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Original research

Core temperature responses of male football players during matches in the heat — Associations with physiological and running demands

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A B S T R A C T

Objectives: This study describes core temperature (T_{core}) responses during football matches in warm to hot conditions. It aims to identify which physiological, running, and perceptual factors are associated with reaching high T_{core} values while controlling for environmental conditions and cooling.
Design: Forty highly trained male youth football players participated in at least two out of four matches held at temperatures between 26 and 42 °C. In three matches, heat mitigation strategies (passive rest and 17 °C drinks, or cold towels and 5 °C drinks) were applied pre-match, at half-time, and in additional breaks per half.
Methods: Match running, heart rates, hydration markers, and perceptual responses were measured and checked for associations with peak T_{core} values via linear mixed models accounting for environmental conditions and heat mitigation strategies.
Results: Peak T_{core} was 39.2 ± 0.5 °C (range: 37.9–40.1 °C). Higher total distance ($\beta = 0.39$ [0.13, 0.64], $p = 0.004$) and distance at low-to-moderate speeds ($\beta = 0.44$ [0.18, 0.69], $p = 0.001$) were associated with higher peak T_{core}, while walking distance was inversely associated ($\beta = -0.42$ [−0.69, −0.15], $p = 0.003$). High-speed and sprinting distances were not associated with peak T_{core}. Higher heart rate ($\beta = 0.37$ [0.10, 0.64], $p = 0.008$), sweat loss ($\beta = 0.38$ [0.14, 0.62], $p = 0.002$) and body mass loss ($\beta = 0.20$ [0.00, 0.40], $p = 0.047$) were also associated with higher peak T_{core}. Rating-of-fatigue ($p = 0.74$), perceived exertion ($p = 0.78$), and thermal sensation ($p = 0.98$) were not associated with peak T_{core}.
Conclusions: High T_{core} peaks were observed in all conditions and were associated with higher heart rate, sweat loss, and match running. Covering more distance at low-to-moderate speed was associated with a higher heat strain, whereas walking more (instead of running) was associated with lower T_{core} peaks.

Practical implications

- High heat strain can be reached during football, even in moderate heat, which led to the development of one case of heat illness in this study. Sports federations and teams should therefore explore strategies to prevent and treat heat illnesses.
- Sub-optimal hydration was regularly observed at pre-match measurements, highlighting the need for teams to consider strategies to avoid the potential consequences of hypohydration for both players' health and performance.
- Covering more distance (especially at low–moderate intensity) was associated with higher heat strain. Hence, football teams might consider reducing running distance during the warm-up or adjusting their playing style and tactics to reduce heat strain.

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- Players with higher running loads might benefit from individualized cooling and hydration strategies, as they might experience greater heat strain.

1. Introduction

Due to global warming, outdoor sports athletes across all performance levels are increasingly exposed to hot environmental conditions.[1,2] Consequently, playing football (soccer) in the heat has emerged as a growing concern for players' health and performance.[3–5] During exercise, three primary determinants contribute to heat stress: exercise intensity drives metabolic heat production, and environmental conditions and clothing determine heat dissipation capacities.[6] Any heat stress results in an individual heat strain, which is moderated by personal and situational factors, such as acclimatization or hydration status.[7] In hotter and more humid conditions, heat dissipation mechanisms such as sweating and subcutaneous vasodilation become less efficient. In warmer conditions, dry heat loss becomes impaired, or even reversed, when ambient temperature exceeds skin temperature. In more humid conditions sweat evaporation becomes impaired, resulting in greater cardiovascular strain and decreased performance.[8]

If heat dissipation cannot offset heat gain (from metabolic heat production or environmental heat stress), elevated core temperatures (T_{core}) can be observed in various sports, such as football.[9] While a high T_{core} is not necessarily linked to health adversities, excessive heat strain may lead to the development of exertional heat illnesses (EHIs) ranging from cramps, nausea and headaches to life-threatening exertional heat stroke (EHS).[10] Furthermore, playing football in higher heat stress may be associated with an increased risk of injury.[5]

Despite this, only four field-based studies have assessed T_{core} responses during football match-play under different environmental conditions,[12–14] one of them including the investigation of a pre-cooling method.[11] These authors investigated male recreational,[12] semi-professional,[14] elite,[13] and professional[11,12] players in experimental[12–14] or competitive[11] matches. Reported mean peak T_{core} values in these studies ranged from 38.5 ± 0.6 °C in 16 °C ambient temperature (T) and 47 % relative humidity (RH)[12] to 39.7 ± 0.1 °C recorded in 43 °C T and 12 % RH.[13] Individual values exceeding 40 °C were also reported.[11,13,14] However, these studies were limited to small sample sizes with seven to seventeen participants and did not examine associations with other match parameters.

Although it has been demonstrated that football can lead to substantial heat strain, there remains a lack of insight into the individual factors related to developing a high T_{core}. As football players often compete under the same environmental conditions and wear similar clothing, individual differences in heat stress may be driven by the intensity of the exercise.[8] This is in line with previous studies showing that running performance and other match-actions are reduced in the heat, which is often described as a form of pacing to mitigate heat strain.[15–17] However, whether reduced running volumes in football are associated with maintaining a lower T_{core} is yet to be investigated.

In addition to reducing running volumes, other heat mitigation strategies exist, namely, maintaining hydration,[8] implementing additional breaks per half,[18] and applying cooling techniques.[19] Currently, most heat policies in football involve the introduction of additional breaks per half.[3] These additional breaks serve at least as an opportunity to rest and hydrate and could potentially be used to apply cooling strategies like iced towels.[20] The FIFA Football Emergency Medicine Manual outlines that cooling breaks, including cold drinks and towels soaked in iced water, are mandatory to be introduced when WBGT is 32 °C.[21] Laboratory-based studies suggest that such strategies can attenuate T_{core} rise, but high heat strain can develop nonetheless.[18,20] The matches presented in this study were also part of another study investigating the effects of pre-cooling and cooling breaks in actual football matches. The findings confirmed outcomes from laboratory studies, showing that additional drinks and cooling breaks attenuated the continuous T_{core} rise, but high T_{core} values developed even in moderate heat.[22] Therefore, it remains relevant to investigate which match-based factors are associated with high T_{core}, even when heat mitigation strategies are implemented.

This study will be the first to describe T_{core} responses across four football matches played under different environmental conditions and using different heat mitigation strategies. The study aims to identify which physiological, running and perceptual factors are consistently associated with high peak T_{core} values during match play, while controlling for environmental conditions and heat mitigation strategies used. We hypothesize that elevated T_{core} peaks would be associated with greater distances covered, higher heart rates, and greater sweat losses.

2. Methods

2.1. Participants

Forty highly trained[23] male footballers (18 ± 1 years) from a professional Mexican club's youth academy participated in this study. Each player participated in at least two out of the four experimental matches, with four players participating in all matches. Participants had 3 to 4 training sessions and 1 to 2 matches per week. The daily average maximum temperature in the four weeks preceding Match 1 and Match 2 was 32.8 ± 5.6 °C, and for Match 3 and Match 4, it was 35.8 ± 4.2 °C.[24] All participants were therefore seasonally acclimatized, having trained in hot conditions for more than 2 weeks prior to the testing. In every match, the starting 20 outfield players and both goalkeepers participated in the study, resulting in 88 individual observations. Of those, 22 had to be excluded from the analysis due to the following technical issues: telemetric pills remaining in the stomach (n = 15), telemetric pills being excreted too early (n = 4), GPS device failures (n = 1), or participant injury (n = 2). This resulted in 66 individual player T_{core} measurements from 61 outfield players and 5 goalkeepers. Following an explanation of study procedures and measurements during an initial familiarization session, participants provided written informed consent. The study was pre-registered at the German Clinical Trials Register (DRKS-ID: DRKS00032208) and institutional ethics approval was granted by the Ethics Committee of the Faculty for Human and Business Sciences of Saarland University (No: 23-14). The study design, consisting of regular football matches, did not allow for the inclusion of female participants in the male teams, as this would not be representative of actual football settings. Additionally, differences exist between male and female players in terms of physical capacities[47] and match running performance.[48] Sex-related differences have also been reported, attributed to a larger body surface-to-body mass ratio and lower sweat rates in females.[49] Therefore, a replication of this research with female football players is highly warranted.

2.2. Overview

The four matches analyzed in this study were experimental matches conducted as part of a controlled research project investigating football matches in warm to hot conditions. Matches followed official 90-minute formats, with three referees present. The matches were held at varying environmental conditions and used different acute heat mitigation strategies. The strategies consisted of either cooling breaks (CB: cold towels dipped in water [5–7 °C] applied to the head, neck and upper body and ingestion of cold drinks [5 °C]) or drinks breaks (DB: passive rest and ingestions of temperate drinks [17 °C]). These breaks were performed for 10 min before and after the warm-up as a pre-cooling before the match, for 10 min during half-time and as additional 3-minute cooling or drinks breaks, at the 25th minute of each half-time. One match was conducted as a regular 90-minute match with no breaks (NB). The influence of these heat mitigation strategies is reported in a separate work.[22] Across the four matches, this resulted in seven distinct conditions: (1) 24.0 °C WBGT - CB; (2) 24.0 °C WBGT - DB; (3) 25.5 °C WBGT - NB; (4) 26.9 °C WBGT - CB; (5) 26.9 °C WBGT - DB; (6) 33.0 °C WBGT - CB; and (7) 33.0 °C WBGT - DB. Accordingly, combined match data was analyzed to assess associations between T_{core} and match running and physiological responses while controlling for the influence of WBGT and heat mitigation strategies.

2.3. Measurements

In the morning, 4 to 5 h before each match, participants ingested telemetric pills (eCelcius Performance, BodyCap, Hérouville-Saint-Clair, France) for continuous T_{core} monitoring at 30 second intervals. This method has been shown to be valid and reliable for monitoring T_{core}.[25] T_{core} is presented continuously and as the peak and mean for the entire match.

Before each match, participants were fitted with a global positioning system (GPS) device (WIMU Pro Elite Tracking System, Hudl, Lincoln, USA), previously reported to be valid for measuring running performance in team sports,[26] and a heart rate (HR) monitor (Garmin HRM Dual™, Garmin International, Inc., Olathe, USA). Running performance is presented as "per minute" to reflect time-relative performance and includes total (TD), walking (WD: 0–6 km/h), low to moderate-speed (LMSD: 6–18 km/h), high-speed (HSD: 18–24 km/h), and sprint (SD: >24 km/h) distance. HR is presented as the mean per match.

Participants' hydration was assessed by monitoring changes in body mass, fluid intake, and saliva osmolarity (SOSM). Nude body mass was measured pre- and post-match, as well as pre- and post-bathroom use, to monitor sweat and urine loss during the testing period. Fluid intake was monitored using individualized bottles, with participants being instructed not to spit, spill, or shower with the drink. The fluid remaining in the bottle was measured post-match. Sweat loss was calculated as: $Sweat\ Loss = Weight_{Baseline} - Weight_{Post} + Fluid\ Intake - Urine\ Loss$. Body mass loss was calculated using pre- and post-match body mass. SOSM was measured pre- and post-match using a handheld device (MX3 LAB Pro, MX3 Diagnostics, Austin, USA), which has been shown to reliably assess changes in hydration status.[27] Participants' hydration status was classified as hydrated (<65 mOsmol), mildly dehydrated (65–100 mOsmol), moderately dehydrated (100–150 mOsmol) and severely dehydrated (>150 mOsmol). These categories were provided by the company MX3 and are based on the SOSM values reported in the literature and distributions across the MX3 customer population. Additionally, sweat sodium concentration (SSC) was measured using sweat patches (5 × 7 cm; Tegaderm, 3M, USA) applied to the participant's forearm. The patches were applied before the match and affixed with medical tape to aim for a tightly sealed fit. However, water leaking into the patch, especially while players were using the wet towels for cooling, cannot be ruled out. The patches stayed on the arm for the full experimental match and were analyzed immediately post-match with the same mobile system (MX3 Lab Pro, MX3 Diagnostics, Austin, USA), according to previously validated procedures.[28]

Perceptual responses were recorded using the Rating-of-Fatigue (RoF) ranging from "not fatigued at all" (0) to "total fatigue/exhaustion" (10),[29] the Rating of Perceived Exertion (RPE) on a scale from "no effort" (0) to "maximum effort" (10)[30] and Thermal Sensation (TS) ranging from "very cold" (−5) to "very hot" (5).[31] These were recorded pre-match (except RPE), at halftime and post-match and are presented as peak values reported per match.

2.4. Statistical analyses

This is an observational study and data are reported as mean and standard deviation to describe characteristics of each match (Table 1). However, participants, environmental conditions and heat mitigation strategies differed across and even during these matches. Therefore, there was no statistical comparison performed between the matches and comparisons between different heat mitigation strategies used are reported in a separate work.[22] To investigate associations between physiological, running and perceptual factors with peak T_{core}, linear mixed models were performed. Environmental conditions (specifically, WBGT) and the heat mitigation strategies employed (HMS) were included as a fixed effect in these models to control for their potential influence on T_{core} and the participants were included as a random effect. This approach accounts for the repeated measures design with an unequal number of observations per participant and resulted in the following linear mixed models:

$$\text{peak } T_{core} \sim \text{Parameter} + (\text{WBGT} \times \text{HMS}) + (1|\text{Player ID}).$$

Model outcomes are reported as estimates and 95 % confidence intervals (CI95), standardized estimates (β) and standardized CI95 and explained variance (R^2). Effects were categorized as small ($\beta > 0.1$), medium ($\beta > 0.3$) or large ($\beta > 0.5$)[32]; explained variance was categorized as small ($R^2 > 0.01$), medium ($R^2 > 0.09$) or large ($R^2 > 0.25$).[33] Significance was set at $\alpha = 0.05$, but as each predictor was analyzed in a separate model, corrections for multiple comparisons were applied. Both a false discovery rate correction based on the Benjamini–Hochberg method and the Bonferroni correction were used. Interpreting results based on the Bonferroni correction shifted the alpha level to $p < 0.0036$, as in total fourteen associations were investigated. Hence both the raw *p*-values (for interpretation of Bonferroni correction) and the adjusted *p*-values (according to Benjamini–Hochberg) were reported for a transparent interpretation of results. The R software (Version 4.4.1) was used to perform all data analyses and create the figures. Goalkeepers were not included in the main analysis, due to their different running profile; nevertheless, their T_{core} values are reported separately.

3. Results

A descriptive summary of environmental, physiological, running, and perceptual markers per match is presented in Table 1. Across all four matches, the mean peak T_{core} was 39.2 °C ± 0.5 and ranged from 37.9 to 40.1 °C. Across all 61 individual player observations, T_{core} surpassed 39.0 °C in 72 % of cases (n = 44), 39.5 °C in 28 % cases (n = 17), and 40 °C in 2 % (n = 1). Fig. 1 shows the mean continuous variation of T_{core} throughout each match and per individual player. T_{core} responses in Matches 1, 2, and 4 show where a break was held before and after the warm-up and at the 25th minute of each half. In Match 3, no pre-match breaks nor additional breaks at the 25th minute of the halves were held. Fig. 2 shows the individual T_{core} development of each of the five valid T_{core} observations of the goalkeepers (who reached peak T_{core} values of 39.2 ± 0.4 °C).

Overall TD covered was 106.6 ± 8.5 m/min, representing 37.3 ± 3.7 m/min at walking speed, 61.1 ± 10.6 m/min at low-to-moderate speed, 6.9 ± 2.4 m/min at high-speed and 1.35 ± 1.0 m/min at sprinting speed. Participants mean sweat loss was 3.0 ± 0.7 L per match and fluid intake was 1.4 ± 0.5 L, resulting in a mean body mass loss of 2.3 ± 0.8 %. Participants started the match with a SOSM of 65.44 ± 20.1 mOsmol and ended with 102.6 ± 42.0 mOsmol post-match. Based on SOSM values, 29 participants were classified as hydrated, 30 as mildly and 2 as moderately dehydrated. Post-match observations indicated 12 hydrated, 19 mildly, 16 moderately and 14 severely dehydrated players and sweat sodium concentration was 772 ± 332.4 mg/L. Participants reached a RoF of 7.3 ± 1.6, RPE of 7.0 ± 1.9 and TS of 2.7 ± 1.2.

Across all participants' observations, total distance, walking distance and low-to-moderate speed distance, heart rate and sweat loss were associated with T_{core} (Table 2). Covering greater total distances was associated with higher peak T_{core} ($\beta = 0.39$ [0.13, 0.64], $p = 0.004$). Additionally, greater distance covered at low-to-moderate speed was associated with higher peak T_{core} ($\beta = 0.44$ [0.18, 0.69], $p = 0.001$). The distance covered walking was negatively associated with a high

Table 1
Mean and standard deviation values and range [mean ± SD (min–max)] for selected parameters per match, with matches ordered left to right from low to high wet-bulb globe temperature (WBGT).

	Match 2	Match 3	Match 1	Match 4
Situational				
WBGT (°C)	**24.0**	**25.5**	**26.9**	**33.0**
Temperature (°C)	28.4	26.0	29.3	42.1
Relative humidity (%)	30.8	80.9	50.6	36.5
In-play breaks	Yes	No	Yes	Yes
Valid T_{core} and GPS (n)	14	18	10	19
Physiological				
Peak T_{core} (°C)	38.9 ± 0.45 (37.9–39.5)	39.4 ± 0.40 (38.7–40.1)	39.5 ± 0.46 (38.5–39.9)	39.3 ± 0.41 (38.5–39.9)
Mean T_{core} (°C)	38.4 ± 0.43 (37.7–38.9)	38.9 ± 0.40 (38.2–39.4)	38.9 ± 0.44 (37.9–39.4)	38.6 ± 0.30 (38.2–39.4)
Mean heart rate (bpm)	163.8 ± 9.4 (147–174)	170.7 ± 9.80 (146–185)	171.0 ± 10.1 (149–183)	167.5 ± 8.10 (151–178)
Sweat loss (L)	2.9 ± 0.30 (2.3–3.3)	2.7 ± 0.70 (1.3–3.8)	2.7 ± 0.62 (2.2–4.2)	3.4 ± 0.76 (2.1–4.7)
Fluid intake (L)	1.4 ± 0.34 (0.7–2.0)	1.1 ± 0.27 (0.6–1.6)	1.3 ± 0.33 (1.0–2.0)	1.9 ± 0.56 (1.1–3.0)
Body mass loss (%)	2.1 ± 0.54 (1.1–3.2)	2.5 ± 0.83 (0.4–3.7)	2.2 ± 0.7 (1.5–4.0)	2.2 ± 0.95 (0.2–3.5)
Pre-match SOSM (mOsmol)	63.9 ± 9.3	67.7 ± 28.9	62.9 ± 18.2	65.8 ± 17.8
Post-match SOSM (mOsmol)	80.1 ± 23.9	101.0 ± 29.3	95.8 ± 55.9	123.9 ± 45.7
Dehydrated players pre-match	43 %	56 %	60 %	53 %
Dehydrated players post-match	64 %	94 %	70 %	84 %
Sweat sodium composition	728.6 ± 282.6	756.7 ± 469.6	885.0 ± 207.5	762.6 ± 268.3
Running performance (m/min)				
Total distance	107.9 ± 9.20 (91–121)	106.5 ± 9.92 (90–130)	110.4 ± 4.32 (105–118)	103.6 ± 7.79 (93–120)
Walking (<6 km/h)	35.9 ± 4.1	37.5 ± 3.4	34.9 ± 3.0	39.3 ± 3.1
Low–moderate-speed (6–18 km/h)	61.5 ± 11.5	61.2 ± 11.3	67.2 ± 7.6	57.3 ± 9.7
High-speed (18.1–24 km/h)	8.4 ± 2.9	6.8 ± 2.2	7.2 ± 2.5	5.7 ± 1.8
Sprinting (>24 km/h)	2.0 ± 1.3	1.1 ± 0.9	1.2 ± 0.8	1.2 ± 0.7
Perceptual				
Peak thermal sensation	7.1 ± 1.3	7.4 ± 0.9	7.1 ± 1.3	8.8 ± 0.4
Peak rating of fatigue	5.9 ± 1.4	7.8 ± 1.1	6.0 ± 1.5	8.4 ± 0.9
Peak RPE	5.4 ± 1.3	7.7 ± 1.7	5.7 ± 1.5	8.1 ± 1.4

Abbreviations: WBGT = wet-bulb globe temperature; T_{core} = core temperature; HR = heart rate; SOSM = saliva osmolality; RPE = rating of perceived exertion.

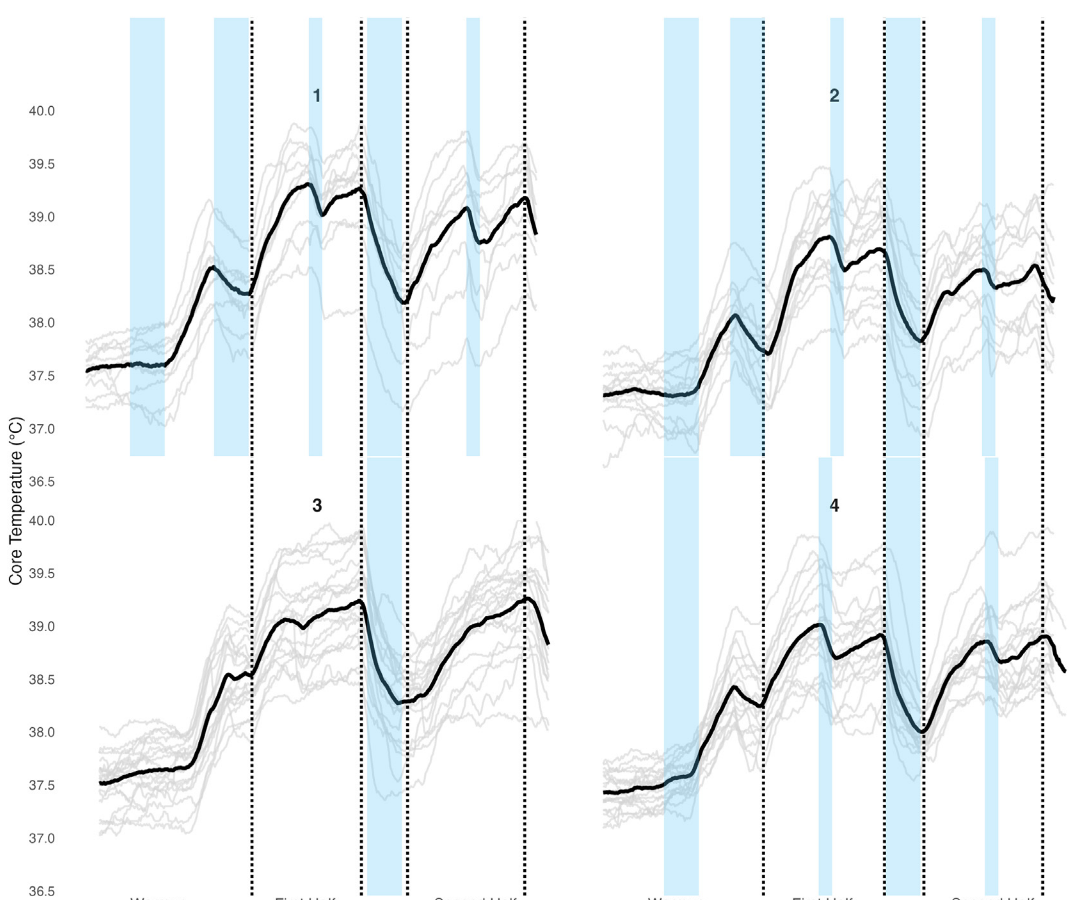

Fig. 1. T_{core} development per match for all participants (black) and each individual observation (gray).

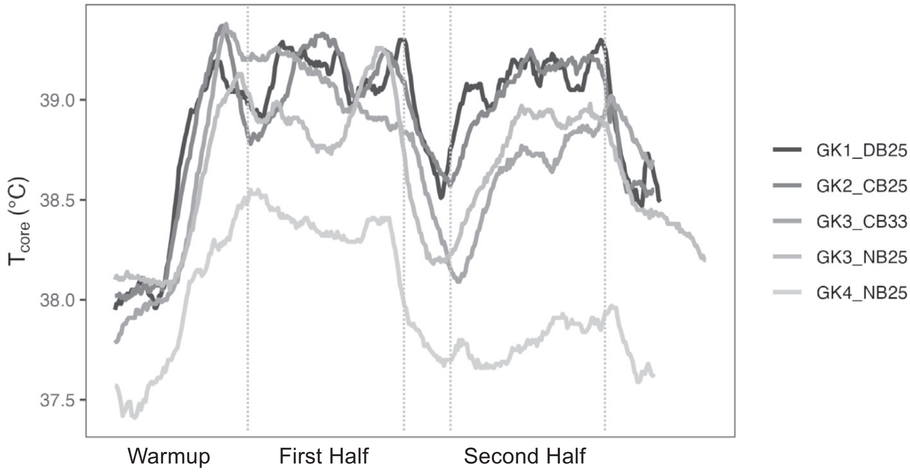

Fig. 2. Associations between different markers and peak T_{core}.

peak T_{core} (β = −0.42 [−0.69, −0.15], p = 0.003). High-speed running (β = 0.08 [−0.20, 0.35], p = 0.58) and sprinting (β = 0.02 [−0.23, 0.27], p = 0.89) distances were not associated with peak T_{core}. A higher HR was associated with a higher T_{core} (β = 0.37 [0.10, 0.64], p = 0.008). Additionally, higher sweat loss (β = 0.38 [0.14, 0.62], p = 0.002) and body mass loss (β = 0.20 [0.00, 0.40], p = 0.047) were also associated with higher peak T_{core}, but not fluid intake (β = 0.30 [−0.02, 0.62], p = 0.07), pre-match SOSM (β = −0.07 [−0.29, 0.15], p = 0.54) or post-match SOSM (β = 0.20 [−0.03, 0.43], p = 0.09). Peak TS (β = 0.01 [−0.30, 0.30], p = 0.98), RoF (β = 0.06 [−0.32, 0.44], p = 0.74) and RPE (β = 0.04 [−0.26, 0.34], p = 0.78) were not associated with peak T_{core}. Fig. 3 presents the linear relationships between peak T_{core} and selected running performance, physiological and perceptual markers. Fig. 4 illustrates the effect size (β) for each of the tested associations, ranking them from the largest positive association to the largest negative association.

3.1. Case reports of players reaching T_{core} ≥ 39.9 °C

During this study, seven players reached a T_{core} ≥ 39.9 °C. Their individual values and characteristics are presented in Supplementary Table 1. One of these players reached a T_{core} higher than 40 °C. This was recorded at the end of Match 3 (i.e., the match with no additional breaks). This player, a wide midfielder, covered 114 m/min and had a mean HR of 169 bpm. Over the course of the match, he lost 2 L of sweat (1.9 % body mass loss); however, he started the match moderately hypo-hydrated, resulting in severe dehydration post-match. Furthermore, one case of EHI was recorded during Match 4, at 33 °C WBGT. The affected participant (a forward) suffered from muscle cramps in the second half, while exhibiting a peak T_{core} of 39.9 °C, a sweat loss of 4.2 L (2.2 % body mass loss) and severe dehydration post-match (SOSM = 150 mOsmol). He covered 106 m/min TD, including 2.9 m/min at sprinting speed, the highest sprinting distance of all participants in that match. The other five players reaching a T_{core} of 39.9 °C were either central midfielders (n = 3) or central defenders (n = 2), lost 2.7–4.2 L of sweat (2.2–4.0 % body mass loss), and covered distances of 104–130 m/min with mean heart rates of 161–183 bpm (max HR = 180–206 bpm). Of these seven observations, four occurred in Match 3, two in Match 1, and one in Match 4.

4. Discussion

This study examined 40 highly-trained and seasonally acclimatized youth football players across four matches, resulting in 66 sets of T_{core} measurements in environmental conditions ranging from 26 to 42 °C T (24–33 °C WBGT). In each match, similarly elevated T_{core} peaks (39.2 ± 0.5 °C) were observed consistently, with at least some participants reaching 39.5 °C or higher in each match. Increased T_{core} was associated with covering a greater total distance and distance at low-to-moderate-speed (6–18 km/h), whereas retaining a lower T_{core} was associated with more walking (0–6 km/h). Additionally, a high T_{core} was associated with physiological markers, such as a higher HR, sweat loss and body mass loss, but not perceptual markers, such as RoF, TS or RPE.

Table 2
Linear mixed model outcomes.

	Estimate (CI95)	β: standardized estimate (CI95)	R^2 (marginal)	p-Value	p-Value (fdr-adjusted)
TD	0.02 (0.01, 0.03)	0.39 (0.14, 0.64)	0.341	0.004**	0.013*
WD	−0.05 (−0.09, −0.02)	−0.42 (−0.69, −0.15)	0.349	0.003**,#	0.013*
LMSD	0.02 (0.01, 0.03)	0.44 (0.18, 0.69)	0.375	0.001***,#	0.013*
HSD	0.01 (−0.04, 0.07)	0.08 (−0.20, 0.35)	0.206	0.577	0.807
SD	0.01 (−0.11, 0.13)	0.02 (−0.23, 0.27)	0.202	0.894	0.963
HR	0.02 (0.01, 0.03)	0.37 (0.10, 0.64)	0.305	0.008**	0.024*
Fluid intake	0.27 (−0.01, 0.55)	0.3 (−0.02, 0.62)	0.256	0.068	0.136
Sweat loss	0.26 (0.10, 0.41)	0.38 (0.14, 0.62)	0.302	0.002**,#	0.013*
Body mass loss	0.12 (0.01, 0.23)	0.20 (0.01, 0.40)	0.228	0.047*	0.109
Pre-SOSM	−0.00 (−0.01, 0.00)	−0.07 (−0.29, 0.15)	0.204	0.537	0.807
Post-SOSM	0.00 (0.00, 0.01)	0.20 (−0.03, 0.43)	0.23	0.091	0.159
TS	0.00 (−0.11, 0.12)	0.01 (−0.30, 0.30)	0.202	0.975	0.975
RoF	0.02 (−0.09, 0.12)	0.06 (−0.32, 0.44)	0.204	0.741	0.906
RPE	0.01 (−0.06, 0.08)	0.04 (−0.26, 0.34)	0.203	0.777	0.906

*p < 0.05; **p < 0.01; ***p < 0.001; #p < 0.0036 (Bonferroni corrected p-value); fdr-adjusted = false discovery rate adjusted (according to Benjamini–Hochberg method).
Abbreviations: TD = total distance covered; WD = walking distance; LMSD = low-to-moderate speed distance; HSD = high-speed distance; SD = sprint distance; HR = heart rate; SOSM = saliva osmolality; TS = thermal sensation; RoF = rating of fatigue; RPE = rating of perceived exertion.

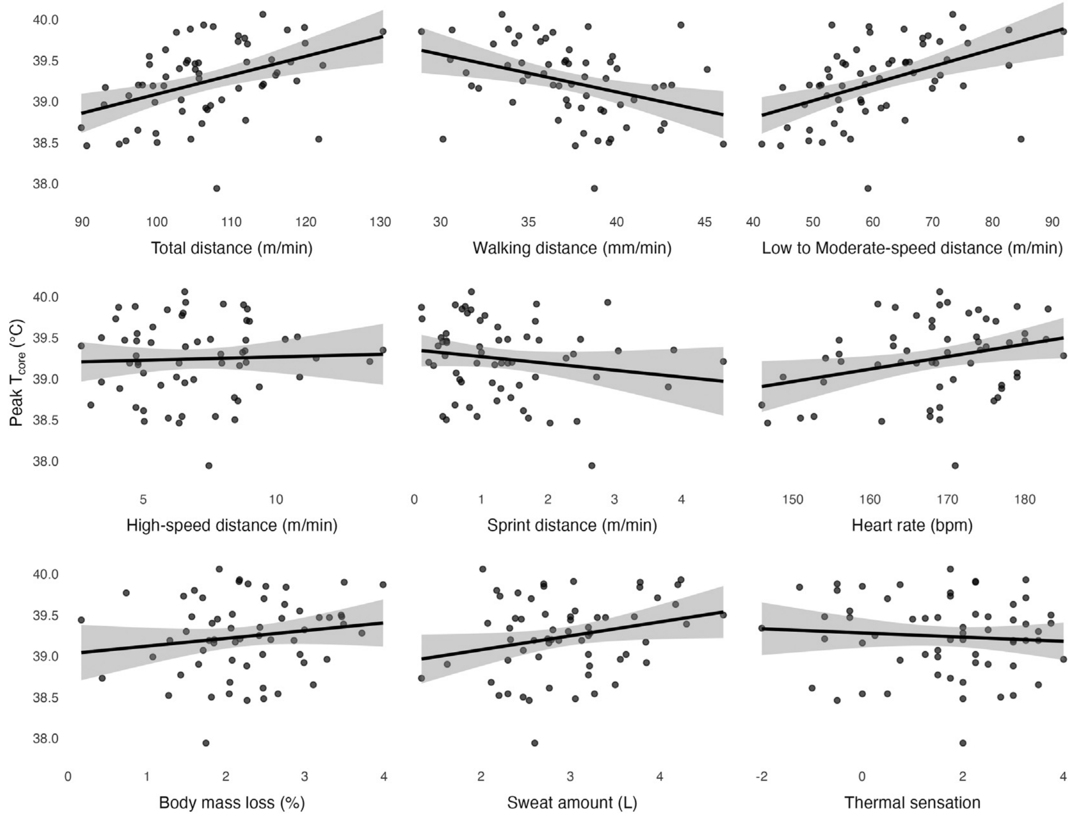

Fig. 3. Factors associated with a higher peak T_{core} showing the standardized coefficient β (point) and 95 % confidence interval (whiskers) in black when $p < 0.05$ and gray when $p > 0.05$ for linear mixed models controlling for the influence of different conditions including match environmental conditions and break conditions.

The peak T_{core} values reported are slightly lower compared to those of previous field-based studies, which have observed mean peaks of 39.3 ± 0.5 °C,[12] 39.6 ± 0.3 °C,[14] 39.7 ± 0.1 °C,[13] and 39.9 ± 0.4 °C.[11] The higher peak T_{core} values might be linked to several factors. Firstly, hotter environmental conditions were observed in prior studies, including matches at 34–36 °C[14] and 43 °C[13] and the participating players were not acclimatized to such conditions.[13,14] Additionally, in Mohr et al.[13] players covered higher running volumes compared to this study. In Duffield et al.[11] actual league competition was investigated, where intensities might be higher compared to experimental matches in youth competitions. Interestingly, Edwards and Clark[12] found that recreational players reached a peak T_{core} of 39.3 ± 0.5 °C even when playing at just 16 °C, while the professional players remained at a lower T_{core}. Finally, in three of the four matches observed for this study, pre-cooling, drinks and cooling breaks were implemented as heat mitigation strategies, while previous studies investigated regular matches without cooling breaks. In the current data, 17 participants reached a T_{core} of 39.5 °C or higher. Of these 17 observations, six occurred in Match 1, six in Match 3, and five in Match 4, indicating that in Match 2 the heat strain was arguably lower. The highest WBGT was recorded in Match 4, but this was also the match with the lowest total running distance covered. Additionally, relative humidity was high in Match 1 (51 %) and Match 3 (81 %), which were settings where WBGT is known to underestimate heat stress.[34]

Match running performance in this study was comparable to that reported previously in similar age groups[35] and even elite competition,[36] with players covering 106.6 ± 8.5 m/min: 35 % walking, 57 % at low-to-moderate speeds, 7 % at high speeds, and 1 % sprinting. The sweat loss of 3 L per match, corresponding to a body mass loss of 2.3 %, also aligns with previously reported ranges of 1.8 to 4.1 L and 1.6 to 2.3 %, respectively.[12–14] Concerningly, SOSM measurements indicated that 52 % of participants were not optimally hydrated pre-match. This value increased post-match to 80 %, including 16 players categorized as moderately and 14 as severely dehydrated. Although the use of saliva osmolarity to assess hydration status in a field and team sport setting requires further validation, this mirrors existing studies, where 41 %[37] and 66 %[38] of football players were training in a dehydrated state.

In the presented match observations, reaching high T_{core} values was associated with running performance metrics. This is consistent with existing theories in thermoregulation: the metabolic rate (here based on individual match demands) is a key driver of heat strain.[6,8,39] Previous studies have observed that players reduce their total distance covered in hotter environmental conditions[16,40]; however, the present study is the first to confirm that this reduction is associated with maintaining a lower T_{core}. Specifically, participants covered less distance at low-to-moderate speeds and covered increased distances walking. This shift to a lower intensity illustrates how exercise intensity and, consequently, metabolic rate and metabolic heat production are related to the observed heat strain.[6,8] These results suggest that the overall match strategy and tactical considerations in the heat might be adapted to manage heat strain, as noted previously in Australian football.[41] Additionally, teams or players aiming to maintain tactical match approaches that rely on covering high running distances, even when playing in the heat may need to consider intensified acute heat-mitigation strategies, for instance, applying internal or external cooling or to closely monitoring players' hydration status to promote optimal euhydration. Goalkeepers also reached high peak T_{core} values exceeding 39 °C. Interestingly, in contrast to outfield players, goalkeepers reached peaks toward the end of the warm-up instead of during the match. This might reflect that goalkeepers cover more running distance during the warm-up than during actual match-play.

A higher HR, sweat loss and body mass loss were also associated with a higher T_{core}, showing how the elevated heat strain is associated with an increased thermoregulatory response, including subcutaneous

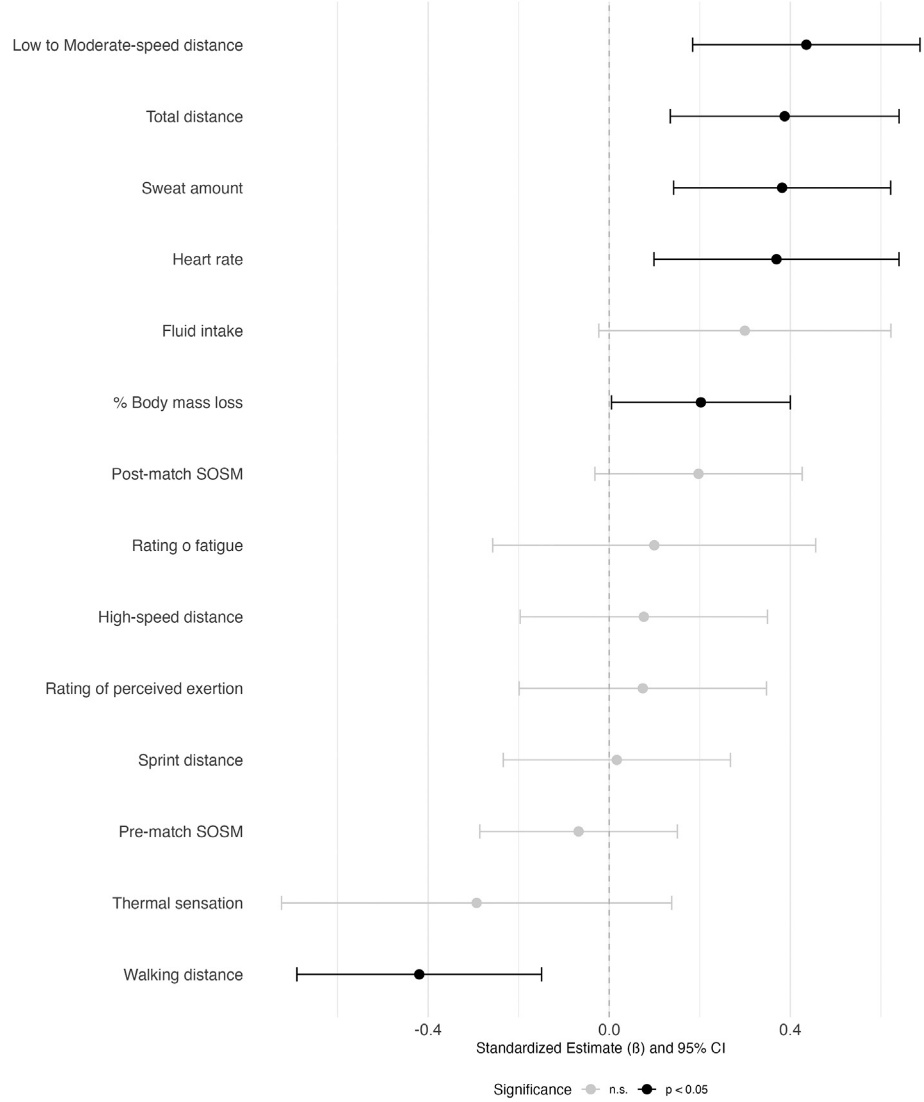

Fig. 4. T_{core} development of goalkeepers.

vasodilation and sweating to dissipate heat.[8] Both mechanisms, either due to the blood volume shift or dehydration, reduce the central blood volume, resulting in a lower cardiac filling and stroke volume which leads to a higher cardiovascular strain in the heat.[42] In contrast, perceptual factors were not associated with T_{core}, confirming existing studies, which have indicated that thermal sensation and discomfort were less associated with T_{core}, but rather with T_{skin}.[11,18,43]

In football, investigations on the incidence of EHIs are scarce. In American collegiate soccer competition, 0.7 and 1.1 EHIs were reported per 10,000 athlete exposures during the season and pre-season.[44] However, actual incidences are likely higher, due to many suspected non-reported cases.[10] As both EHI and EHS incidences are reported to increase with the growing heat exposure worldwide, it is important to identify the factors associated with elevated heat strain in athletic populations.[45] During this study one case of EHI (muscle cramps; T_{core} of 39.9 °C) was suspected during the match at 33 °C WBGT. The affected participant had high sweat loss (4.2 L) and body mass loss (2.2 %), was dehydrated post-match (SOSM = 150 mOsmol), and covered high total and sprinting distance.

Despite its strengths in ecological validity, a field-based data-collection also has limitations that need to be addressed. Two important considerations are that the matches were held under different environmental conditions and participants employed different heat mitigation strategies. This may hamper the interpretation of T_{core} variation but reflects real-world scenarios. Those factors were included as fixed effects in the mixed models to identify the parameters that are consistently associated with reaching a high T_{core} regardless of mitigation strategies or objective external circumstances. Additionally, 22 observations had to be excluded due to telemetric pills remaining in the stomach (n = 15) or being excreted too early (n = 4), GPS device failures (n = 1), or participant injury (n = 2). Telemetric pills remaining in the stomach was mainly an issue in the first match when this occurred in 11 participants. For the following matches the timing for pill ingestion was adjusted from 4 to 5 h before match start, resulting in only four more pills remaining in the stomach, but the same number of pills was being excreted prior to data-collection. This underscores the difficulties to simultaneously monitor T_{core} in large groups. Finally, this study investigated seasonally acclimatized and highly trained male youth footballers. Future research should also examine other populations, including younger or older players, females, amateurs and unacclimatized athletes. A trend for covering greater overall and high-speed distances was observed in younger age groups, potentially related to a lower match tactical and technical understanding,[35] which could result in a higher heat strain in younger football players, who additionally might have less experience in pacing. Two recent studies investigating treadmill running simulating football and cooling procedures in a hot environment revealed different outcomes for male and female participants.[20,46] Amateur players might be affected differently by hot conditions due to their lower fitness levels and unacclimatized athletes could be expected to experience higher heat strains.[8] Therefore, further studies with different cohorts are needed to determine T_{core} responses in other settings.

5. Conclusion

In conclusion, football players experienced a high heat strain with elevated T_{core} values and high sweat losses, even under moderate conditions (24 °C WBGT) and despite being seasonally acclimatized. Reaching a high T_{core} was associated with covering greater total and low-to-moderate-speed distance, lower walking distance, and higher heart rate and sweat loss.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2025.12.009.

Informed consent

Following an explanation of study procedures and measurements during an initial familiarization session, participants provided written informed consent.

Confirmation of ethical compliance

Ethical approval was granted by the Ethics Committee of the Faculty for Human and Business Sciences of Saarland University (Ref No.: 23-14).

Clinical trial register statement

This study was registered at the German Clinical Trials Register with the DRKS-ID: DRKS00032208, which can be accessed at: https://drks.de/search/en/trial/DRKS00032208.

CRediT authorship contribution statement

Edgar Schwarz: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Catarina B. Oliveira:** Conceptualization, Resources, Investigation, Writing – review & editing. **Monica Duarte Muñoz:** Conceptualization, Resources, Investigation, Writing – review & editing. **Agustín Alanis:** Conceptualization, Investigation, Project administration, Resources. **Marcela Alanis:** Investigation, Resources. **Aldo Lara:** Investigation, Resources. **Alfredo Freeze:** Investigation, Resources, Supervision. **Júlio A. Costa:** Conceptualization, Resources, Writing – review & editing. **Leander Eckerle:** Formal analysis, Writing – original draft. **Tim Meyer:** Conceptualization, Supervision, Funding acquisition, Methodology, Resources, Validation, Writing – review & editing. **Rob Duffield:** Conceptualization, Supervision, Funding acquisition, Methodology, Resources, Validation, Investigation, Writing – review & editing.

Declaration of interest statement

The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. Edgar Schwarz receives a scholarship from the 'Deutsche Fußball Liga GmbH' (DFL) that is operating the German Bundesliga 1 & 2. Tim Meyer is chairman of a DFL working group entitled 'Medicine in Professional Football' and chairman of UEFA's and the German FA's (DFB) medical committees. Rob Duffield is the Head of Research and Development at Football Australia. Julio A. Costa works as a Sport Scientist for the Portuguese Football Federation.

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Data availability

The datasets generated during and/or analyzed during the current study are not publicly available due to being team specific data of Club Tigres UANL but are available from the corresponding author upon reasonable request.

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