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Hydration Status and Thermal Stress as Predictors of Fatigue and Performance Decline in Sub-Elite Soccer Players

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Abstract

Background. Soccer players competing in tropical climates experience combined dehydration, thermal strain, and metabolic stress, yet field-based evidence linking these factors to performance decline remains limited.

Objectives. This study aimed to examine the predictive relationships between hydration status, thermal stress, metabolic factors, and fatigue-related performance decline in sub-elite soccer players under tropical heat conditions.

Materials and Methods. Thirty male sub-elite soccer players (22.4 ± 3.1 years) participated in a simulated 90-minute match conducted in temperatures ranging from 31 to 33°C, with relative humidity levels between 65 and 75%. Hydration (bioimpedance), blood lactate, muscle temperature, heart rate, shooting accuracy, and anaerobic power (RAST) were assessed pre-, mid-, and post-match. Repeated-measures ANOVA and multiple regression were used ($p < 0.05$).

Results. TBW decreased significantly (−4.2%), while lactate (1.3 → 10.4 mmol·L^{-1}) and muscle temperature (33.4 → 37.1°C) increased across match segments ($p < 0.001$). Shooting accuracy (−14%) and peak anaerobic power (−4.6%) declined post-match. Regression analysis identified ΔTBW ($\beta = -0.41$, $p = 0.008$) and peak lactate ($\beta = 0.48$, $p = 0.003$) as significant predictors of fatigue ($R^2 = 0.61$).

Conclusions. The findings indicate that loss of hydration, thermal strain, and metabolic accumulation are all important signs of a subject's deterioration in performance levels under tropical match conditions. Athletes can improve their health and performance by drinking enough fluids and keeping their body temperature under control.

Keywords: hydration status, thermal stress, fatigue, anaerobic performance, tropical environment.

Introduction

The interaction of multiple physiological factors has a significant impact on soccer performance, particularly in hot and humid weather conditions. In tropical climates, athletes often endure compounded stress from dehydration, elevated muscle temperature, and metabolic accumulation, all of which expedite fatigue and diminish technical precision (Périard et al., 2021; Pellicer-Caller et al., 2023). This issue is especially important for players in Southeast Asia, where the temperature often rises above 30°C and the humidity rises above 70%. This problem puts a constant strain on their ability to regulate their body temperature during training and competition (Che Muhamed et al., 2016).

Research indicates that even mild dehydration (2–3% of body mass loss) can result in considerable reductions in aerobic endurance, cognitive function, and neuromuscular control (Armstrong et al., 2025; Casa et al., 2015). Elevated muscle temperature (>37°C) has been shown to hinder neuromuscular coordination and increase perceived exertion, thereby diminishing motor accuracy and skill execution (Sébastien Racinais et al., 2017; Flouris et al., 2015; Raj et al., 2021). At the same time, a high level of lactate in the blood during short bursts of high-intensity exercise indicates that anaerobic glycolysis is working harder, which accelerates metabolic fatigue and limits the body's ability to perform repeated sprints (Hafidz et al., 2025; Cairns & Lindinger, 2025). Even though these relationships are well-known, the combined effect of hydration status, thermal stress, and metabolic indicators on fatigue and performance decline during realistic match simulations is still not well understood, especially in sub-elite soccer players who don't always have access to advanced recovery and hydration monitoring systems (Chapelle et al., 2020; Nuccio et al., 2017).

Nonetheless, limited adoption of field-based experimental designs exists that concurrently monitor various physiological indicators during simulated match play in authentic tropical settings (Edwards & Clark, 2006; Gibson et al., 2019). Additionally, recent studies have predominantly concentrated on elite or professional players, leading to a gap in research regarding sub-elite populations that constitute the developmental basis of regional and university leagues (Plakias et al., 2024). These athletes frequently face similar training demands without adequate medical and environmental support systems, which may intensify the detrimental effects of heat and dehydration on their performance (Mohr et al., 2005). Consequently, it is essential to address these knowledge gaps to develop effective monitoring and intervention strategies that improve athlete readiness, reduce fatigue, and promote ongoing participation in sports.

Despite extensive laboratory evidence on dehydration, hyperthermia, and metabolic stress, field-based studies simultaneously examining their combined predictive power on fatigue and performance decline under authentic tropical match conditions remain scarce. Previous research has typically isolated single physiological variables, lacked ecological validity, or focused primarily on elite players. The present study addresses this research gap by integrating multidimensional physiological monitoring with performance testing during a realistic simulated match. The scientific novelty lies in identifying the simultaneous contribution of hydration status, thermal strain, and metabolic accumulation to fatigue-related performance decline in sub-elite players, a population that is underrepresented yet highly exposed to tropical environmental stressors.

Investigating the predictive relationships between hydration status, thermal stress, metabolic factors, and fatigue and performance decline in sub-elite soccer players exposed to tropical heat is the primary objective of this study. Specifically, this study aimed to (1) quantify temporal variations in hydration, lactate concentration, and muscle temperature during a simulated match; (2) evaluate their respective effects on technical accuracy and anaerobic performance; and (3) determine which physiological variables most accurately predict the fatigue response. It is hoped that this research will contribute to the development of evidence-based hydration and thermal management protocols that enhance the safety and performance of athletes competing in hot environments. Furthermore, it also supports global efforts to achieve SDG 3, ensuring healthy lives and promoting well-being through safe and effective sports participation.

Materials and Methods

This research employed a quasi-experimental quantitative design to examine the physiological interactions among hydration status, heart rate, blood lactate, and muscle temperature concerning the onset of fatigue in sub-elite soccer players competing in a hot environment. The study utilized a purposive randomized one-group pretest–posttest design to investigate the causal effects and predictive relationships among the variables in field-based conditions, thereby ensuring significant ecological validity.

Study Participants

The study involved thirty male soccer players from UNESA FC, categorized as sub-elite athletes participating in regional and university leagues, and supervised by the Sport and Exercise Research Center at Universitas Negeri Surabaya (UNESA). All participants were between the ages of 18 and 30, had at least 10 years of organized training experience, and trained regularly 4 to 6 times a week, doing both technical-tactical and conditioning programs. We chose this group of people on purpose because sub-elite athletes have performance profiles that are similar to those of professionals but often don't have advanced systems for managing hydration and recovery, especially in hot and humid conditions.

The purposive sampling technique was employed to select participants for this study based on the following inclusion criteria: (1) being an active athlete at UNESA FC during the 2025 competition season, (2) not having any musculoskeletal injury or medical contraindication in the preceding three months, (3) being capable of performing maximal physical exercise without the risk of cardiovascular complications, and (4) providing informed consent by agreeing and signing. Before the experiment, the team doctor checked the health of all the participants by measuring their resting heart rate, blood pressure, and body composition using bioelectrical impedance analysis (BIA).

Before signing the informed consent form, each participant got a clear verbal and written explanation of the study's purpose, protocol, and possible risks or benefits. This study received formal institutional authorization from the Sport & Exercise Research Center (SERC), Universitas Negeri Surabaya. The research protocol was reviewed and approved through the institutional permission letter numbered 146892/UN38.III.2/TU.00.00/2025, issued on 28 August 2025. All procedures conformed to the ethical principles of the Declaration of Helsinki, and written informed consent was obtained from all participants prior to data collection. The study took place at the UNESA Sports Complex, where the temperature was kept between 31 and 33 degrees Celsius and the relative humidity was kept between 65 and 75 percent. The research facility was a realistic setting for soccer performance in tropical climates.

Study Organization

The experimental procedure was methodically organized into six consecutive phases: preparation, warm-up, first-half simulation, halftime recovery, second-half simulation, and post-match evaluation, concluding with a brief recovery monitoring session. This organization made sure that the methods were strict, the environment was stable, and the physiological and performance data could be repeated in real-world settings. All trials took place at the UNESA Sport

Complex in Surabaya, Indonesia, where the temperature ranged from 31 to 33 degrees Celsius and the humidity ranged from 65 to 75 percent. This condition is typical of a tropical match environment (Bouscaren et al., 2021; Périard et al., 2021).

At 6:00 a.m., all participants gathered for medical screening, informed consent, and getting to know the testing tools and the environment. The session lasted about 60 minutes, during which time they measured resting heart rate and other body measurements. This step made sure that each subject met the requirements for inclusion and understood how the experiment would work. After that, there was a 10-minute dynamic warm-up (jogging, mobility, and stretching) and baseline testing. The pre-test battery measured heart rate (HR-pre), hydration status (pre), muscle temperature (pre), blood lactate concentration (pre), shooting accuracy (pre), and anaerobic power using the Running-based Anaerobic Sprint Test (RAST-pre). To reduce fatigue effects prior to the main protocol, participants subsequently engaged in a 60-minute passive rest period before the next phase.

A training simulation for the first half of the game was done to match the physical demands of competitive soccer. Participants engaged in 45 minutes of soccer-specific intermittent running, divided into three 15-minute segments consisting of 30-second sprints (90–95% HRmax), 90-second jogging intervals (65–75% HRmax), and 120-second walking recovery periods. Heart rate was continuously monitored, and Ratings of Perceived Exertion (RPE) were documented at the conclusion of each block to maintain a consistent workload and perceived effort (Drust et al., 2000; Stone & Oliver, 2009). After the first half, the participants were given controlled rehydration (3–5 mL/kg body weight) and a 15-minute rest period to recover. Measurements taken in the middle of the test, like HR (middle), hydration (middle), muscle temperature (middle), and blood lactate (middle), were used to see how well the body was recovering and how much heat it was making.

The second half was a repeat of the first half, with short-distance running and tactical drills like short passes and recovery sprints. This half also lasted 45 minutes, and the players' heart rates and RPE were constantly recorded to show how fit and strong they were. As soon as the second half was over, the participants took a post-match fatigue test. This test measured their hydration (post), muscle temperature (post), blood lactate (post), shooting accuracy (post) (Dambroz et al., 2022), and RAST performance (post) to see how fatigue affected their performance (Hafidz et al., 2025).

Finally, the recovery monitoring phase included 10 minutes of passive sitting rest, during which HR, lactate, and muscle temperature were continuously monitored to assess the acute recovery response following exercise-induced heat stress. All physiological and performance evaluations adhered to the standardized measurement schedule delineated in Fig. 1 and table 1, thereby ensuring methodological reliability and reproducibility.

A digital thermometer-hygrometer (Testo 608-H2, Germany) was used to keep an eye on the environment during the experiment to make sure the thermal exposure was always the same. According to current sports hydration guidelines, players' hydration levels were adjusted based on

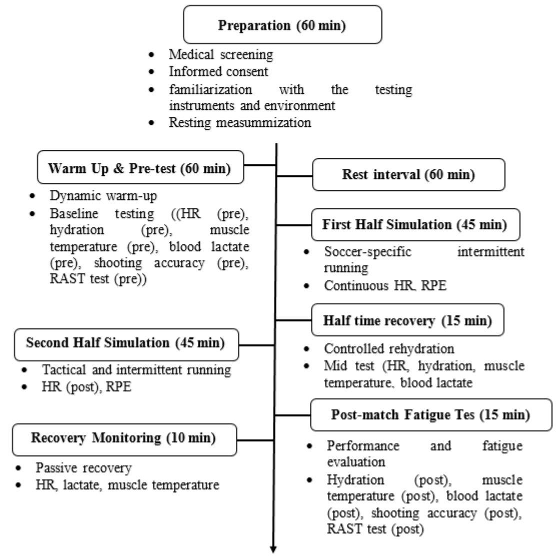

Fig 1. Experimental Design and Sequence of Physiological and Performance Measurements During the Simulated Soccer Match Protocol

their weight loss, and rehydration volumes were set at 3–5 mL/kg of body weight (Ceylan & Santos, 2022; Fernández-Álvarez et al., 2022; Klimesova et al., 2022). Real-time heart rate data was sent to make sure that training loads were between 85 and 95 percent of each person's HRmax, which was found using the Karvonen formula (She et al., 2015).

Fingertip capillary sampling was used to get blood lactate samples (20 μL) at three times: before, during, and after. To make sure that surface temperature recording was accurate, a contact thermistor was placed over the muscle belly of the gastrocnemius medialis to measure muscle temperature (Flouris et al., 2015; Raj et al., 2021). Certified sport scientists and physiologists from the Sport & Exercise Research Center at UNESA oversaw the data collection to make sure that the process was consistent and valid.

Measurement

We used standardized operational procedures to measure all physiological and performance variables. This was done to confirm that the results were reliable, valid, and reproducible, in line with international sport science measurement protocols (Batterham & Hopkins, 2015; Sirotic & Coutts, 2008). All measurements were taken in controlled environmental conditions (ambient temperature 31–34°C; relative humidity 65–75%), and certified technicians from the Sport and Exercise Research Center at Universitas Negeri Surabaya calibrated all the devices before they were used.

We used a portable analyzer (InBody 370S, Seoul, Korea) to measure hydration levels using the bioelectrical impedance analysis (BIA) method. Data collection for this study was conducted in three phases (pre-exercise, mid-exercise, and post-exercise). The system calculated total body water (TBW) and the extracellular to intracellular fluid ratio with participants standing on a BIA barefoot and with dry feet. These data were then expressed as a percentage change in hydration status. To ensure accuracy, athletes avoided

Table 1. Phased Organization of Experimental Procedures and Corresponding Physiological Measurements in the Simulated Soccer Match

Phase	Activity	Description	Duration	Measurements Collected
Preparation	Orientation, medical screening, and familiarization	Participants assembled at 06:00 a.m. for medical check-up, informed consent, and familiarization with the testing instruments and environment under controlled thermal conditions.	60 min	Resting HR, anthropometric profile
Warm-up & Pre-test	Dynamic warm-up and baseline testing	10-minute dynamic warm-up (jogging, stretching, and mobility drills) followed by baseline assessments to establish pre-exercise physiological values.	60 min	HR (pre), hydration (pre), muscle temperature (pre), blood lactate (pre), shooting accuracy (pre), RAST test (pre)
Rest Interval	Passive rest period	To eliminate residual fatigue from pre-testing and ensure physiological stability before the main simulation.	60 min	—
Exercise Simulation – First Half	Soccer-specific intermittent running	3 × 15-min running blocks alternating 30 s sprint (90–95% HRmax), 90 s jogging (65–75% HRmax), and 120 s walking recovery. RPE recorded after each block.	45 min	Continuous HR, RPE
Halftime Recovery	Controlled rehydration and mid-test	15-min passive recovery with rehydration (3–5 mL/kg BW). Mid-test data recorded to assess thermal and hydration response.	15 min	HR (mid), hydration (mid), muscle temperature (mid), blood lactate (mid)
Exercise Simulation – Second Half	Tactical and intermittent running	Repetition of first-half protocol integrated with tactical drills (short-passing and sprint recovery tasks) to simulate match intensity.	45 min	HR (post), RPE
Post-match Fatigue Test	Performance and fatigue evaluation	Post-exercise testing for physiological and skill-related fatigue indicators.	15 min	Hydration (post), muscle temperature (post), blood lactate (post), shooting accuracy (post), RAST test (post)
Recovery Monitoring	Passive recovery and assessment	10-min seated recovery with continuous monitoring of physiological restoration following exercise-induced thermal stress.	10 min	HR, lactate, muscle temperature

food and caffeine two hours before the test and emptied their bladders thirty minutes beforehand (Sampieri et al., 2024). Pre- and post-exercise weight measurements allowed us to determine fluid loss, and we adjusted the rehydration rate between 3 and 5 mL/kg body weight, following current sports hydration guidelines (Ceylan & Santos, 2022; Fernández-Álvarez et al., 2022).

A Polar H10 telemetry sensor (Polar Electro, Kempele, Finland) was used to monitor heart rate in real time and continuously throughout the protocol. Data were collected at one-second intervals and displayed as a percentage of each individual's HRmax, which was determined using the Karvonen formula (HRmax = 220 – age) and adjusted for resting HR (She et al., 2015). HR was measured at the start of exercise, during the first and second halves of exercise, and after exercise to evaluate exertional response and recovery. Mean and maximum heart rates were used as indicators of internal load and cardiovascular strain (Dimkpa et al., 2023; Schneider et al., 2018).

Fingertip samples (20 µL) taken with a sterile lancet were used to measure capillary blood lactate concentration at three different times: before, during, and after exercise. The Roche Cobas Accutrend Plus (Roche Diagnostics, Germany) was used for analysis. This device provides fast and accurate readings in less than one minute. To reduce contamination, the first drop of blood was discarded, and subsequent drops were placed on a lactate strip according to the manufacturer's instructions. This method allows for measurement of the anaerobic glycolytic response and the level of metabolic exhaustion (Beneke et al., 2011; Kafrawi et al., 2025).

We used a digital contact thermistor (Testo 608-H2, Germany) to monitor the local muscle temperature. It was placed at the gastrocnemius medialis muscle belly of the dominant leg. We measured how the body reacts to heat over time before the warm-up, after the first half, and after the match. To keep the sensor from moving, hypoallergenic medical tape was used to hold it in place. This technique yields accurate noninvasive assessments of intramuscular temperature fluctuations during thermal stress (Flouris et al., 2015; Raj et al., 2021)

A standardized soccer shooting accuracy protocol was used to test shooting accuracy. This protocol was made to test technical precision and motor control degradation caused by fatigue in sub-elite players. The test took place on a soccer field that was the right size and had a FIFA-approved ball (size 5, weight 420–445 g) and a standard goal (7.32 × 2.44 m). There was a target scoring grid in the goal area that split the surface into six scoring zones: two central zones for low-precision areas and four corner zones (upper-left, upper-right, lower-left, and lower-right) for high-precision areas. Following the performance scoring model set up by Dörge et al. (2002) and Lees & Nolan (1998), each target zone was given a point value from 1 to 5, with higher points for shots that hit the upper corners and lower points for shots that hit the middle.

To reduce learning bias, each participant attempted 10 penalty shots from a distance of 11 meters, randomly alternating between their dominant and non-dominant feet (Ali et al., 2007; Izovska et al., 2016). Prior to the test, the players performed a standard 5-minute technical warm-up that included controlled passing and shooting to help them become accustomed to handling the ball. Participants were instructed to shoot accurately while maintaining the pace of the game. A high-speed digital camera (240 fps, Sony RX10 IV, Japan) was mounted 5 meters behind the ball at a right angle to the ball to record each shot. This procedure was performed to allow for later visualization of the shot placement and trajectory.

All trials were conducted twice—before exercise (pre-test) and immediately after the second half of the simulation (post-test)—to evaluate the effect of exercise-induced fatigue on technical shooting performance. To ensure consistency, all sessions used the same ball, shooting surface, and weather conditions. To minimize recovery bias, the interval between attempts was set at 20 seconds (Rampinini et al., 2009). This approach has been supported by prior research, showing high intra-class correlation coefficients (ICC = 0.88–0.93) for shooting accuracy and consistency within soccer-specific scenarios (Ali et al., 2007; Marques et al., 2011). Using both accuracy percentage and point-weighted indices allows for a more comprehensive assessment of performance, capturing both spatial accuracy and motor control decline caused by fatigue (Dambroz et al., 2022; Ferraz et al., 2012).

Anaerobic endurance was evaluated using the Running-Based Anaerobic Sprint Test or RAST test. This test involves six maximum sprints over a distance of 35 meters, with each sprint interspersed with a ten-second passive recovery period. All sprints were conducted on a standard indoor track, and participants were instructed to exert their maximum effort during each sprint. Sprint times were recorded with a stopwatch, and anaerobic power variables (peak power, average power, and fatigue index) were calculated according to the standard RAST protocol (Wibowo et al., 2025).

Immediately after each 15-minute simulated exercise segment, participants evaluated their perceived exertion using the Borg Rating of Perceived Exertion (RPE) Scale (6–20) (Williams, 2017). They were asked to rate how intense they perceived the game to be, which serves as a subjective measure of internal load and psychological strain, in addition to physiological data (Inoue et al., 2022). We used a Testo 608-H2 digital thermo-hygrometer to monitor ambient temperature and relative humidity throughout the test. These measurements ensured a stable environment. Data were recorded every five minutes and maintained within a target range (31–34°C; 65–75% RH). This monitoring helped ensure that all sessions accurately mimicked actual tropical conditions (Akerman et al., 2016; Helmer et al., 2025; Xu et al., 2022).

Statistical Analysis.

A priori power analysis was performed using G Power 3.1 to determine the minimum required sample size. For repeated-measures ANOVA with three measurements (pre-, mid-, post-test), an effect size of $f = 0.30$ (medium), $\alpha = 0.05$, and power $(1-\beta) = 0.80$ indicated a minimum required sample of $N = 24$. The final sample ($N = 30$) exceeded this threshold, ensuring adequate statistical power. This study used IBM SPSS Statistics version 25.0 and Microsoft Excel 2016 for data validation and visualization. All analyses were performed at a significance level of $p < 0.05$. We carefully checked the data to ensure accuracy and completeness. The Mahalanobis distance method was used to identify any potential outliers and prevent data distortion. Descriptive statistics were calculated for all dependent and independent variables, including hydration status, heart rate, blood lactate, muscle temperature, and fatigue index. The Shapiro–Wilk test assessed normality, while the Levene test verified homogeneity of variance. Paired-sample t-tests analyzed intra-group variation over time for parametric data sets. Repeated-measures ANOVA was used to evaluate the overall impact of time and interaction effects on physiological variables. When the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied. Multivariate analysis of variance (MANOVA) tested multivariate interactions among physiological indicators, and the Pearson product-moment correlation coefficient (r) assessed the strength and direction of correlations among continuous physiological variables. Additionally, a multiple linear regression analysis was performed with the fatigue performance score as the dependent variable and hydration percentage change, mean heart rate, peak lactate level, and mean muscle temperature as predictors..

Results

Thirty male soccer players from UNESA FC who were not considered elite volunteered to participate in the study. The average age of the group was 22.4 ± 3.1 years, the average height was 173.6 ± 5.2 cm, the average weight was 68.1 ± 6.1 kg, and the average duration of training was 10.8 ± 1.9 years. Participants attended between four and six training sessions each week, which included technical, tactical, and conditioning exercises led by certified coaches. We measured an average resting heart rate of 64.8 ± 3.7 bpm while participants rested in a thermoneutral environment (room temperature 32.1 ± 0.8°C; relative humidity 70.3 ± 3.5%). The positional distribution was three goalkeepers (10%), nine defenders (30%), twelve midfielders (40%), and six forwards (20%). This reflects the typical composition of a university soccer team in Indonesia. The participants' body size and physiological profile generally resembled that of sub-elite tropical athletes who frequently compete in hot weather.

Prior to inferential analysis, all data were examined to ensure compliance with statistical assumptions. The Shapiro–Wilk test verified that all physiological and

Table 2. Temporal Changes in Physiological Parameters (Hydration, Blood Lactate, and Muscle Temperature) Across the Match Simulation

Variable	Pre	Mid	Post	p (Time Effect)	Partial η^2
Total Body Water (L)	42.6 ± 1.9	41.2 ± 1.9	40.8 ± 2.0	<0.001	0.79
Blood Lactate (mmol·L-1)	1.3 ± 0.2	6.7 ± 0.8	10.4 ± 0.9	<0.001	0.88
Muscle Temperature (°C)	33.4 ± 0.3	35.4 ± 0.7	37.1 ± 0.4	<0.001	0.83

performance variables exhibited normal distribution ($p > 0.05$), while Levene's test indicated homogeneity of variance across time points ($p > 0.05$). These findings support the application of parametric tests, such as paired t-tests and repeated-measures ANOVA, for data analysis.

Descriptive statistics showed a clear temporal trend throughout the simulated soccer match. Total body water (TBW) gradually decreased from pre-test to post-test (42.6 ± 1.9 → 40.8 ± 2.0 L), indicating dehydration during the session. Blood lactate concentration increased sharply (1.3 ± 0.2 → 10.4 ± 0.9 mmol·L^{-1}), indicating a significant increase in anaerobic metabolism. During the match, muscle temperature continued to rise (33.4 ± 0.3 → 37.1 ± 0.4136 °C), indicating that the body struggled to maintain a stable temperature.

Repeated-measures ANOVA validated significant main effects of time on all three physiological variables (Table 2). The analysis showed a big effect size for TBW ($F_{(2,58)} = 39.7$, $p < 0.001$, $\eta^2_p = 0.79$), blood lactate ($F_{(2,58)} = 76.4$, $p < 0.001$, $\eta^2_p = 0.88$), and muscle temperature ($F_{(2,58)} = 52.6$, $p < 0.001$, $\eta^2_p = 0.83$). These findings indicate that the match simulation protocol successfully produced dehydration, metabolic accumulation, and thermal load similar to competitive match conditions in a tropical environment.

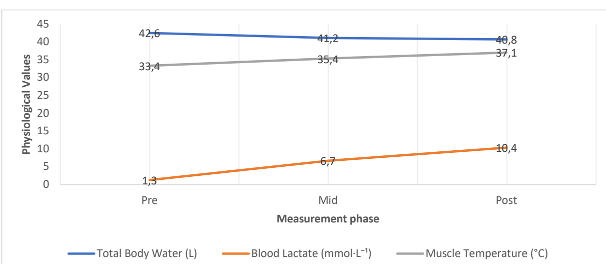

Fig 2. Temporal Changes in Physiological Parameters During Match Simulation

The η^2_p value (0.79–0.88) indicates a large effect size, reflecting strong temporal changes across the simulated matches. The assumption tests suggest that the parametric analysis is suitable, and the combined descriptive and inferential results indicate that the experimental protocol led to significant physiological changes. These alterations in hydration, metabolism, and temperature lay the groundwork for understanding future performance-related outcomes. The next section examines how high levels of cardiovascular strain and perception directly impact players' technical accuracy and anaerobic power after the simulated matches.

Cardiovascular response data indicate that participants maintained a high physiological load throughout the simulated matches. The mean relative heart rate was 86.7 ± 3.2% HRmax, and the peak heart rate was 95.1 ± 2.1% HRmax. These data indicate that the players worked near their anaerobic threshold for most of the session. The Borg RPE scale, which measures subjective exertion, showed a large spike between the first and second halves of the match. Mean RPE increased from 13.9 ± 1.2 to 17.1 ± 1.0, confirming an increase in physiological fatigue over time ($t_{(29)} = 9.84$, $p < 0.001$, Cohen's $d = 2.75$). This increase in perception was accompanied by increases in heart rate and metabolic variables, indicating a synchronized pattern of cardiovascular strain and perception throughout the simulated competition.

Table 3. Cardiovascular and Perceptual Responses During the First and Second Halves of the Simulated Match.

Variable	First Half	Second Half	$t_{(29)}$	p	Cohen's d
Mean HR (%HRmax)	86.7 ± 3.2	—	—	—	—
Peak HR (%HRmax)	95.1 ± 2.1	—	—	—	—
RPE	13.9 ± 1.2	17.1 ± 1.0	9.84	< 0.001	2.75

These results confirm that the training protocol successfully induces prolonged, high-intensity cardiovascular stress, consistent with match conditions. Substantial increases in perceived exertion further illustrate the players' cohesive physiological assessment of their effort as the session progresses. After determining the level of performance decline, the next step involved analyzing the interrelationships between changes in physiological parameters and identifying those most closely associated with fatigue.

Performance analysis revealed significant declines in technical and anaerobic skills following the match simulation (Table 4). Shooting accuracy significantly declined by approximately 14%, decreasing from 78.4 ± 4.2% to 64.3 ± 5.1% ($t_{(29)} = -10.42$, $p < 0.001$, $d = 1.90$), indicating impaired motor precision under fatigue. Likewise, RAST peak power diminished from 723.6 ± 28.4 W to 690.3 ± 31.2 W ($t_{(29)} = -4.62$, $p < 0.001$, $d = 0.84$), whereas the fatigue index escalated from 8.9 ± 0.6 to 10.7 ± 0.8 ($t_{(29)} = 5.13$, $p < 0.001$, $d = 0.93$). These results collectively indicate a significant decline in neuromuscular performance after high-intensity activity.

Paired t-tests on physiological variables corroborate these findings, showing a significant decrease in total body water (TBW) ($p < 0.001$) and a significant increase in blood lactate and muscle temperature ($p < 0.001$). The degree of variation between variables suggests that metabolic and thermoregulatory stress lead to a decrease in technical output and power after competition.

Figure 3 illustrates the changes in technical and physiological performance indicators from before to after the high-temperature test. There were significant decreases in shot accuracy (−14%) and peak power (−4.6%), accompanied by significant increases in the fatigue index,

Table 4. Pre- to Post-Test Comparison of Technical and Anaerobic Performance Indicators Under Heat Stress Conditions.

Variable	Pre-Test	Post-Test	t(29)	p	Cohen's d
Shooting Accuracy (%)	78.4 ± 4.2	64.3 ± 5.1	−10.42	< 0.001	1.90
Peak Power (W)	723.6 ± 28.4	690.3 ± 31.2	−4.62	< 0.001	0.84
Fatigue Index	8.9 ± 0.6	10.7 ± 0.8	5.13	< 0.001	0.93
Total Body Water (L)	42.6 ± 1.9	40.8 ± 2.0	−8.02	< 0.001	1.47
Blood Lactate (mmol·L-1)	1.3 ± 0.2	10.4 ± 0.9	37.81	< 0.001	6.90
Muscle Temperature (°C)	33.4 ± 0.3	37.1 ± 0.4	44.20	< 0.001	8.07

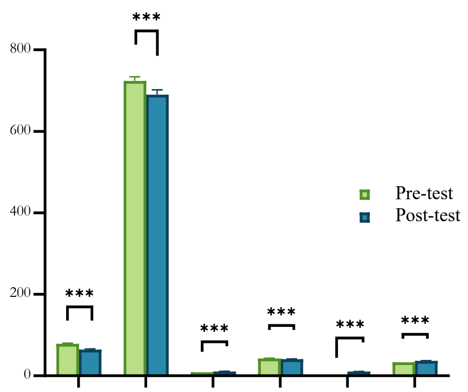

Fig. 3. Pre- to Post-Test Changes in Technical and Physiological Performance Indicators Under Heat Stress Conditions. Data are presented as mean ± SD; ***p < 0.001 compared with pre-test values

lactate concentration, and muscle temperature ($p < 0.001$). This trend highlights the cumulative effect of dehydration and metabolic overload on fatigue-related performance declines. Overall, these results indicate that match simulation creates a dry physiological environment, increases metabolic stress, and raises body temperature, all of which result in significant decreases in technical accuracy and anaerobic performance capacity. Given the strong correlation between physiological variables, further analysis used multiple regression to determine which factors collectively contributed to the variation in fatigue performance scores.

Correlation analysis revealed a strong relationship between physiological indicators and fatigue-related performance (Table 5). Fatigue performance scores exhibited a strong negative correlation with ΔHydration (% change in TBW; $r = -0.56$, $p = 0.002$). This indicates that as fluid loss increases, fatigue levels also increase. On the other hand, peak lactate showed a strong positive correlation with fatigue ($r = 0.63$, $p < 0.001$), meaning that higher metabolic accumulation rates were associated with lower performance levels. A moderate but significant correlation was identified between mean HR (%HRmax) ($r = 0.41$, $p = 0.027$) and mean muscle temperature ($r = 0.38$, $p = 0.039$), both of which influence fatigue perception and performance decline.

Multiple regression analysis revealed that the model significantly predicted fatigue performance ($R^2 = 0.61$, Adjusted $R^2 = 0.57$, $F_{(4,25)} = 9.85$, $p < 0.001$). Peak lactate ($\beta = 0.48$, $p = 0.003$) and ΔHydration ($\beta = -0.41$, $p = 0.008$) were the strongest independent predictors of fatigue. Mean HR ($\beta = 0.23$, $p = 0.074$) and mean muscle temperature ($\beta = 0.19$, $p = 0.089$) contributed modestly but did not reach

Table 5. Correlation Between Physiological Stress Markers and Fatigue Performance Scores in Sub-Elite Soccer Players.

Variable Pair	r	p
ΔHydration (%) vs Fatigue Score	−0.56	0.002
Mean HR (%HRmax) vs Fatigue Score	0.41	0.027
Peak Lactate (mmol·L-1) vs Fatigue Score	0.63	< 0.001
Mean Temp (°C) vs Fatigue Score	0.38	0.039

statistical significance. Confidence intervals for all predictors ranged from 95% CI [0.12 to 0.61] for lactate to [−0.62 to −0.18] for ΔHydration, while standard errors remained within acceptable limits (SE = 0.06–0.11). These results indicate that dehydration and the accumulation of metabolic by-products are the primary factors influencing post-match fatigue. Furthermore, cardiovascular and thermal stress factors add up, which shows that fatigue is a response that includes metabolic, thermoregulatory, and circulatory load.

Discussion

The principal findings demonstrate that progressive dehydration, heightened blood lactate concentrations, and elevated muscle temperature are associated with significant reductions in technical accuracy and anaerobic power, alongside considerable increases in cardiovascular load and perceived exertion. Correlational analysis indicated that total body water loss and peak lactate concentration were the most significant predictors of post-match fatigue, whereas mean heart rate and mean muscle temperature exerted a moderate influence on the overall fatigue index. These findings collectively emphasize that fatigue in heat-stressed match conditions is a multifactorial phenomenon involving metabolic, thermoregulatory, and circulatory elements (Cramer et al., 2022; Gnanasigamani et al., 2025).

The decrease in total body water indicates unregulated fluid loss during high-intensity intermittent activity, which may influence plasma volume and peripheral blood flow to the engaged muscles. A 2–3% loss of body mass due to dehydration has been demonstrated to hinder neuromuscular function, diminish running performance, and compromise fine motor control, especially in hot and humid conditions (Armstrong et al., 2025; Casa et al., 2015). This mechanism aligns with the substantial negative correlation observed between hydration variability and fatigue scores in this study, indicating that fluid balance is essential for sustaining technical precision and anaerobic performance during extended physical exertion.

A substantial increase in blood lactate indicates a significant reliance on anaerobic glycolysis during the simulation. Increased lactate concentrations in skeletal muscle can disrupt the excitation-contraction relationship, alter pH balance, and inhibit calcium reabsorption, thus exacerbating neuromuscular fatigue (Beneke et al., 2011; Kafrawi et al., 2025). The increase from 1.3 to 10.4 mmol L^{-1} aligns with the metabolic intensity observed in competitive matches in tropical climates, thus strengthening the ecological validity of the simulation procedure (Chapelle et al., 2020; Shirreffs & Shirreffs, 2010). The concomitant decrease in shooting accuracy and anaerobic power suggests that metabolic overload directly impacts both technical and physiological performance elements (Ioannou & Flouris, 2020).

It is important to note that muscle temperature increased steadily during the simulation. Moderate increases in intramuscular temperature can increase enzyme activity and force production. Studies have shown that temperatures above 37°C can inhibit nerve impulse conduction and cause fatigue (Flouris et al., 2015; Raj et al., 2021). Thermal stress exacerbates central motor output dysfunction, thereby exacerbating fatigue by complicating voluntary activation (Iguchi & Shields, 2011). These results are consistent with recent studies showing that cooling interventions significantly reduce thermal stress and maintain optimal performance during heat exposure (Bongers et al., 2017; Khorshid & Song, 2025).

When contextualized within the current literature, these findings align with the global consensus on heat-induced performance impairment in team sports. The International Olympic Committee (IOC) and the American College of Sports Medicine (ACSM) have collaborated to examine the importance of maintaining hydration, addressing heat stress, and measuring internal strain to enhance performance in high temperatures (Armstrong et al., 2025; McDermott et al., 2017; Sawka et al., 2007). This study reinforces these principles through empirical data collected in the field under tropical conditions, combining laboratory results with the practical context of sport. Furthermore, the use of RAST as a credible and reliable measure of anaerobic performance confirms its efficacy in longitudinal athlete monitoring, despite its slightly reduced peak power estimates compared to the Wingate test (Hafidz et al., 2025; Wibowo et al., 2025).

There are numerous practical implications from a coaching and applied sports science perspective. First, athletes should pay attention to their hydration levels during training and competition. This can be done by weighing yourself before and after a session or by using a portable device such as a BIA analyzer or urine specific gravity meter. Developing a personalized rehydration plan, such as the one used here (3–5 mL/kg at halftime), can help maintain performance and correct fluid imbalances (Pryor et al., 2018; S. Racinais et al., 2015). Second, pre- and post-cooling strategies, such as ice vests, cold towels, or cold water immersion, should be used frequently to reduce heat stress levels, especially when competing in tropical climates (Robin et al., 2024; Roriz et al., 2022). Third, a structured heat acclimatization program lasting 10 to 14 days has been shown to lower heart rate, reduce fatigue, and help teams cope better with the heat (Lorenzo et al., 2010). This is an important way for teams to prepare for competition in hot weather.

Current findings suggest that perceived strain is closely related to physiological load; therefore, incorporating these metrics could improve in-game decision-making and reduce fatigue-related errors or injuries. Furthermore, coaches should have players perform technical drills while fatigued, such as shooting or passing after sprinting, to help them maintain sharp skills and maintain accurate motor skills under pressure. Finally, coaches should consistently conduct RAST or comparable on-field assessments of anaerobic performance to evaluate recovery and adaptive progress throughout the training cycle (Wibowo et al., 2025).

This study acknowledges specific limitations, despite robust experimental controls. The study sample was limited to sub-elite male players from a single university team, thus limiting generalizability to other levels of competition, age demographics, or female athletes. BIA is a useful and non-invasive way to assess hydration, but it can be affected by changes in skin temperature and electrical impedance when the body heats up. The RAST is a reliable test, but it may slightly underestimate peak power output compared to the Wingate protocol performed in the laboratory (Zagatto et al., 2009). Future research should incorporate additional biomarkers, including urine osmolality or plasma volume, to facilitate a more comprehensive analysis. Therefore, caution should be exercised when considering absolute performance values. Future research should investigate controlled interventions—such as variations in rehydration formulation, cooling techniques, or acclimatization periods—to evaluate their effects on physiological and technical recovery. Longitudinal studies examining the neuromuscular and cognitive mechanisms that lead to fatigue-induced skill decline would improve understanding of the mechanisms influencing soccer performance in high temperatures.

Conclusions

This study demonstrates that simulated soccer matches in a hot and humid tropical environment cause significant physiological stress—characterized by progressive dehydration, elevated blood lactate levels, and increased muscle temperature—which collectively reduce technical precision and anaerobic capacity. The strong correlation between fluid loss, metabolic accumulation, and fatigue validates that a synergistic interaction between circulatory, metabolic, and thermoregulatory processes drives performance declines during heat stress. These results suggest that hydration and thermal regulation are crucial for sub-elite players' performance in matches and their recovery speed.

In practice, maintaining fluid balance and reducing thermal stress should be central to coaching and performance plans. To help players avoid heat exhaustion, coaches should utilize individualized hydration monitoring, structured rehydration (3–5 mL kg^{-1} during rest periods), and targeted cooling methods such as pre-cooling or pre-cooling. Adding short-term heat acclimatization and technical drills performed while fatigued can help further improve skill tolerance and stability during competition. Incorporating these evidence-based strategies into training and competition preparation can enhance physiological readiness and maintain performance in athletes competing in high temperatures.

AI Transparency Statement

Artificial Intelligence (AI) tools were used solely to support linguistic refinement and formatting during manuscript preparation. AI was not used to generate scientific content, analyze data, interpret findings, or conduct any part of the research methodology. All scientific arguments, results, and conclusions were produced exclusively by the authors.

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Conflict of Interest

All researchers declare that there is no conflict of interest in this research.

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Стан гідратації та тепловий стрес як предиктори втоми та зниження результативності у футболістів субелітного рівня

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 12 с., 5 табл., 3 рис., 59 джерел.

Обґрунтування. Футболісти, які беруть участь у змаганнях в умовах тропічного клімату, зазнають комбінованого впливу дегідратації, теплового навантаження та метаболічного стресу, проте дані, що підтверджують зв'язок цих факторів із зниженням результативності, залишаються обмеженими.

Цілі. Мета цього дослідження полягала у вивченні прогнозованих взаємозв'язків між станом гідратації, тепловим стресом, метаболічними факторами та зниженням результативності, зумовленим втомою, у футболістів субелітного рівня, які грають в умовах тропічної спеки.

Матеріали та методи. Тридцять чоловіків-футболістів субелітного рівня (22.4 ± 3.1 роки) взяли участь у модельованому 90-хвилинному матчі, що проводився при температурі від 31 до 33 °C та відносній вологості повітря між 65 та 75 %. Показники гідратації (біоімпедансний аналіз), лактату в крові, температури м'язів, частоти серцевих скорочень, точності ударів та анаеробної потужності (тест на вимірювання швидкості і сили під час серії спринтів) оцінювали на передматчевому етапі, під час та після проведення матчу. Застосовано дисперсійний аналіз з повторними вимірами та множинну регресію ($p < 0.05$).

Результати. Показник загальної кількості води в організмі (ЗКВО) значно зменшився (−4.2%), тоді як рівні лактату (1.3 → 10.4 ммоль/л$^{-1}$) і температури м'язів (33.4 → 37.1 °C) збільшилися протягом сегментів матчу ($p < 0.001$). На післяматчевому етапі спостерігалося зниження точності ударів (−14%) і пікової анаеробної потужності (−4.6%). Регресійний аналіз визначив ΔЗКВО ($\beta = -0.41$, $p = 0.008$) і піковий лактат ($\beta = 0.48$, $p = 0.003$) як значущі предиктори втоми ($R^2 = 0.61$).

Висновки. Результати дослідження вказують, що дегідратація, теплове навантаження та метаболічне накопичення є важливими ознаками погіршення рівня результативності суб'єкта під час проведення матчів в умовах тропічного клімату. Спортсмени можуть поліпшити своє здоров'я та продуктивність, вживаючи достатню кількість рідини та контролюючи температуру тіла.

Ключові слова: стан гідратації, тепловий стрес, втома, анаеробна продуктивність, тропічне середовище.

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