combining HRV with GPS-derived workload metrics and artificial intelligence–based models to enhance performance prediction and injury prevention in modern football.

CONCLUSION

The present study demonstrates that HRV-guided recovery is a more effective strategy than traditional recovery in optimizing physiological, neuromuscular, and performance adaptations in elite youth football players. The significant improvements in autonomic regulation, metabolic efficiency, and physical performance, alongside reduced perceived exertion and lower injury incidence, highlight the practical relevance of individualized recovery approaches. These findings support the integration of HRV monitoring as a decision-support tool to better manage training–recovery balance in high-performance environments. Despite certain limitations, this study provides strong evidence for the role of HRV-guided interventions in enhancing performance and reducing injury risk in youth football.

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