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Monitoring external and internal training and match loads in professional soccer players during excessive heat stress

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ALIREZA RABBANI[1], FILIPE MANUEL CLEMENTE[2,3,4], ŽELJKO BANIĆEVIĆ[5], IVANA BANIĆEVIĆ[5], RUI MIGUEL SILVA[2]

[1] Sport Science Department, Al Jazira Football Academy, Abu Dhabi, UAE
[2] Escola Superior Desporto e Lazer, Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial de Nun'Álvares, Viana do Castelo, Portugal
[3] Gdansk University of Physical Education and Sport, Gdańsk, Poland
[4] Sport Physical Activity and Health Research & Innovation Center, Viana do Castelo, Portugal
[5] Health, Exercise and Research Center (HERC), Dubai, UAE

ABSTRACT
Purpose. This study explored how heat stress affects training and match load in professional soccer by monitoring ten elite players during sessions under normal (18–24°C) and high (34–45°C) temperatures.
Methods. Ten outfield men's soccer players from a professional team competing in the United Arab Emirates (UAE) Pro League participated in the study. A repeated-measures study design was employed to analyse the training load demands on the same players under normal (18–24°C) and high (34–45°C) temperature conditions throughout the training camp period. External loads, such as total distance (TD), high metabolic load distance (HMLD), mechanical work (MW), and maximal velocity (MaxV), as well as internal load, via Edwards' Training Impulse (TRIMP), were analysed.
Results. The study found that heat influenced training and match loads to varying degrees. On match day (MD), TD per minute (TD $\cdot$ min^{-1}) decreased slightly (effect size [ES] = –0.55), with larger reductions observed on MD-2 (ES = –2.14) and MD-1 (ES = –1.59). Specifically, the reduction in TD.min-1 was greatest on MD-2 and MD-1, while only a small decrease was observed on MD. HMLD per minute (HMLD $\cdot$ min^{-1}) also showed a significant reduction, with a moderate decrease on MD-1 (ES = –1.03) and MD (ES = –0.78). MW per minute (MW $\cdot$ min^{-1}) was notably lower on MD-2 (ES = –1.50), moderately reduced on MD-1 (ES = –0.84), and slightly reduced on MD (ES = –0.45). Maximal velocity (MaxV) slightly increased on MD (ES = 0.47). TRIMP increased across all days, indicating a higher internal load under heat, with a moderate increase on MD-2 (ES = 0.77), MD-1 (ES = 0.73), and MD (ES = 0.83).
Conclusions. The study showed the different effects of heat on external and internal training loads, suggesting that while external loads decrease due to the physiological strain of heat, internal load compensates by increasing. This response may indicate a greater effort to maintain performance levels despite heat stress. These findings show that heat-induced changes in training load can help implement strategies for optimising athlete performance and recovery during periods of heat exposure.
Key words: football, sports training, monitoring, performance, thermoregulation

Introduction

Heat stress, defined as the physiological strain experienced when the body is exposed to elevated temperatures, can significantly affect performance and recovery during exercise. Heat stress may trigger increased sweating for evaporative cooling, which can lead to dehydration and reduced blood plasma volume [1]. This physiological response can impair cardiovascular function by decreasing stroke volume and increasing heart rate to maintain adequate blood flow to working muscles [1]. Additionally, high temperatures can hinder enzyme activities essential for muscle contraction and energy production, resulting in reduced exer-

Correspondence address: Filipe Manuel Clemente, Escola Superior Desporto e Lazer, Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial de Nun'Álvares, 4900-347 Viana do Castelo, Portugal, e-mail: filipe.clemente5@gmail.com; https://orcid.org/0000-0001-9813-2842

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cise performance and increased fatigue [2]. As such, heat stress can compromise thermoregulatory mechanisms, heightening the risk of heat-related illnesses and reducing overall exercise capacity [3].

Research has shown that heat stress affects internal physiological responses (such as heart rate and perceived exertion) and external training loads (such as locomotor and mechanical demands) during physical exertion. Specifically, high temperatures can reduce running speeds and the distance covered, as athletes find it difficult to sustain their usual intensity due to increased physiological strain [4]. Internally, heat stress can elevate cardiovascular demands, meaning players experience higher levels of perceived exertion, even at reduced effort levels, contributing to premature fatigue [5]. Dehydration from excessive sweating can also disrupt thermoregulation and electrolyte balance, further exacerbating fatigue [6]. These disruptions can negatively affect the effectiveness of training and performance during high-intensity soccer sessions.

While much of the existing literature focuses on heat stress during match performance, with studies highlighting its impact on low-intensity running, high-speed running, and sprinting [7], the effects of heat stress during training on other relevant external load measures remain underexplored. Specifically, external load variables such as total distance (TD), high metabolic load distance (HMLD), mechanical work (MW), and maximal velocity (MaxV) represent critical measures of physical performance and reflect the different locomotor demands placed on athletes during soccer activities [8, 9]. Similarly, internal load using Edwards' Training Impulse (TRIMP) provides a composite measure of cardiovascular and metabolic stress based on heart rate, making it a robust indicator of physiological strain in different conditions [10]. Training contexts differ from matches in structure, intensity, and objectives, making it critical to study the impact of heat stress in training environments separately from matches. Matches are inherently competitive, requiring players to exert maximum effort despite environmental conditions, while training sessions are designed to optimise physical adaptations, often in more controlled settings. Therefore, directly applying match-related findings to training may overlook the unique needs and goals of training, which could result in ineffective or suboptimal adaptations [11].

The need for acclimatisation during training in hot environments has been highlighted, as heat stress may impact fatigue and recovery patterns [12]. A study of elite soccer players during a heat acclimatisation camp showed that perceived exertion decreased over time, alongside improvements in neuromuscular efficiency and a reduction in heart rate responses, despite slight increases in fatigue and decreases in sleep quality [12]. Despite these findings, there is limited evidence on how heat stress specifically impacts training loads compared to normal conditions. The effects of heat stress on training loads and recovery have not been studied extensively. It is crucial to understand whether the negative impacts on performance and recovery observed during matches are also present in training sessions and whether specific strategies need to be implemented during training to mitigate these effects. It is important to address this knowledge gap to ensure that heat stress does not hinder training outcomes or physical adaptations.

The current study compared selected external and internal load measures during normal and hot weather conditions during training and match days in elite male professional soccer players. By focusing on training, the study aimed to provide a foundation for tailored heat management strategies that can enhance safety and performance during preparation phases. We hypothesised that external load measures would show significant impairments while heart rate responses would significantly increase under heat conditions. This is consistent with previous findings that external performance metrics, such as running distance, tend to decrease in hot environments due to thermoregulatory strain, whereas cardiovascular responses (e.g., heart rate) are elevated to compensate for reduced stroke volume and increased metabolic demands [5].

Material and methods

Study design

A repeated-measures study design was employed to analyse the load monitoring demands on the same players under normal (18–24°C) and high (34–45°C) temperature conditions throughout the training camp period.

Setting

Training and match data were collected during the pre-season phase, from 28th July to 27th August 2022. The professional team attended a camp in Slovenia for three weeks and returned to the United Arab Emirates (UAE) to complete pre-season preparation. The team completed six friendly matches, including three during the last two weeks of the Slovenia camp and three in the first two weeks after returning from the camp in the UAE. The camp in Slovenia was at a relatively normal temperature (18–24°C with 15–35% humidity) compared to the heat stress in the UAE (34–45°C with 40–60% humidity). Given that the training sessions were designed by the coaching staff to reflect the natural variation in the team's preparation, they were not identical, which is typical in field-based team sports.

The study assessed how heat stress influenced player responses to load monitoring under real-world conditions. Therefore, the sessions varied according to the strategic needs of the team. Three training sessions from two days before the match (MD-2) and two training sessions from the day before the match (MD-1) under each condition (normal vs heat) were selected for analysis. These sessions were chosen based on their consistent inclusion in the team's pre-season training cycle, with MD-2 typically involving higher-intensity efforts and MD-1 focusing on recovery and readiness. A total of 10 training sessions (three MD-2 and two MD-1 of each condition) and six matches were included in the analysis. The average of each session was included in analyses to standardise the comparisons.

Participants

Ten outfield male soccer players (age = 28.1 ± 3.5 years; body mass = 77.3 ± 4.4 kg; height = 181.2 ± 6.7 cm) from a professional team competing in the UAE Pro League participated in the study (Table 1). While the small sample size is acknowledged, it is in line with similar studies using small cohorts due to the nature of field-based, real-world performance research in professional sports. Given the constraints of studying elite athletes in competitive settings, the study provides valuable insights despite the limited sample [13]. As part of a convenience sampling method, the inclusion criteria for analysis were (i) participation in more than 45 min of playtime, (ii) attendance at all training sessions and matches, and (iii) no injuries or illnesses during the observation period. The data were collected by the club's sports science staff for the monitoring process in which player activities are routinely measured over the course of the competitive season, so ethics committee clearance was not required [14]. However, the club provided written consent to use the data for research purposes and to publish scientific papers.

Procedures

The days before matches followed the same methodological approach as outlined previously, with data computed per minute of play or training to standardise comparisons. Inclusion criteria required at least 45 min of play in two matches and participation in at least two MD-2 and MD-1 training sessions under any conditions (i.e., normal vs heat). It should be noted that the decision to limit the data collection to MD-2 and MD-1 sessions was based on the structured nature of these sessions within the team's pre-season training cycle, where MD-2 typically represents higher-intensity efforts, and MD-1 focuses on readiness and recovery. Although it is recognised that training sessions vary in content according to the coaching staff's strategic prescriptions, the study's primary focus was on the impact of environmental heat stress on player responses, and these naturally occurring differences in training loads reflect the real-world variability that professional athletes experience.

Load measures

During all training and matches, selected training load measures were collected for analysis. These measures included TD (expressed in metres), MW (expressed in arbitrary units), defined as the sum of accelerations and decelerations > 3 $m \cdot s^{-2}$, HMLD (expressed in metres), calculated as the total amount of high-speed running distance coupled with the TD of accelerations and decelerations, maximum velocity (MaxV; expressed in metres per second), and heart rate [8]. Heart rate was continuously monitored using heart rate monitors worn by the participants during all training sessions and matches. The monitors were placed on the participants' chests, and heart rate data were recorded at a frequency of 1 Hz. The data were used to calculate internal load via TRIMP (expressed in arbitrary units), which was later computed as an internal load measure, an index of the accumulated physiological stress during exercise [15]. External load measures were collected using the STATSport GPS system (Apex, 10 Hz; 100 Hz tri-axial accelerometer, and 10 Hz magnetometer). The GPS unit was positioned on the participant's back, midway between the scapulae, in a snug-fitting harness to

Table 1. Player characteristics

Age (y)	Body mass (kg)	Height (cm)	CMJ (cm)	V_{IFT} (km $\cdot$ h^{-1})
28.1 ± 3.5	77.3 ± 4.4	181.2 ± 6.7	41.5 ± 5.8	19.3 ± 0.8

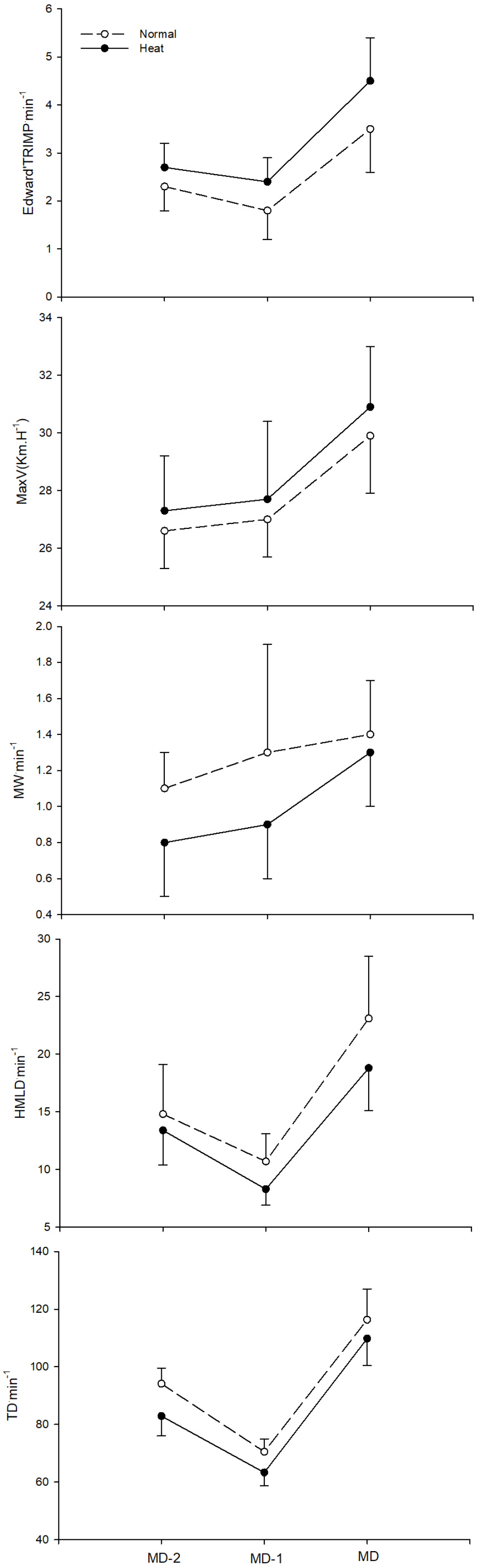
CM – countermovement jump, V_{IFT} – maximal velocity reached in the last stage of 30–15 intermittent fitness test ensure secure placement during movement. The GPS system recorded position, velocity, acceleration, and deceleration, allowing for detailed analysis of player activity. The accuracy of the GPS system was validated in previous studies, with results confirming its ability to evaluate linear running and sport-specific activity. Specifically, the Apex units (10 and 18 Hz) demonstrated high accuracy, with a bias of less than 5% in the selected external load measures, such as TD and HMLD [16].

Statistical analyses

Data in the text, tables, and figures are presented as means with a 95% confidence limit (CL) or standard deviation (SD), as specified. All selected external load measures were divided by the minutes played to standardise comparisons. A repeated-measures design was used to analyse within-subject changes in the selected external load measures across different conditions (normal vs heat). Changes in the selected external load measures within each group were analysed using magnitude-based inference (MBI) [17]. MBI was used to evaluate the magnitude of changes, providing a practical method for interpreting the effects in a small sample size, as is common in repeated-measures designs. The MBI is a probabilistic assessment of whether the observed changes are meaningful, with an emphasis on whether a change is likely to be a true effect. The smallest worthwhile change was calculated by multiplying the between-subject standard deviation by 0.2 [17]. Threshold values for standardised changes were categorised as small (> 0.2 ≤ 0.6), moderate (> 0.6 ≤ 1.2), large (> 1.2 ≤ 2.0), or very large (> 2.0) [20]. Probabilities were also used to assess the likelihood of meaningful changes, with the following scale: 25–75%, possible; 75–95%, likely; 95–99%, very likely; > 99%, almost certain [17]. This approach was chosen due to its suitability for repeated-measures designs with small sample sizes, allowing for robust and meaningful interpretation of the data despite potential dropouts and sample size imbalances.

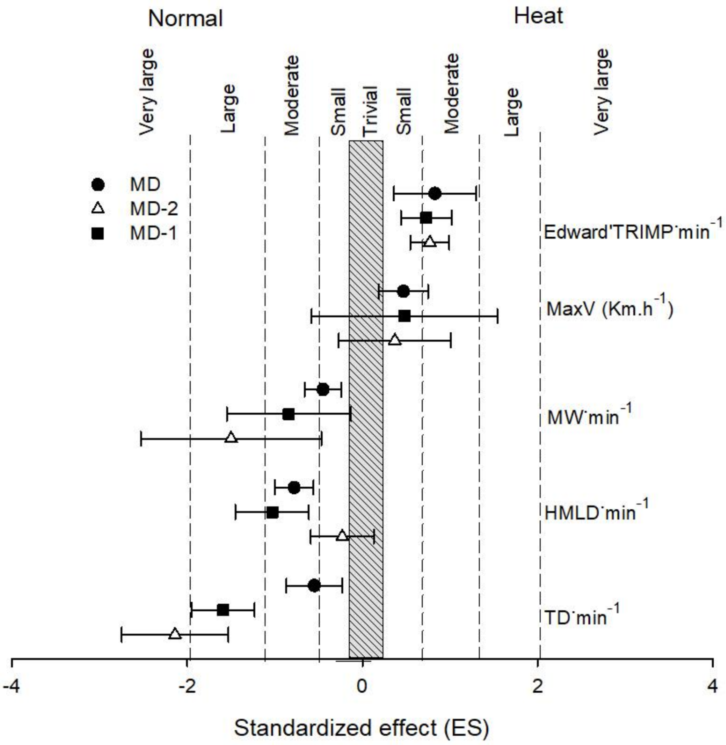
Results

Figure 1 shows changes in selected training load measures during heat. The data showed that TD per minute (TD · min^{-1}, expressed in metres per minute) decreased by a small magnitude during match day (MD) in heat (standardised effect; effect size [ES] = –0.55, CL = –0.87, –0.23; coefficient of variation [CV] = 5.2%). Compared to normal conditions, TD · min^{-1} also



TD – total distance, HMLD – high metabolic load distance, MW – mechanical work (MW, the sum number of accelerations and decelerations > 3 m^2), MaxV – maximal velocity, Edwards' TRIMP – Edwards' training impulse.
Error bars represent the typical error. To improve visualisation, the symmetrical positive and negative error bars were removed

Figure 1. Changes in selected training load measures during the heat



TD – total distance, HMLD – high metabolic load distance,
MW – mechanical work (MW, the sum number of accelerations and decelerations > 3 m^2), MaxV – maximal velocity

Figure 2. Standardised change (ES) in selected training load measures

decreased by a very large magnitude during MD-2 (ES = –2.14, CL = –2.75, –1.59; CV = 4.8%), and a large magnitude during MD-1 (ES = –1.59; CL = –1.95, –1.23; CV = 4.5%). HMLD per minute (HMLD · min^{-1}, expressed in metres per minute) decreased possibly with small magnitude during MD-2 in heat (ES: –0.23, CLs [–0.59; 0.12]; CV: 6.1%). Compared to normal conditions, HMLD · min^{-1} also decreased, most likely with moderate magnitude during MD-1 (ES = –1.03; CL = –1.45, –0.6; CV = 5.9%) and MD (ES = –0.78, CL = –1.0, –0.56; CV = 5.7%). MW · min^{-1} decreased during heat with a large magnitude during MD-2 (ES = –1.50; CL = –2.53; –0.47; CV = 6.8%), moderate magnitude during MD-1 (ES = –0.84; CL = –1.55, –0.13; CV = 6.5%), and small magnitude during MD (ES = –0.45; CL = –0.66, –0.23; CV = 6.3%). MaxV showed unclear changes during MD-2 and MD-1 in heat (CV = 4.0% and 3.8%, respectively). However, a small increase in MaxV was observed during MD in heat (ES = 0.47; CL = 0.19, -0.76; CV = 4.2%). TRIMP increased with moderate magnitude during MD-2 (ES = 0.77; CL = 0.55, 0.99; CV = 6.0%) and MD-1 (ES = 0.73; CL = 0.44, 1.02; CV = 5.8%). Similarly, TRIMP increased with moderate magnitude during MD in heat (ES = 0.83, CL = 0.36, 1.3; CV = 5.5%) (Figure 2).

Discussion

The present study compared selected external and internal load measures during normal and hot weather conditions during training and match days. The study specifically compared the differences in external and internal load metrics under normal versus heat conditions, focusing on subsequent measurement days (MD-2, MD-1, and MD). The main results showed that, except for the MaxV measure, all external load measures decreased during the heat stress. In contrast, internal load, represented by TRIMP, increased significantly under heat stress during training and match days.

Our findings indicated a significant reduction in TD · min^{-1}, particularly on match days and the days leading up to matches under heat stress. When comparing normal and heat conditions, this decrease was notably more pronounced in the heat, highlighting the impact of environmental factors on overall running volume. This observation is consistent with previous research on the effects of environmental heat on physical and locomotor performance, where external heat conditions affect the body's ability to regulate temperature, leading to significant reductions in performance [18]. Specifically, the acclimatisation period led to a significant reduction in TD covered during matches in hot conditions, with an average decrease of 6.0 ± 5.8% ($p \leq 0.002$) [18]. Previous research has shown that elite soccer players experience a reduction in TD covered when training in the heat, which was positively related to changes in core temperature [19]. This decrease in TD can be attributed to the body's attempt to manage heat load by reducing overall running volume, thereby conserving energy for thermoregulation [20, 21]. Similarly, low ambient temperatures have also been shown to impact physical performance in soccer players. A study examining elite soccer players in sub-zero temperatures reported marked reductions in sprint distance under these conditions, with every 1°C decrease below –5°C leading to a 19.2 m (1.6%) reduction in sprint distance [22]. This demonstrates that extreme environmental conditions, whether heat or cold, can impose specific constraints on high-intensity performance, potentially requiring tailored management strategies to maintain athletic output.

Interestingly, MaxV showed a slight increase during MD under heat, which contrasts with typical expectations. However, this increase was not consistent across all time points, indicating that heat's effect on sprinting ability might be more complex. When comparing normal and heat conditions, this increase in MaxV suggests that high-intensity efforts, such as sprinting, might not always be negatively affected by heat. This could be attributed to the shorter duration of such efforts compared to prolonged running [23, 24]. Consistent with our findings, Coker et al. [20] showed no significant differences in high-intensity running, high-speed running, and sprinting distances across different heat stress conditions. On the other hand, Racinais et al. [18] found a decline in high-speed running and sprinting in hot environments. Such discrepancies between these studies may be due to variations in the specific conditions of heat exposure, the acclimatisation level of participants, and the hydration strategies employed [25]. However, it may be suggested that while TD and other lower-intensity activities could be affected by heat, high-intensity efforts may not show a statistically significant change when normalised for playing time.

The observed decrease in HMLD $\cdot$ min^{-1} in the present study reflected a reduction in high-metabolic efforts during heat stress. This decrease was significantly greater in heat conditions compared to normal conditions, indicating that environmental heat imposes additional constraints on athletes' ability to engage in high-intensity, metabolically demanding activities [26]. The reduction suggests that under higher environmental heat conditions, athletes tend to decrease their engagement in activities that require substantial metabolic power. Such modification represents a physiological mechanism aimed at regulating internal body temperature and conserving energy to mitigate the risk of overheating. Moreover, this may expose a limitation of using HMLD for assessing performance under heat conditions, as it might not fully capture the changes in energy expenditure or the anaerobic contributions during heat stress, considering that the athletes can still maintain high-intensity efforts despite the heat condition [27]. Similarly, MW.min-1 showed a notable decrease, indicating less physical exertion in terms of mechanical output in heat conditions. This corroborates the work of Duffield et al. [28], which suggested that heat impacts the efficiency of muscle work. As a consequence of increased internal core body temperature, athletes may adopt pacing strategies to limit the core body temperature increases by reducing nonessential efforts [28].

Finally, the increase in TRIMP under heat conditions observed in the present study highlights a higher physiological strain despite the overall reduced external loads. When comparing normal and heat conditions, this difference in TRIMP responses shows that players experience greater cardiovascular and metabolic stress under heat stress, even as external workload decreases [29]. This implies that while players decrease the external load in the heat, the cardiovascular and metabolic stress remains high due to thermoregulatory demands. This fact was previously evidenced by the significant increase in core temperature during a soccer match played under high heat conditions [29]. The higher core temperature indicates an increased internal load, which can be reflected by the physiological adaptations required to manage heat stress [29]. The increase in TRIMP during heat stress reflects the greater physiological effort required to perform at the reduced external load levels. This can be partially corroborated by O'Connor et al. [30], who found that higher heat conditions significantly increase internal load measures, such as higher percentages of time spent above 85% of maximum heart rate and higher ratings of perceived exertion, indicating a more strenuous physiological state despite potentially lower external load activity. Overall, heat exposure leads to reductions in external load measures, such as TD $\cdot$ min^{-1}, HMLD $\cdot$ min^{-1}, and MW $\cdot$ min^{-1}, and results in a simultaneous increase in internal load measures, such as TRIMP.

The present study had some limitations. The sample size was relatively small, and the study was conducted within a specific climatic context, which might not apply to all environments. Future research could explore the long-term effects of heat acclimatisation on internal and external load measures, investigate the impact of hydration strategies, and include a broader demographic to enhance the generalisability of the findings. Additionally, incorporating physiological markers such as core temperature or sweat rate could provide a greater understanding of the mechanisms behind the observed changes in internal and external load measures under heat. Another limitation was that humidity was not considered a variable in the analysis despite its potential influence on external and internal load measures. Future research should aim to explore the combined effects of temperature and humidity on athlete performance and physiological responses in heat stress conditions.

Despite the study limitations, the findings offer several practical applications for managing training and match conditions during excessive heat stress. Coaches should closely monitor external and internal load metrics to understand how players respond to heat, as reduced external loads do not imply reduced physiological strain. Progressive heat acclimatisation should be implemented to prepare players for high-temperature conditions, and training intensity and duration should be adjusted based on environmental factors. Hydration strategies and cooling techniques are essential for mitigating the effects of heat on internal load and overall performance. Scheduling matches or more intense training sessions during cooler parts of the day (early morning or at night) and integrating hydration breaks can help optimise performance in hot climates. Lastly, individualising training programmes using internal load measures such as TRIMP can ensure that players are adequately prepared to cope with the training demands while minimising heat-related risks.

Conclusions

Excessive heat stress significantly impacted external and internal training loads in professional soccer players. TD, HMLD, and MW per minute decreased notably, particularly on match days and the preceding training days (MD-1 and MD-2), likely reflecting pacing strategies to conserve energy and regulate body temperature. Interestingly, MaxV increased slightly on match days, suggesting that high-intensity efforts may be less affected by heat stress. Despite reduced external loads, internal load (e.g., TRIMP) increased significantly under heat, indicating a greater physiological strain due to compensatory cardiovascular and metabolic responses. These findings highlight that while external performance measures decline, the physiological demands of training and matches remain elevated during heat stress.

Data availability

The datasets used and/or analysed during the current study are not publicly available. The data are available from the corresponding author upon reasonable request.

Ethical approval

The data were collected by the club's sports science staff for the monitoring process in which player activities are routinely measured over the course of the competitive season, so ethics committee clearance was not required [14]. However, the club provided written consent to use the data for research purposes and to publish scientific papers.

Informed consent

Informed consent has been obtained from all individuals included in this study.

Conflict of interest

The authors state no conflict of interest.

Disclosure statement

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