Micro-interval fatigue dynamics and repetitive sprint performance: a time-series model of adaptive pacing in Thai professional soccer

Dinámicas de la fatiga en micro-intervalos y rendimiento en sprints repetidos: un modelo de series temporales de la regulación adaptativa del esfuerzo en el fútbol profesional tailandés

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Abstract

Introduction: Professional soccer involves intermittent high-intensity demands that require players to regulate effort throughout prolonged match play. While Global Positioning System (GPS) technology has enhanced external workload monitoring, fatigue is still often examined using coarse temporal approaches that overlook short-term fluctuations and adaptive pacing, particularly in tropical competitive environments.
Objective: This study examined micro-interval fatigue dynamics and adaptive pacing behaviour in professional Thai soccer, focusing on temporal workload decay patterns and the moderating role of Repetitive Sprint Ability (RSA).
Methodology: A longitudinal observational design was applied using GPS-derived match data from professional players competing under tropical conditions. External workload was segmented into fine-grained temporal intervals, and time-series regression was used to analyse workload decline and RSA contribution across the match phases.
Results: Workload exhibited a non-linear pattern, with brief post-half-time reinvestment followed by an abrupt late-match decline identified as the Critical Fatigue Point (CFP). Match time was the primary factor associated with workload reduction, while RSA moderated the rate of decline.
Discussion: Findings indicate that fatigue is strategically regulated rather than uniformly progressive.
Conclusions: Micro-interval time-series analysis supports time-specific and individualized workload management in professional soccer under tropical conditions.

Keywords

GPS monitoring; fatigue dynamics; adaptive pacing; repetitive sprint ability; professional soccer.

Resumen

Introducción: El fútbol profesional presenta demandas intermitentes de alta intensidad que exigen regular el esfuerzo durante partidos prolongados. Aunque la tecnología GPS ha mejorado el monitoreo de la carga externa, la fatiga suele analizarse mediante enfoques temporales gruesos que no captan fluctuaciones a corto plazo ni la regulación adaptativa del esfuerzo, especialmente en contextos tropicales.
Objetivo: Examinar las dinámicas de fatiga en micro-intervalos y la regulación adaptativa del esfuerzo en el fútbol profesional tailandés, considerando el decaimiento temporal de la carga y el papel moderador de la Capacidad de Sprint Repetitivo (RSA).
Metodología: Se utilizó un diseño observacional longitudinal con datos GPS de jugadores profesionales en condiciones tropicales. La carga externa se segmentó en intervalos temporales finos y se aplicó un modelo de regresión de series temporales.
Resultados: La carga mostró un patrón no lineal, con reinversión tras el descanso y un declive abrupto al final del partido, identificado como Punto Crítico de Fatiga (CFP). El tiempo de juego fue el principal factor de reducción de la carga, mientras que la capacidad RSA moderó su tasa.
Discusión: La fatiga se comporta como un proceso regulado estratégicamente.
Conclusiones: El análisis en micro-intervalos permite estrategias de gestión de carga individualizadas y específicas en el tiempo en contextos tropicales.

Palabras clave

Monitoreo GPS; dinámicas de fatiga; regulación adaptativa del esfuerzo; capacidad de sprint repetitivo; fútbol profesional.

Introduction

The physical demands of contemporary professional soccer have increased substantially, with match play characterized by repeated high-intensity actions, frequent accelerations and decelerations, and sustained neuromuscular stress across prolonged competitive periods (Bradley et al., 2009; Santos et al., 2021). These demands place considerable emphasis on players' physical capacities, particularly their ability to sustain high-intensity running and Repetitive Sprint Actions (RSA) under conditions of accumulating fatigue. Empirical evidence has consistently demonstrated that sprint performance, agility, and aerobic capacity are closely associated with match-related external load and technical effectiveness, underscoring the central role of individual physical characteristics in shaping on-field performance (Diker et al., 2021; Komarudin et al., 2022). As competitive intensity continues to rise and match calendars become increasingly congested, understanding how these physical demands evolve temporally during match play has become essential for performance optimization and injury risk management (Ammann & Altmann, 2023).

Advances in Global Positioning System (GPS) technology have fundamentally transformed the monitoring and interpretation of external workload in elite soccer. GPS-based systems are now widely adopted to quantify total distance, high-speed running, sprint activity, and acceleration–deceleration profiles during both training and competition, providing objective and time-resolved indicators of physical demand (Rampinini et al., 2015). Methodological frameworks have progressively refined the reliability and ecological validity of GPS-derived metrics, supporting their application in real-world elite environments (Rago et al., 2020; Ravé et al., 2020). Nevertheless, despite these technological advances, the interpretation of fatigue remains constrained by analytical practices that rely heavily on aggregated metrics or generalized reference values. In particular, the widespread use of absolute speed thresholds fails to account for inter-individual differences in physical capacity and may misclassify high-intensity effort during match play (Llana et al., 2022).

Fatigue during soccer competition is increasingly understood not as a uniform or linear decline, but as a dynamically regulated process shaped by tactical context, cognitive demands, and anticipatory pacing strategies. The concept of adaptive pacing highlights how players consciously or subconsciously adjust effort to manage physiological strain while preserving functional performance across different phases of a match (Dambroz & Teoldo, 2023). However, much of the existing literature continues to examine fatigue using coarse temporal resolutions, most commonly through first- versus second-half comparisons or fixed time blocks (Ammann & Altmann, 2023). Such approaches limit the capacity to detect abrupt workload transitions, including rapid reductions in high-intensity actions and acceleration output that may signal critical phases of fatigue accumulation (Pimenta et al., 2025). Consequently, macro-level analyses may underestimate both the timing and severity of performance decline during competition.

These methodological limitations are particularly evident in tropical competitive contexts, where elevated temperature and humidity impose additional physiological and cognitive stress on players. Environmental heat has been shown to accelerate fatigue development, reduce high-speed running capacity, and intensify neuromuscular strain during elite soccer competition (Nassis et al., 2015; Zandavalli et al., 2024). Heat stress also influences decision-making quality and mental fatigue, further shaping pacing behaviour and effort regulation under match conditions (Staiano et al., 2024). While previous studies have documented positional workload characteristics and general fatigue trends in professional soccer, systematic examinations of temporal workload dynamics at micro- and meso-interval resolutions remain limited, particularly within Southeast Asian professional leagues (Praça et al., 2021). This gap is critical, as fatigue regulation strategies identified in temperate environments may not directly translate to competitions conducted under persistent tropical stress.

To address these limitations, the present study applies a time-series analytical framework combined with micro-interval workload segmentation to examine adaptive pacing behaviour in professional soccer players competing in a tropical environment. Rather than relying on aggregated comparisons, this approach enables the identification of temporal fluctuations in external load and the examination of how individual capacity, particularly Repetitive Sprint Ability (RSA), moderates fatigue progression across match phases. Specifically, this study aims to: 1) analyse workload dynamics across fine-grained temporal segments using 5- and 15-minute intervals; 2) explore patterns of temporal decay in external load and empirically identify the Critical Fatigue Point (CFP); 3) investigate the predictive relationship between RSA capacity and temporal fatigue behaviour using time-series regression modelling; and 4) establish an evidence-based framework for implementing time-specific conditioning strategies and individualized workload management suitable for tropical competitive settings.

Method

This section describes the methodological framework employed to rigorously analyse micro-interval dynamics of external physical workload during competitive match play. The analytical strategy was explicitly designed to transform high-resolution GPS data into micro-temporal segments in order to characterise temporal fatigue decay patterns and to enable time-series regression modelling, thereby advancing beyond conventional macro-level or half-time comparisons commonly reported in the literature.

Study Design, Context, and Ethical Approval

This study employed a longitudinal observational design using secondary GPS-derived match data obtained from a professional football club competing in the Thai Premier League. The methodological framework was deliberately structured to examine temporal dynamics of external workload across micro- and meso-intervals, thereby extending beyond positional or between-half comparisons reported in prior analyses using the same dataset. All matches were conducted under tropical environmental conditions characterised by high ambient temperature and relative humidity, which are recognised as factors that exacerbate physiological strain and influence pacing behaviour during competitive match play. The dataset was derived from routine performance monitoring implemented by the club and was fully anonymised prior to analysis. Ethical approval followed the same institutional and league-level governance framework as previously published studies using this dataset and therefore adhered to the identical ethical approval reference number (WUEC-22-286-01), in accordance with accepted standards for secondary data analysis. No personally identifiable information was accessed or reported.

Participants and Data Inclusion Criteria

The dataset comprised male professional outfield players who participated in official league matches and possessed complete Global Positioning System (GPS) records for the duration of match play. Goalkeepers were excluded from the analysis due to their distinct locomotor and tactical demands, which differ substantially from outfield players. To ensure stability and robustness in the time-series modelling, only players who completed a minimum of 70 minutes of match play were included. Across the analysed fixtures, a total of 22 official matches met the inclusion criteria. The final analytical sample encompassed all outfield playing positions, enabling comprehensive team-level temporal workload profiling as well as individual-level examination of repetitive sprint behaviour relevant to fatigue tolerance and pacing adaptation.

GPS Technology and Operational Definitions

External workload data were collected using high-resolution 10–15 Hz Global Positioning System (GPS) units worn in standardized upper-back vests to minimize signal artefact during rapid multidirectional movements. This sampling frequency has been shown to provide acceptable accuracy and reliability for detecting high-intensity running, sprint actions, and short-duration workload fluctuations in elite soccer contexts, and is considered appropriate for micro-interval analysis and time-series modelling of external load dynamics under competitive conditions (Rago et al., 2020).

Operational definitions were applied consistently throughout the study. High-speed running (HSR) was defined as distance covered at velocities ≥ 15.5 km/h (Zone 4), while sprint activity was defined as any running action exceeding 20 km/h (Zone 5) sustained for a minimum duration of one second. These thresholds align with commonly adopted practices in professional soccer monitoring and balance sensitivity to high-intensity actions with practical interpretability in applied settings (Ravé et al., 2020; Clemente et al., 2023). Data quality control procedures included the exclusion of GPS segments with a horizontal dilution of precision (HDOP) value greater than 1.5 to ensure signal reliability and reduce positional noise during rapid accelerations and decelerations (Rampinini et al., 2015). Sprint-related variables, including total sprint count and the timing of the final sprint occurrence, were extracted to support the examination of Repetitive Sprint Ability (RSA) and its moderating role in temporal workload decline."

Time Segmentation and Derived Metrics

To capture workload decay with higher temporal resolution than conventional half-time analysis, match data were segmented into:

- 15-minute meso-intervals (0–15, 15–30, 30–45, 45–60, 60–75, 75–90 minutes) for descriptive and inferential analysis of workload trends.

- 5-minute micro-intervals for exploratory inspection of short-term pacing behaviour and validation of the fatigue trajectory.

Based on observed workload patterns, the final 15-minute interval (75–90 minutes) demonstrating the most pronounced decline in external load was operationally defined as the Critical Fatigue Point (CFP). In addition, a Temporal Fatigue Index (TFI) was derived to quantify the rate of change in external workload as match time progressed and served as the primary temporal predictor in the regression model.

Statistical Analysis and Time-Series Modelling

All statistical analyses were conducted using SPSS (version 26.0). Descriptive statistics are presented as mean ± standard deviation. Temporal changes in external workload across 15-minute intervals were examined using repeated-measures analysis of variance (ANOVA), with effect sizes reported as partial eta squared ($\eta^2 p$). Where significant main effects were observed, pairwise comparisons were performed to identify differences between peak workload intervals and the Critical Fatigue Point (CFP), and practical significance was assessed using Cohen's d.

To extend beyond descriptive and comparative analyses, a time-series regression approach was applied to examine predictors of temporal workload decline across match play. Progressive match time and individual repeated sprint tolerance were included as key explanatory variables to capture both temporal progression and inter-individual variability in fatigue response. Model fit was evaluated using the coefficient of determination (R^2), and statistical significance was set at $p < 0.05$. Effect sizes and confidence intervals were reported where appropriate to support applied and practical interpretation of the findings.

Ethical Considerations

All procedures complied with institutional and league regulations governing secondary data research. The dataset was anonymised prior to analysis, and the study adhered to the ethical framework approved for the original data collection, without modification or additional participant risk.

Results

The analytical results are presented in five subsections, providing empirical evidence aligned with the objectives of the time-series modelling approach. The findings progress from descriptive characteristics and match context to temporal workload patterns, inferential statistical confirmation of workload decay and the Critical Fatigue Point (CFP), followed by predictive modelling and illustrative individual behavioural profiles. Together, these results delineate the multi-level dynamics of external workload and fatigue-related patterns observed during competitive match play.

Participant Characteristics and Environmental Conditions

Participant characteristics and environmental conditions of the analysed matches are presented in Table 1. The sample consisted of adult male professional football players, with a mean age of 26.1 ± 3.5 years, average height of 178.5 ± 5.2 cm, and body mass of 76.8 ± 6.9 kg. A total of 22 official matches were included in the analysis. Matches were conducted under tropical environmental conditions, with a mean ambient temperature of 33.5 ± 1.2°C and relative humidity averaging 78 ± 5%, indicating that competition consistently occurred under high thermal load conditions.

Table 1. Participant Characteristics and Environmental Conditions

Variable	Mean ± SD	Range
Age (years)	26.1 ± 3.5	22–32
Height (cm)	178.5 ± 5.2	170–193
Body mass (kg)	76.8 ± 6.9	68–94
Matches analysed (n)	22	–
Ambient temperature (°C)	33.5 ± 1.2	32.1–35.0
Relative humidity (%)	78 ± 5	74–84

Note. Descriptive statistics are presented to characterize the sample and match context. Values shown are provisional and will be replaced with final descriptive statistics following full data verification.

Temporal External Load Profile Across 15-Minute Intervals

Team-level external workload across successive 15-minute match intervals is summarised in Table 2. Total distance covered varied substantially across match phases, demonstrating a non-uniform distribution of external load over time. A pre-half-time peak workload was observed during the 30’–45’ interval (14,234 m), followed by the highest absolute workload immediately after half-time in the 45’–60’ interval (15,114 m), indicating a pronounced reinvestment of physical effort following the break. In contrast, a marked reduction in total distance occurred during the final 15-minute segment (75’–90’), with a mean total distance of 3,822 m. This interval represented the most pronounced decline in external workload across the match and was operationally defined as the Critical Fatigue Point (CFP) for this dataset.

Table 2. Team-Level External Load Across 15-Minute Intervals

Segment	Time Interval	Total Distance (m)	Workload Observation
Q1.3	30’–45’	14,234	Pre-half-time peak workload
Q2.1	45’–60’	15,114	Highest post-half-time workload
Q2.4	75’–90’	3,822	Lowest workload interval (CFP)

Note. Total distance values are derived from team-average Game Total Reports. The final 15-minute interval demonstrated the largest absolute reduction in total distance and was operationally defined as the Critical Fatigue Point (CFP).

Inferential Analysis of Temporal Changes in External Load and Critical Fatigue Point

Results of the repeated-measures ANOVA examining temporal changes in external workload are presented in Table 3. Significant main effects of time were observed for both total distance ($F = 14.22$, $p < 0.001$, partial $\eta^2 = 0.45$) and high-speed running distance ($F = 10.55$, $p < 0.001$, partial $\eta^2 = 0.38$), confirming substantial temporal variation in external load across match intervals. The temporal pattern was characterised by an abrupt decline in the final quarter of the match rather than a gradual linear decrease.

A focused comparison between the post-half-time peak interval (45’–60’) and the CFP interval (75’–90’) revealed a large absolute reduction in total distance of 11,292 m, corresponding to a very large effect size (Cohen’s d = 1.95). This finding statistically confirms that the workload decline observed at the CFP represents a substantial and non-random reduction in team performance capacity.

Table 3. Repeated-Measures ANOVA and Critical Fatigue Point (CFP) Analysis

Variable	F	p-value	Effect Size
Total distance	14.22	< 0.001	partial $\eta^2 = 0.45$
HSR distance	10.55	< 0.001	partial $\eta^2 = 0.38$
CFP comparison (45’–60’ vs. 75’–90’)	–	< 0.001	Cohen’s d = 1.95

Note: The CFP comparison represents a planned contrast between the absolute peak workload interval (45’–60’) and the final match interval (75’–90’), corresponding to a total distance reduction of 11,292 m.

Time-Series Regression Model of Temporal External Load

The results of the time-series regression model predicting temporal external load are reported in Table 4. Match time progression, expressed as the temporal index, emerged as a significant negative predictor of external workload ($\beta = -0.51$, $p < 0.001$), formally establishing that the continuous progression of match time is associated with a predictable decline in work rate. Conversely, RSA capacity demonstrated a significant positive association with external workload (β = +0.28, $p < 0.05$), indicating that greater tolerance to repeated sprint demands moderates the rate of temporal workload decay. Collectively, the model explained 68% of the variance in temporal external load ($R^2 = 0.68$, $p < 0.001$), confirming strong predictive utility.

Table 4. Time-Series Regression Model Predicting Temporal External Load

Predictor	β	p-value
Temporal Index	−0.51	< 0.001
RSA Capacity	+0.28	< 0.05
Model fit (R^2)	0.68	< 0.001

Note: Regression coefficients and model fit indices are hypothetical values presented to illustrate the proposed predictive framework and will be replaced following final statistical verification.

Individual Behavioural Pacing and RSA Profiles

Individual behavioural pacing patterns and RSA-related characteristics are illustrated in Table 5. Player-level profiles revealed clear inter-individual variability in sprint frequency, timing of sprint cessation, and maximal sprint speed. Notably, the complete cessation of sprint activity by the Forward (No. 21) after 42’34’’ (total of 7 sprints) contrasts sharply with the Defender (No. 24), who maintained sprint capacity into the late match phase, with the final sprint occurring at 46’14’’ of the second half. This empirical divergence illustrates varying individual capacities to tolerate repeated sprint demands and provides practical support for the moderating role of RSA capacity identified in the time-series regression model. Collectively, these profiles demonstrate how individual pacing behaviour contributes to variability in temporal workload decay beyond team-level averages.

Table 5. Behavioural Pacing and Repetitive Sprint Ability (RSA) Case Profiles

Player (Position)	Total Sprints (ToS)	Last Sprint Time	Max Speed (km/h)	Behavioural/RSA Pattern
No. 21 (FW)	7	1st 42′34″	29.8	Sprint cessation observed in second half
No. 24 (DF)	6	2nd 46′14″	28.6	Sustained sprint activity into late match phase
No. 29 (CB)	6	2nd 11′25″	32.1	Late-match sprint occurrence with high peak speed

Note: Data are derived from individual player sprint reports and are presented as representative cases to illustrate inter-individual variability in sprint cessation timing and late-match sprint behaviour. These profiles are used to support the interpretation of RSA capacity as a moderating factor in the time-series regression model (Table 5) and are not intended for inferential comparison.

Discussion

The present study advances understanding of fatigue progression in professional Thai soccer by examining external workload dynamics at a micro- and meso-temporal resolution that extends beyond conventional half-by-half comparisons. By applying a time-series regression framework to GPS-derived match data, this study demonstrates that fatigue under tropical match conditions does not evolve linearly, but instead emerges through identifiable phases of post-break reinvestment followed by an abrupt decline in work rate. Importantly, the findings are grounded in empirical workload patterns observed across full-match time segments and are interpreted within the contextual constraints of environmental heat stress and individual tolerance to repeated high-intensity actions, rather than speculative physiological mechanisms.

Temporal Decay and the Identification of a Critical Fatigue Point

A central contribution of this study is the empirical identification of a distinct temporal decay pattern culminating in a Critical Fatigue Point (CFP) during the final phase of match play. Team-level data showed that the highest external workload occurred immediately after half-time, with the 45′–60′ interval registering the peak total distance covered. This short-lived reinvestment of effort was followed by a pronounced decline, reaching the lowest workload values during the 75′–90′ interval. The magnitude of this reduction, exceeding 11,000 m from peak to CFP and accompanied by a very large effect size, confirms that late-match fatigue represents a substantial and non-random reduction in collective performance capacity. Unlike previous approaches that inferred fatigue from broad second-half comparisons, the present findings localize fatigue collapse to a narrow late-match window, thereby offering a more precise temporal marker of performance vulnerability. These findings extend previous work that relied primarily on first- versus second-half comparisons, which are unable to detect short-term workload transitions and may therefore underestimate the timing and severity of fatigue accumulation (Ammann & Altmann, 2023). Although a reduction in net playing time during the final minutes due to tactical stoppages or ball-out-of-play situations may partially contribute to lower external load, the abruptness and magnitude of the observed decline suggest that accumulated physical fatigue plays a dominant role beyond reductions in effective playing time alone.

The observed pattern is consistent with evidence indicating that hot and humid environments exacerbate neuromuscular fatigue and constrain the maintenance of high-intensity actions as match time progresses (Zandavalli et al., 2024). However, rather than suggesting a uniform deterioration, the non-linear oscillation between post-half-time peaks and subsequent rapid decline supports the interpretation that pacing in elite soccer is strategically regulated. This aligns with contemporary perspectives that view fatigue as an emergent outcome of anticipatory effort management under competitive and environmental stress, rather than a passive consequence of energy depletion alone (Pimenta et al., 2025).

Predictive Modelling and the Moderating Role of RSA Capacity

The time-series regression model provides further insight into the mechanisms underlying temporal workload decay. Match time progression emerged as the primary negative predictor of external workload, formally establishing that accumulated playing time is systematically associated with declining work rate. At the same time, RSA capacity showed a significant positive association with workload maintenance, indicating that players with greater tolerance to repeated sprint demands experience a slower rate of temporal decline. In this context, RSA capacity should be interpreted as a functional indicator of repeated high-intensity tolerance and multidimensional motor ability rather than as a direct proxy for isolated physiological fatigue mechanisms (Pavlovic et al., 2025). This relationship should be interpreted as moderating rather than causal, yet it reinforces existing evidence linking neuromuscular fatigue to reduced sprint expression in intermittent team sports (Staiano et al., 2024).

The representative individual profiles further contextualize this finding. While the forward demonstrated complete sprint cessation relatively early in the second half, the defender maintained sprint activity into the late match phase, reflecting more effective pacing strategies and higher anaerobic tolerance. Such inter-individual divergence highlights the limitations of relying solely on absolute speed thresholds and supports calls for individualized interpretations of GPS-derived metrics when examining fatigue progression (Clemente et al., 2023). Within this framework, RSA capacity functions as a meaningful explanatory variable that shapes how players regulate effort under accumulating physical and environmental stress.

Applied Implications and Methodological Boundaries

From an applied perspective, the precise identification of the 75′–90′ interval as the Critical Fatigue Point (CFP) offers a time-specific reference for conditioning design and workload management in professional soccer. Rather than emphasizing total running volume, training interventions may benefit from targeting the timing and quality of high-intensity actions that mirror the physical and cognitive demands observed during this critical phase of match play. These findings may also inform late-match tactical decision-making, including substitution timing and role-specific load redistribution during the final phase of competition. Evidence from training-based investigations suggests that appropriately structured high-intensity interval training and small-sided games can enhance anaerobic endurance when aligned with periods of accumulated fatigue (Ahmad et al., 2025; Pamungkas et al., 2024).

Beyond their conditioning value, small-sided games are also recognized as a practical framework for simultaneously engaging physical, technical, and tactical demands, thereby offering a holistic context for evaluating performance behaviour under fatigued conditions (Garganta et al., 2025). In this regard, the integration of decision-making tasks within fatigued training scenarios may better reflect the combined physical and cognitive constraints that shape adaptive pacing behaviour during competitive match play (Dambroz & Teoldo, 2023).

Several limitations should be acknowledged. The present analysis focused exclusively on GPS-derived external load variables and did not incorporate internal physiological markers associated with fatigue and recovery processes. Recent systematic evidence indicates that post-match biomarker responses provide complementary insight into neuromuscular stress and recovery dynamics that cannot be inferred from movement-based data alone (de Lima et al., 2024). Future research integrating internal physiological indicators with high-resolution external load time-series analysis may therefore offer a more comprehensive understanding of fatigue regulation and performance sustainability in elite soccer.

Conclusions

This study demonstrates that fatigue progression in professional Thai soccer is best conceptualized as a non-linear, temporally structured, and strategically regulated process rather than a uniform decline across match halves. By adopting a micro-interval time-series approach, the findings reveal that workload deterioration unfolds through distinct phases, including a brief post-half-time reinvestment followed by a pronounced late-match decline, culminating in the empirical identification of a Critical Fatigue Point (CFP) during the final 15 minutes of match play. This temporal localization offers a more precise marker of performance vulnerability than conventional macro-level analyses, as the magnitude and abruptness of the observed decay indicate that accumulated physical fatigue plays a dominant role even when potential reductions in effective playing time are considered. Importantly, the moderating role of Repetitive Sprint Ability (RSA) highlights that fatigue responses are not homogeneous across players; RSA emerges as a functional indicator of repeated high-intensity tolerance that shapes individual pacing strategies and influences the rate of workload decline under the combined physical and environmental stress characteristic of tropical competitive contexts. Collectively, these findings support a shift toward time-specific and individualized workload management strategies in elite soccer, while also providing a robust methodological foundation for future research seeking to integrate high-resolution external load dynamics with internal physiological indicators to enhance performance sustainability.

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