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Football in the Heat:
Performance, Health and Mitigation Strategies

by Edgar Schwarz

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under the supervision of

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in conjunction with the

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Preface I: Certificate of Original Authorship

I, Edgar Schwarz, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Institute of Sport and Preventive Medicine of the Medical Faculty at Saarland University, and School of Sport Exercise and Rehabilitation of the Faculty of Health at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree at any other academic institution except as fully acknowledged within this text. This thesis is the result of a Collaborative Doctoral Research Degree program between Saarland University and the University of Technology Sydney.

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Preface II: Presentation of included Studies

This is a cumulative thesis, comprising a compilation of five individual studies, framed by a general introduction, theoretical background and discussion. Studies 1, 2, and 3 are already published and the corresponding references are included in this thesis. Study 4 is currently in the second round of revisions for the Journal “Sports Medicine”. The contents of studies 1 - 4 are presented exactly as published or submitted, but the formatting has been adapted to fit the overall format of this thesis. Therefore, subheadings and some specific sections can differ slightly between the studies, as they reflect the journal-specific requirements. Study 5 is presented as a final draft, reviewed by all co-authors and ready for submission. References for all five studies and the umbrella text are collated in the “Reference” section at the end of the thesis. Figures and tables are numbered continuously throughout the thesis, across all individual studies. As a result, the numbering does not correspond to that in the original publications.

Preface III: List of Studies relevant to this Thesis

i. Schwarz, E., Duffield, R., Novak, A.R., Görres, T., Meyer, T. (2024). Associations Between Match Running Performance and Environmental Temperatures in 4 Professional Football Leagues. *International Journal of Sports Physiology and Performance, 20(*1), 109-119. https://doi.org/10.1123/ijspp.2024-0248

ii. Schwarz, E., Duffield, R., Novak, A. R., Compton, D., Meyer, T. (2025). Associations Between Match Play Characteristics and Environmental Temperatures in 4 Professional Football Leagues. *European Journal of Sport Science, 25(*3), e12256. https://doi.org/10.1002/ejsc.12256

iii. Schwarz E, Duffield R, Lu D, Fullagar H, aus der Fünten K, Skorski S, Tröß T, Hadji A, Meyer T. (2025). Associations Between Injury Occurrence and Environmental Temperatures in the Australian and German Professional Football Leagues. *Environmental Epidemiology*, *9(*1), e364. https://doi.org/10.1097/EE9.0000000000000364

iv. Schwarz E, Oliveira CB, Muñoz MD, Alanis A, Alanis M, Lara A, Freeze A, Costa JA, Meyer T, Duffield R. (under review). Effects of Pre-Cooling and Cooling Breaks on Thermoregulatory, Physiological and Performance Responses during Football in Moderate and Hot Temperatures. *Sports Medicine. Under 2nd Revision.*

v. Schwarz E, Oliveira CB, Muñoz MD, Alanis A, Alanis M, Lara A, Freeze A, Costa JA, Eckerle L, Meyer T, Duffield R (final draft for submission). Core Temperatures Responses during Football Matches in the Heat – Associations with Physiological and Running Demands.

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Abbreviations

General Parameters

%	Percentage
°	Degree
° C	Degree Celsius
AF	Air flow
BML	Body mass loss
CB	Cooling break
Cross%	Success rate of crosses
DB	Drinking break
Duel%	Success rate of duels
ED	Explosive distance
EHI	Exertional heat illness
EHS	Exertional heat stroke
ExtHT	Extended halftime
FSTR	Football simulating treadmill running
G1, G2, etc.	Group 1, group 2, etc.
GPS	Global positioning system
HI	Heat index
HR	Heart rate
HS	Heat stress
HSD	High-speed distance
HMS	Heat mitigation strategy
L	Liter
L/h	Liters per hour
L/min	Liters per minute
LSD	Low-speed distance
m	Meter
m/min	Meters per minute
m/s	Meters per second
M1, M2, etc.	Match 1, match 2, etc.

min	minute
mOsm	Milliosmole
MSD	Moderate-speed distance
n	Number of participants/observations
NB	No break
NS	Number of Sprints
Pass%	Success rate of passes
PI	Performance indicator
RH	Relative humidity
RoF	Rating of fatigue
RPE	Rating of perceived exertion
SD	Sprint distance
Shot%	Success rate of shots
SR	Solar radiation
SSC	Sweat sodium concentration
T / T_{air}	Ambient air temperature
T1, T2, etc.	Trial 1, trial 2, etc.
$T_{black\ globe}$	Black globe temperature
T_{brain}	Brain temperature
T_{core}	Body core temperature
TD	Total distance
T_{muscle}	Muscle temperature
$T_{natural\ wet\text{-}bulb}$	Natural wet-bulb temperature
TS	Thermal sensation
T_{skin}	Skin temperature
U18/U19/U23	Under 18-, 19- or 23-year-old (age categories in football)
UTCI	Universal thermal climate index
$VO_{2\ max}$	Maximum oxygen uptake
WBGT	Wet-bulb globe temperature

Football leagues and organizations

AFC	Asian Football Confederation
AL	A-League (highest Australian football league)
BL1	Bundesliga 1 (highest German football league)
BL2	Bundesliga 2 (2nd highest German football league)
CAF	Confédération Africaine de Football
CONMEBOL	Confederación Sudamericana de Fútbol
DFB	Deutscher Fußball Bund (German Football Federation)
DFL	Deutsche Fußball Liga GmbH (organization running BL1,2)
FIFA	Fédération Internationale de Football Associations
FIFPRO	Fédération Internationale de Associations des Footballeurs Professionels
IFAB	International Football Association Board
JL	J-League (highest Japanese football league)
Liga MX	Liga MX (highest Mexican football league)
LL	La Liga (highest Spanish football league)
SL	Süper Lig (highest Turkish Football League)
UANL	Universidad Autonoma de Nuevo Leon
UEFA	Union of European Football Associations

Statistical Parameters

ANOVA	Analysis of variance
Beta (ß)	Standardized coefficient (effect size)
CI95	95% confidence interval
GLMM	Generalized linear mixed model
IQR	Inter quartile range
LMM	Linear mixed models
p	P-value
r	Correlation statistic
R^2	R-squared (explained variance)
SD/sd	Standard deviation
Tukeys HSD	Tukey's honest significant difference

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ABSTRACT

Abstract

Introduction. The increasing exposure to hot environmental conditions in football poses a growing challenge. This is driven by both, an expanding match calendar that includes more matches during the hotter summer months, alongside climate change increasing the presence of hotter conditions. Physical activity generates metabolic heat, which needs to be dissipated to maintain a stable core temperature (T_{core}), primarily via skin vasodilation and sweating. In hot and humid conditions, the effectiveness of these thermoregulatory mechanisms is reduced, resulting in elevated cardiovascular strain and accelerated fatigue. This results in an impaired performance and can lead to potential health complications, such as exertional heat illnesses and alterations of injury rates when exercising in the heat. Consequently, football federations have begun implementing heat mitigation strategies and policies, such as additional cooling breaks, at varying thresholds of heat stress. Nonetheless, understanding of the effects of heat on real-world football performance and the efficacy of heat mitigation strategies remains limited, with most evidence derived from laboratory settings.

Aims. This thesis presents five original investigations addressing five key aims: The first three observational studies aimed at investigating the associations between environmental temperatures and i) match running performance, ii) match play characteristics, and iii) injury occurrence in real-world football matches. The fourth experimental study (iv) aimed to assess the effects of pre-cooling and cooling breaks on thermoregulatory, physiological and performance responses during real football matches. The fifth observational study's aim (v) was to describe T_{core} responses in football and identify associations with physiological and performance factors.

Methods. Three large observational studies were performed to address aims i-iii), characterizing the effects of heat on football matches. Large multi-league data sets were collected from open-source websites or shared directly by league organisations, containing match information (location, date, time, etc.) and performance (running or technical-/tactical actions) or injury data per match for both teams. Retrospectively,

temperature (T) and wet-bulb globe temperature (WBGT) were aligned to each of these matches using a weighted interpolation of historical environmental data from up to four weather stations close to the match venue. For the first study, mixed linear models were applied to assess associations between environmental temperatures and match running performance across 1610 matches from four professional football leagues. In the second study, mixed linear models were used to identify associations between environmental temperatures and match characteristics across 1585 matches from four professional football leagues. The third study used generalized linear mixed models to investigate associations between environmental temperatures and match injury occurrence across 2612 matches from two professional football leagues.

To address aim iv) and v), a field-based data collection was conducted involving four football matches played in WBGT ranging from 24 to 33 °C. In three of those matches pre-cooling and 3-minute cooling breaks (CB; consisting of iced towels and 5 °C drinks) were compared to performing 3-minute drinking breaks (DB; a passive rest with a 17 °C drink). One match was played as a regular match without additional breaks. For Study 4, mixed linear models were performed to investigate the effects of cooling on T_{core}, heart rate (HR), match running, hydration status, fluid balance and perceptual markers, such as the rating of fatigue (RoF), rating of perceived exertion (RPE) and thermal sensation (TS). For Study 5, the T_{core} responses of the players were explored, and factors associated with developing high T_{core} values identified via mixed linear models, controlling for the effects of different environmental conditions and heat mitigation strategies used.

Results. The observational studies addressing the first three aims of this thesis, revealed performance changes and indicated a potential small relationship to injury occurrence when playing football in hotter conditions. Study 1 showed reductions in total ($p < 0.001$) and high-speed running ($p < 0.001$) distances when WBGT was higher. Study 2 showed that in higher WBGT fewer passes ($p < 0.001$), including passes into the final third ($p = 0.002$), take-ons ($p < 0.001$) and touches ($p < 0.001$) were performed, while the success rate of passes increased ($p = 0.002$). In Study 3, there was a trend for higher injury occurrence in higher WBGT in one of the observed

leagues ($p = 0.05$), but additional data, particularly from matches played in hot conditions, is needed to confirm this relationship.

In the experimental matches, players experienced substantial heat strain (peak T_{core} = 39.2 ± 0.5; range: 37.9 – 40.1 °C) even under moderate conditions of 25 °C WBGT. Implementing additional 3-minute breaks effectively mitigated the continuous rise in T_{core}. Compared to drinking only, cooling reduced sweat loss ($p = 0.005$), but also fluid intake ($p = 0.002$) and improved perceptual responses (p range: < 0.001 to 0.05) in moderate heat stress (25 °C WBGT). Under more severe heat stress (33 °C WBGT), cooling also reduced sweat loss ($p = 0.02$) and body mass loss (= 0.007) and further lowered T_{core} ($p < 0.001$) and HR ($p = 0.007$), whilst preserving match running. When controlling for the variations in WBGT and heat mitigation strategies, higher T_{core} peaks were associated with higher total ($p = 0.004$) and low-to-moderate-speed ($p = 0.001$) distance, heart rate ($p = 0.008$) and sweat loss ($p = 0.002$). Goalkeepers experienced similar T_{core} peaks as outfield players, but typically reached those peaks at the end of the warm-up, due to their limited in-match movement.

Conclusion. This thesis provides robust field-based evidence on associations with playing football under heat stress. Hotter environmental conditions were associated with an impaired running performance and decreased technical and tactical match play actions. Potential implications for an elevated injury risk in the heat need further investigations. Playing football in hot conditions also resulted in a substantial thermoregulatory and physiological strain, which was mitigated by implementing pre-cooling and cooling breaks, particularly under severe heat conditions. Even at moderate WBGT levels (25 °C WBGT), players exhibited high T_{core} values, which was associated with covering more total and low-to-moderate-speed distance. Based on these findings an earlier implementation of additional cooling breaks might be beneficial to mitigate players heat strain. Football teams should consider the adjustments of playing style in the heat in tactical consideration and consider cooling to improve players performance and wellbeing. The findings underscore the need for ongoing monitoring and further research to develop and update evidence-based heat policies in football and protect players health and performance in a warming climate.

INTRODUCTION

Introduction

I1. The “Hot” Topic

Athletes are increasingly exposed to hot environmental conditions, largely driven by increasing temperatures related to global climate change. For example, the frequency of hot days has doubled in most parts of the world, when comparing the decade between 2011 and 2020 to the reference period of 1961 - 1990 (World Meteorological Organization, 2023). This trend is expected to intensify, with longer, more frequent, and more severe heatwaves predicted to occur, even in previously temperate regions (Christidis et al., 2015; Klingelhöfer et al., 2023). This poses a growing challenge for participants in all outdoor sports, in particular in football, due to its global popularity and year-round competition schedules (Gouttebarge et al., 2023). Increasing summer competitions, including expanded international tournaments, new club competitions and off-season “marketing tours” further amplify the risk of exposure to hot conditions. The next three men’s World Cups will be hosted by the United States - Canada - Mexico, (2026), Spain - Morocco - Portugal (2030), and Saudi Arabia (2034), while the next women’s World Cup will be held in Brazil (2027). These regions are expected to present high heat stress to elite footballers. For instance, 10 of the 16 host cities for the 2026 World Cup are projected to face severe heat stress during the tournament period (Linder-Cendrowska et al., 2024). At the youth and amateur level, exposure to high temperatures is also likely to increase, particularly during summer-based tournaments and pre-season periods. For this cohort, hot conditions might be especially dangerous, as they typically lack access to the professional medical support available in elite environments. Thus, the need for effective monitoring, prevention and management of high heat strains is even more relevant. Therefore, football federations, clubs, player associations and researchers have rightfully begun to express their concerns about playing in the heat and are beginning to explore approaches to mitigate high heat strains (Nassis et al., 2024).

I2. Heat and Health

High temperatures typically do not pose a direct threat to young, healthy individuals with a functioning thermoregulatory system. Most heat-related health issues occur in elderly populations and those with pre-existing medical conditions (Epstein & Yanovich, 2019). However, heat can become dangerous during physical exercise, even for well-trained individuals (Roberts et al., 2023). Metabolic activity generates internal heat in proportion to the exercise intensity, which must be dissipated to maintain thermal balance. This is primarily achieved through skin vasodilation and sweating (Bernard et al., 2024). However, in hot and humid environments, the effectiveness of these mechanisms is compromised, leading to a greater cardiovascular strain (Périard et al., 2021). When heat gain exceeds heat loss, core body temperature (T_{core}) rises (Roberts et al., 2023). In many cases, athletes can tolerate elevated T_{core} levels without experiencing clinical symptoms (Singh et al., 2023). Nonetheless, excessive heat strain can result in exertional heat illnesses (EHI) including exertional heat stroke (EHS) in some cases (Périard et al., 2022). EHS is characterized by a critically high T_{core} and central nervous system dysfunction, which can lead to multiple organ failure and, if untreated, death (Laitano et al., 2019).

I3. Heat and Performance

Long before heat-related health adversities occur, heat strain manifests through performance decrements (Nybo et al., 2014). Elevated heat strain accelerates both central and peripheral fatigue, resulting in a performance decrease or earlier termination of the exercise before critical T_{core} values are reached (Périard et al., 2021). However, when highly motivated athletes override fatigue signals, dangerously high T_{core} levels can be attained (Périard et al., 2022). As such, reducing the exercise intensity is a key behavioural response to heat stress (Schlader et al., 2010). Consequently, performance alterations can be observed already at ~15 °C, particularly in endurance and repeated-sprint activities such as football (Maughan et al., 2010). Nonetheless, football performance is complex, involving physical, technical, and cognitive components, all of which are influenced by situational and motivational factors. Therefore, the effects of heat on football performance may diverge from those observed in pure endurance tasks. The most consistently reported finding in football is a reduction in total running distance during matches played in hotter conditions.

Most studies also showed a reduction in high-speed running, though there remains some uncertainty regarding which running speeds are affected (Draper et al., 2022; Illmer & Daumann, 2022; Mohr et al., 2012). Furthermore, tactical and technical behaviour may also be altered, with the most consistent finding being a higher rate of successful passes in the heat (Mohr et al., 2012; Nassis et al., 2015; Zhou et al., 2019). This has been linked to a lower number of duels, challenges and balls lost; which alongside reduced running behaviours described as slower and more static match-play (Mohr et al., 2012). The inconsistency in findings across studies may be attributed to variations in methodology, such as different sample sizes and settings or definitions of heat stress and performance indicators. For instance, one study observed semi-professional players in two experimental matches comparing a match at moderate heat (34 °C + 38% relative humidity (RH)), to a match at "high heat" (36 °C + 61% RH) (Özgünen et al., 2010). In contrast another study observed 2426 professional league matches comparing neutral (< 14 °C) to warm (≥ 14 °C) conditions (Link & Weber, 2015). This highlights the differences in existing studies, especially regarding the use of temperature categories, using various cut-offs for heat stress.

I4. Heat and Injuries

Playing in hot environmental conditions may also influence injury risk in football, which is shaped by both intrinsic (e.g., elevated fatigue) and extrinsic (e.g., environmental heat stress) factors (Dvorak et al., 2000). For instance, heat strain has been shown to impair cognitive function (Gaoua, Racinais, et al., 2011) and is associated with taking riskier decisions (Syndicus et al., 2018). Additionally, coordinative abilities such as proprioception (Ingersoll et al., 1992), postural stability during landing tasks (Distefano et al., 2013) and balance (Mtibaa et al., 2018) are negatively affected in hot conditions. These alterations have been linked to an increased susceptibility to injury (Distefano et al., 2013; Schmit et al., 2017; Spector et al., 2019). Accordingly, a relationship between heat stress and acute injury occurrence has been documented in different general and occupational populations (Martínez-Solanas et al., 2018; Otte im Kampe et al., 2016; Spector et al., 2019). However, there is a lack of research that includes temperature and epidemiological data in athletic contexts, especially team sports settings (Gabbett et al., 2007; Lee & Garraway, 2000).

I5. Heat and Mitigation Policies

To protect athletes from heat-related health issues and performance decrements, various heat mitigation strategies can be employed. The gold standard is a two-week heat acclimatization protocol (Tyler et al., 2016). However, due to organizational and time constraints, this is often not possible. Therefore, more acute strategies are needed, including ensuring the adequate hydration (Maughan & Shirreffs, 2008), implementing additional breaks (Bernard et al., 2024) and applying cooling interventions before or between bouts of exercise (Bongers et al., 2017; Bongers et al., 2015). In football, most heat policies focus on the introduction of additional cooling breaks, as introduced in the 2014 World Cup in Brazil. However, the thresholds for implementing these breaks vary. For example, the Fédération Internationale de Football Associations (FIFA) recommends cooling breaks at 32 °C WBGT, whereas the Football Australia implements them at 26 °C WBGT (Gouttebarge et al., 2023). During these 3-minute breaks, standard procedures typically follow the model used during the 2014 World Cup: players rest and drink, and occasionally apply wet and (presumably) cool towels to the head and neck. Although more effective cooling strategies have been identified in laboratory studies, the current strategy is guided by the practical constraints of a football match.

Over a decade after the introduction of the cooling breaks, more than 80 peer-reviewed studies on playing football in the heat have been published (Plakias et al., 2024), three of those examining the associations between environmental conditions and performance in the 2014 tournament itself (Chmura et al., 2017; Konefał et al., 2014; Nassis et al., 2015). Surprisingly, only three studies have examined the physiological effects of cooling breaks under football-simulated treadmill conditions (Brown et al., 2025; Brown et al., 2024; Chalmers et al., 2019), and only one field-based study (Duffield et al. 2013). Interestingly, that are as many as there have been position statements advocating the use of the breaks in the same period (Chalmers, 2017; Gouttebarge et al., 2023; Nassis et al., 2024). While these investigations in controlled laboratory conditions are essential to establish the physiological concept of cooling breaks, the translation to actual match settings remains unclear. No study has yet assessed the implementation and effects of cooling breaks during real football

matches. Similarly, laboratory evidence suggests that pre-cooling can benefit team sport athletes (Bongers et al., 2017), but only one study has examined pre-cooling in an actual football field setting. That investigation indicated that the benefits associated with cooling do not necessarily translate to real-world conditions (Duffield et al., 2013).

I6. Aims of this Thesis

The overall aim of the first three studies of this thesis is to characterize how (real-world) football matches are affected by elevated environmental temperatures. To address this, large datasets from multiple professional football leagues, across diverse geographic regions were analysed. This approach was chosen to identify robust and generalizable effects of heat on football, contrasting previous studies that focused on smaller datasets from individual competitions. This aim can be divided into three components: investigating the associations between elevated temperatures and match running performance (Study 1), match play characteristics (Study 2), and match injury occurrence in football (Study 3).

The aims of the fourth and fifth study of this thesis are to investigate the effects of pre-cooling and cooling breaks during actual football matches (Study 4) and to characterize T_{core} responses whilst identifying factors associated with reaching high T_{core} values in football players (Study 5). This was addressed through a field-based data collection, comprising four football matches played in warm to hot conditions (24 - 33 °C WBGT). In three of these matches an applicable cooling strategy, consisting of towels dipped in cold water and cold drinks, was applied pre-match, during cooling breaks and at halftime. Across all matches participants' T_{core}, heart rate (HR), match running, hydration status and fluid balance, as well as the rating of fatigue (RoF), rating of perceived exertion (RPE) and thermal sensation (TS) were measured.

According to the five aims, this thesis is structured around five original studies, addressing each of the aims highlighted in *Summary Box 1*. These investigations form the foundation of the thesis and are presented in full length following a general background section. A concluding general discussion synthesizes the findings,

addresses limitations, outlines practical implications, suggests directions for future research and provides a comprehensive conclusion.

Summary Box 1: The five aims of the thesis.

The five aims of the corresponding studies are to investigate:

i) Associations between environmental temperatures and match running performance in football

ii) Associations between environmental temperatures and match play characteristics in football

iii) Associations between environmental temperatures and injury occurrence in football

iv) Effects of pre-cooling and cooling breaks on thermoregulatory, physiological and match running responses during football

v) Core temperature responses in football and associations with physiological and performance demands

BACKGROUND

Background: Exercise in the heat

B1. Thermoregulation in General

Humans are endothermic homeotherms, meaning they regulate a relatively stable homeostatic core body temperature (T_{core}) between 36 - 37 °Celsius (°C) through metabolic processes (Geneva et al., 2019). To achieve this in varying environments, the body's thermoregulatory system, receives input from external (skin) and internal (e.g., mouth, stomach) temperature sensors, known as thermoreceptors (Nybo et al., 2014). When signals indicate a growing deviation in T_{core}, behavioural (voluntary) and autonomic (involuntary) adaptations are initiated. Behavioural adaptations include actions like putting on additional clothing or seeking heat sources in response to cold, versus seeking cooling or reducing work in response to heat (Périard & Racinais, 2019). In contrast, autonomic adaptations are physiological processes that occur without conscious control. For instance, in response to cold, the body constricts subcutaneous blood vessels to retain warm blood in the body's core or generate metabolic heat through thermogenesis (Périard & Racinais, 2019). In response to heat, subcutaneous blood vessels dilate, directing more blood to the skin for heat dissipation, accompanied by eccrine sweating and increased breath rates (Périard & Racinais, 2019).

The margins of T_{core} that humans can sustain are narrow. Hypothermia or hyperthermia can become life-threatening at deviations of just 4 - 5 °C below (Turk, 2010) and above (Périard et al., 2022) the normal range. Although higher fluctuations can be survived, as the most extreme examples include patients who survived a T_{core} of 13.7 °C (Gilbert et al., 2000) and 46.5 °C (Slovis et al., 1982); however both required week-long treatments for multiple organ failures. Long before such extreme T_{core} is reached, cold or warm environmental conditions challenge individuals with underlying health conditions. For instance, during cold waves, vasoconstriction can trigger cardiovascular occlusive diseases and during heat waves, vasodilation increases cardiovascular strain, increasing the risk for cardiac events (Anderson & Bell, 2009). However, healthy individuals can usually sustain a broad range of environmental

temperatures with minimal changes in T_{core} and return to normothermia within minutes and without additional aids (Brearly et al., 2023; Cramer & Jay, 2016).

B2. Thermoregulation during Exercise

During exercise, endogenous metabolic heat production becomes the primary driver of the thermoregulatory response, with environmental conditions playing a secondary role (Périard et al., 2021). When performing physical work, only about 20-25% of the metabolically generated energy is converted into movement, while 75-80% is released as heat (Périard et al., 2021). Consequently, metabolic heat production is closely linked to the metabolic rate and increases with exercise intensity (Cramer & Jay, 2016). This can lead to increases in T_{core} of about 0.5 - 1.5 °C per hour, depending on the exercise intensity, thermal environment, and other personal factors (Bernard et al., 2024). This generated heat must be dissipated from the body to avoid heat related health issues. Heat loss can appear through conduction, convection, radiation, evaporation and as respiratory heat loss (Ravanelli et al., 2019):

Conduction is the direct transfer of heat from the body to a colder object (Cramer & Jay, 2016). In football, this may occur before, in-between or after exercise, in example when ice packs are applied to the body. The rate of heat transfer depends on a) the temperature difference between the skin temperature (T_{skin}) and the object, b) the surface area in contact, and c) the thermal conductivity of the materials (Cramer & Jay, 2016). This is reversed when in contact with an object that has a temperature > T_{skin} (Cramer & Jay, 2016).

Convection is the heat transfer to a liquid or gas, such as water or (during football) air. The rate of heat transfer is determined by a) the body's temperature difference to the water or air, b) the body surface area exposed, c) the thermal conductivity (greater in water than air), and d) the velocity of the water or air flow (Cramer & Jay, 2016). This is reversed when the water or air temperature exceeds T_{skin} (Cramer & Jay, 2016).

Radiation occurs in environments with a mean radiant temperature below T_{skin}, where the body radiates heat in the form of electromagnetic waves (Cramer & Jay, 2016). This is reversed when the mean radiant temperature exceeds T_{skin}, typically when exercising under direct sun exposure (Cramer & Jay, 2016).

Evaporation occurs when sweat or applied water transforms from liquid to gas on the skin, requiring energy in the form of heat. Evaporative cooling is the most important form of cooling during exercise and is the only effective method when ambient temperatures exceed T_{skin} (Cramer & Jay, 2016).

Respiratory heat loss is the sum of the convective heat loss, when cooler inhaled air passes through the airways and lungs and evaporative heat loss when fluid evaporates into the inhaled air as it warms up inside the airways (Cramer & Jay, 2016).

B3. Heat Stress during Exercise

The level of heat stress during exercise, is primarily determined by three factors: the metabolic rate, the environmental conditions and the clothing. On a secondary level, the exposure duration (from minutes to consecutive days) and type (intermediate or constant) further influence heat stress levels (Bernard et al., 2024). In football, clothing, exposure duration and exposure type are largely predetermined, thus the metabolic rate and environmental conditions are mainly responsible for variations in heat stress.

Metabolic rate, or exercise intensity is directly linked to heat stress, in that an increase in oxygen consumption is linearly associated with greater metabolic heat generation (Cramer & Jay, 2016). In football, the oxygen consumption is mainly determined by the players running volumes and intensities. Players will typically cover a distance of 9-14 km during a 90-minute match whilst between 22-24% of these are covered at speeds above 15 km/h, 8-9% above 20 km/h and 2-3% above 25 km/h including hundreds of accelerations, decelerations and changes of direction (Bradley et al., 2010; Dolci et al., 2020). However, the running profile of players can vary

depending on personal and situational factors, such as the playing position and level, the team and opponent tactical approaches, the level of fatigue through previous exposures and also the environmental conditions (Draper et al., 2022; Griffin et al., 2020; Teixeira et al., 2022). Therefore, players can decrease running distances to control their level of metabolic heat stress, as shown in laboratory observations on self-paced exercise (Périard et al., 2021). However, football is not entirely self-paced, as the nature of the match and specific situations determine running behaviour. Thus, even if physical performance can be downregulated, the demands of competitive football will lead to a substantial degree of metabolic heat production, which needs to be dissipated.

Environmental conditions strongly determine how effective heat can be dissipated from the body. The heat dissipation capacities in a certain environment depend on several parameters, such as the ambient temperature (T), relative humidity (RH), air flow (AF) and solar radiation (SR). To produce a more inclusive parameter to assess environmental heat stress, these factors may be combined into more holistic heat stress indices. An often-used heat stress index is the wet-bulb globe temperature (WBGT).

Ambient temperature (T_{air}) is the commonly known temperature measured by a regular thermometer and is typically measured in the shade (e.g., for weather forecasts). Heat is lost via convection when $T_{air} < T_{skin}$ and gained when $T_{air} > T_{skin}$, with the rate of heat exchange depended on the gradient between T_{air} and T_{skin} (Périard et al., 2021). For context, T_{skin}, will usually be between 31 - 35 °C (Périard et al., 2021), thus at $T_{air} \sim 35$ °C convective heat loss will be reversed to heat gain and athletes depend on evaporative heat loss.

Relative humidity (RH) describes the amount of water vapor present in the air in relation to its maximum capacity at a given T_{air} and pressure. Higher humidity reduces the sweat evaporation capacity, as the air is already saturated with water, thus limiting a main source of heat dissipation (Périard et al., 2021).

Air flow (AF) is determined by environmental wind and athlete movement. Without sufficient AF the air surrounding the body quickly warms up and becomes saturated with water from evaporating sweat, creating an insulating layer. Conversely, high AF increases convective and evaporative efficiency (Périard et al., 2021).

Solar radiation (SR) is influenced by the zenith angle of the sun (which depends on the time of day, season and latitude) and cloud cover (Périard et al., 2021) and is the main contributor to the mean radiant temperature ($T_{radiant}$). In football a secondary factor could be the type of pitch, with artificial pitches radiating more heat compared to natural grass (Villavañas et al., 2016). If $T_{radiant} > T_{skin}$, this leads to environmental heat gain (Cramer & Jay, 2016).

Wet-bulb globe temperature (WBGT) is a heat stress index that aims to integrate T, RH, AF and SR into one heat stress assessment (ISO 7243). It was initially developed to assess hot environments and prevent heat illnesses in the military and combines three differently weighted temperature measurements (d'Ambrosio Alfano et al., 2014). The natural wet-bulb temperature ($T_{natural\ wet\text{-}bulb}$), measured by a thermometer wrapped in a wetted cloth, reflects the evaporative cooling efficiency of the environment and makes up for 70% of WBGT. The black globe temperature ($T_{black\ globe}$), measured inside a 15 cm black sphere, captures the radiant heat gain and makes up for 20% of WBGT. The remaining 10% is the T_{air} taken by a regular thermometer, resulting in the following formula (d'Ambrosio Alfano et al., 2014):

$$(0.7\ T_{natural\ wet\text{-}bulb}) + (0.2\ T_{black\ globe}) + (0.1\ T_{air})$$

Whilst various heat stress indices have been proposed since the development of WBGT around 70 years ago, not many have gained similar popularity. To date, WBGT remains the most common index to assess heat stress in sports and occupational settings. However, despite accounting for multiple relevant factors, WBGT has its limitations. For example it is criticized for often underestimating the actual heat stress in high humidity and low air flow environments (Brocherie & Millet, 2015; Budd, 2008). Further, when using WBGT there is no adequate way of accounting for any personal, situational factors or clothing factors (Brocherie &

Millet, 2015). Finally, a major limitation of WBGT is the difficulty in making a correct measurement, needing well calibrated and specialised equipment (Brocherie & Millet, 2015). Different estimation methods (Kong & Huber, 2022) as well as different measurement devices (Cooper et al., 2017) might deliver different WBGT levels.

Newer heat stress indices have aimed at including more factors into their models. By attempting to combine environmental conditions, with factors for the metabolic rate of the activity performed and adjustments for properties of the clothing worn, these indices aim at assessing a more individualized level of observed heat stress. One such example is the Universal Thermal Climate Index (Błażejczyk et al., 2013; Jendritzky et al., 2012). It was developed to assess heat strain across various environmental settings, and includes factors for the environment (T_{air}, RH, AF, SR), but also the metabolism and muscular activity and clothing of the individual (Blazejczyk et al., 2012). However, while such indices may improve the validity of the heat stress measurement, they require complex calculations and specialized equipment. This is often making them less practical for field settings, particularly at lower competition levels, where only measurements of T_{air} and sometimes RH are typically available.

B4. Heat Strain during Exercise

The heat strain is the body's physiological response to heat stress. This is influenced by mediating personal factors, which determine how well an individual can cope with a given heat stress (Bernard et al., 2024). Some key factors in football are the body composition and anthropometrics, the aerobic fitness, the acclimatization status and the hydrations status of players.

Body composition and anthropometrics, determine the possible rate of heat gain and loss. Whilst a higher body surface area aids heat dissipation (more sweat glands and larger area for dry heat exchange), adipose tissue has lower heat capacities (Cramer & Jay, 2016). Furthermore, in weight-bearing exercises, the energy cost (and therefore metabolic heat production) is higher for moving a heavier body (Cramer & Jay, 2016). This means, that taller, but leaner frames are

beneficial for heat dissipation and a higher body surface-to-mass ratio is related to observing lower heat strains (Périard et al., 2021).

Aerobic fitness is proposed to improve the thermoregulatory response and thus heat loss capacities. Aerobic training leads to an increased blood volume and greater cardiac output, which enables an earlier (at a lower T_{core}) activation of cutaneous vasodilation and sweating (Périard et al., 2021). However, this notion is challenged by others showing that during self-paced exercise, athletes with higher aerobic fitness display higher heat strains. This was linked to their higher work-rate, meaning they are only advantaged at a fixed exercise intensity (Mora-Rodriguez, 2012).

Acclimatization status describes how accustomed an individual is to observing heat stress, which determines the efficiency of thermoregulatory responses (Tyler et al., 2016). Full acclimatization can typically be achieved after 2 weeks of exercising in hot conditions. An increase in total body water, expanded plasma volume, reduced heart rate and increased stroke volume enable an earlier onset of and overall improved skin vasodilation and sweat response. Alongside other adaptations, this helps acclimatized athletes to remain a lower heat strain in a given heat stress (Tyler et al., 2016).

Hydration status is a contributor to blood plasma volume and a main determinator for the capacity of sweating. As evaporative heat loss is the most important pathway of heat loss during exercise, an impaired sweat response will exacerbate the observed heat strain in dehydrated athletes compared to hydrated athletes (Stachenfeld, 2014).

In a football match, all 22 players experience the same environmental heat stress and wear the same clothing (except the goalkeeper). The main factors determining which players observe the greater heat stress are therefore their individual anthropometrical and thermoregulatory differences, determining heat dissipation, and their exercise related metabolic rate, determining their heat generation. Players that run faster and

cover more distance, should be the ones observing the higher heat stress. As a result, differences in the observed heat strain are also largely influenced by personal factors. Players that display a higher aerobic fitness, would in theory observe a lower heat strain, at a given intensity. But those players are typically also the ones that cover a greater distance. Whilst the acclimatization status should be similar across a team, this may vary between teams from different locations. The hydration status might be the most variable out of the personal factors (Maughan & Shirreffs, 2008). Summary Box 2 summarizes factors potentially leading to high heat strains in football.

Summary Box 2: Risk factors for high heat strains in football.

Environment	High temperatures, high humidity, low airflow, high solar radiation Non-acclimatized players (e.g., start of summer, start of-preseason, travelling to a hotter environment, unusual early heat days in spring) Consecutive days (and nights) of heat exposure
Exercise	High exercise intensity; Prolonged exercise without sufficient breaks; Players with low fitness levels (e.g., during pre-season, a player returns to play after injury or sickness)
Motivation	High motivation (e.g., important competition; peer and coach pressure in training; internal competition for spots in the team)
Anthropometrics	Lower body surface area; Higher body mass
Dehydration	Due to poor hydration or consecutive/prolonged heat exposures and trainings
Health status	Previous or ongoing mild infectious diseases (e.g., common cold, flue, gastrointestinal diseases)
Other Factors	Poor sleep; Poor nutrition; Sunburn; Previously sustained heat illnesses; Drug use (e.g., amphetamines, cocaine, alcohol)

(Cramer & Jay, 2016; Périard et al., 2021; Roberts et al., 2023)

B5. Physiology of Exercising in the Heat

With increasing heat strain during exercise, T_{core} and T_{skin} begin to rise, and a range of thermoregulatory responses are enabled to dissipate heat. The most important physiological processes specific to exercising in the heat, include blood flow alterations, cardiovascular adaptations and the increased sweat response.

Blood flow alterations are enabled to dissipate heat at the skin, but during exercise other competing demands require a high blood supply as well. At rest, skin blood flow makes up for around 5-10% (~0.5 L/min) of cardiac output, but this can increase to up to 50-70% (~8 L/min) with heat strain (Lossius et al., 1993). This is competing with the exercise-depended demands of the muscle blood flow (Périard et al., 2021). At submaximal exercise, these concurrent demands increase cardiovascular strain, but sufficient muscle oxygen delivery can usually be maintained (Périard et al., 2021). However, at near maximal exhaustion in the heat, blood flow to both muscle and skin decreases compared to in cooler environments, resulting in a lower maximum oxygen uptake ($VO_{2\,max}$) that can be reached in hotter conditions (Nybo et al., 2014). A further competitor for blood flow is the brain, with cerebral blood flow progressively declining during exercise in the heat compared to in cooler environments (Périard et al., 2021). This is attributed not only to the blood flow redistribution but also to arterial hypotension and hyperventilation-induced hypocapnia (Nybo et al., 2014).

Cardiovascular adaptations to exercising in the heat are also linked to the subcutaneous vasodilation. The shift in blood volume to the skin leads to a decreased central blood volume and thus cardiac ventricular filling, resulting in a lower stroke volume and a compensatory increase in heart rate (Nybo et al., 2014). When exercising at a steady work rate, this results in an increased heart rate and oxygen uptake, to meet the greater demands of cardiac output, compared to performing the same work in cooler environments (Périard et al., 2021). Opposed to exercise with a fixed intensity, participants would decrease the work rate in self-

paced exercise under hot compared to cool conditions (Périard et al., 2021). Team sports are usually representing a mix of both. Whilst some match situations call for certain physical activities and thus determine the intensity, overall match intensity can be regulated by players or rather teams as a collective. Hence it was observed in football that players decrease their running activities, leading to similar heart rate responses in football matches played in hot and cool environments (Mohr et al., 2012; Slattery & Coutts, 2019).

The sweat response is an essential source of heat loss when exercising in hot environments. However, during prolonged exercise, this can lead to dehydration, and reductions in blood plasma volume. This further exacerbates the strain on the cardiovascular system, which is already challenged by supplying the skin, muscles and brain with sufficient blood flow (Périard et al., 2021). The sweat response can be highly individualised between, and even within the same, individuals and depends on personal factors such as their hydration and acclimatization status (Maughan & Shirreffs, 2008). For instance, in one football match in hot conditions (32 °C WBGT), sweat losses ranged from 2.9 to 6.2 L and less than half of this sweat loss was replaced by fluid intake (Aragón-Vargas et al., 2009).

Together, these physiological adaptations enable heat dissipation and aim to prevent the rise in T_{core}. However, if exercising in high heat, T_{core} can rise quickly, nonetheless. In the review of Singh et al. (2023), they found that ~12% of all athlete observations included in the review reached a T_{core} of > 40 °C. For example, in elite cycling a T_{core} of 41.5 °C (Racinais, Moussay, et al., 2019) and in running 41.7 °C were reported (Byrne et al., 2006). In intermitted sports, the ratio of athletes with such a high T_{core} values was lower compared to endurance based sports (Singh et al., 2023). However, also in football a high T_{core} approaching 40 °C was observed in almost every investigation (Aragón-Vargas et al., 2009; Duffield et al., 2013; Edwards & Clark, 2006; Mohr et al., 2012; Özgünen et al., 2010). The literature on T_{core} responses in actual football match-play is scarce but is summarized in more detail in the introduction to Study 5 and Table 20.

B6. Athletic Performance in the Heat

Endurance performance is markedly impaired in hotter compared to cooler environments, with impairments already progressing at above 10 °C (Montain et al., 2007). In general, the increased heat strain and thermoregulatory burden, resulting in an increased cardiovascular strain and eventually whole-body hyperthermia, lead to an earlier onset and higher levels of fatigue (Nybo et al., 2014). In exercise with a constant work rate, this leads to a reduced time to exhaustion and a lower $VO_{2\ max}$ reached in hotter conditions (Arngrímsson et al., 2004). In self-paced work, athletes will usually decrease the work rate with increasing heat strain (Périard et al., 2021). During maximal effort endurance exercise in the heat, performance impairments are clearly influenced by the increased cardiovascular challenge to simultaneously support skin (thermoregulation), muscle (performance), and brain (survival) blood flow (Nybo et al., 2014). During submaximal endurance exercise, muscle and skin oxygenation remain unchanged, but performance impairments occur nevertheless, showing how elevated skin, core and brain temperatures can directly influence centrally regulated fatigue (Nybo, 2014). However, the development of hyperthermia-induced fatigue remains complex and often individualised (Périard et al., 2021).

In contrast, explosive and sprint performances (< 30 seconds) are usually improved in the heat. This is linked to higher muscle temperatures, beneficial for contractile abilities of the muscle (Girard et al., 2015). However, when performing repeated sprints, this benefit will eventually be overwritten by the increased cardiovascular strain and fatigue in the heat, resulting in a decreased voluntary muscle activation. Thus, especially when marked hyperthermia is present, a worsening of repeated and intermitted sprint performance is observed (Girard et al., 2015).

Periods of prolonged cognitive or exercise activity will result in mental and physical fatigue, and eventually impairments of cognitive functioning. Heat strain has been shown to exacerbate these impairments by increasing physical fatigue, but also directly influencing cognitive function (Schmit et al., 2017). The relationship of heat strain and cognitive function is described to follow an inverted U-shape (Schmit et al., 2017). Initial increases in T_{core} of up to 38.5 °C result in a higher alertness, mostly

resulting in quicker reaction times. However, at higher heat strains, this relationship reverts and impairments start to appear as a function of task complexity (Schmit et al., 2017). This means that firstly, complex tasks, like complex visual processing, decision-making and working memory tasks, are impaired. The more severe the heat strain and accompanied fatigue, the less cortical attention remains for cognitive tasks, decreasing even easier tasks. In extreme hyperthermia (> 40 °C) strong impairments of cognitive processes can be observed, in the form of increased errors and impulsivity (Coehoorn et al., 2020; Schmit et al., 2017). Next to the speed and accuracy of task, also the qualities of decision-making can be altered in hot environments. For example, participants have been found to take riskier decision when heat stress was present (Chang et al., 2017; Syndicus et al., 2018).

In football, these effects manifest in an alteration in running performance and tactical and technical performance indicators in the heat. Most existing studies report reductions in total and high-speed running and higher peak speeds reached in the heat (Draper et al., 2022; Illmer & Daumann, 2022). Further, the pass-rate has been shown to increase in hotter conditions, while the number of duels and challenges decreased (Mohr et al., 2012). A detailed summary of the literature regarding effects of hot environmental conditions on football performance will be presented in the introduction chapters to Study 1 and Table 1 (running performance), and Study 2 and Table 5 (match-play characteristics).

B7. Acute Injuries in the Heat

The influence of heat strain, along with the associated acceleration of fatigue and alterations in cognitive performance, has been discussed as a potential risk factor for acute locomotor injuries (Distefano et al., 2013; Schmit et al., 2017; Spector et al., 2019). This relationship is thought to be mediated by reductions in neuromuscular and coordinative capacity when heat strain is present (Distefano et al., 2013; Gaoua, Grantham, et al., 2011). For example, impaired proprioception and coordination may result in delayed or inappropriate planning of movement strategies and compromise muscular pre-activation during tackling or landing actions. Under heat stress, this has been shown to lead to higher centre-of-pressure excursions and elliptical sways during

dynamic balance tests (Distefano et al., 2013). Additionally, increased risk-taking behaviour (Syndicus et al., 2018) and poorer decision-making (Schmit et al., 2017) under heat stress have been proposed as contributing factors to an elevated injury risk.

Accordingly, increased injury rates have been observed in occupational fields and the general public during periods of high environmental heat stress (Martínez-Solanas et al., 2018; Otte im Kampe et al., 2016; Spector et al., 2019). However, this relationship remains under-investigated in athletic populations. For instance, in track and field athletes a lower incidence rate was reported for time-loss injuries, specifically for muscular injuries in high-speed disciplines (Edouard et al., 2025). This may be related to an enhanced muscle elasticity and contractility in warmer conditions, although the underlying mechanisms remain unclear.

In team sport athletes, the evidence is even more limited. Only two studies in Rugby have investigated associations between environmental temperatures and injuries. These studies have not demonstrated a relationship between heat and injury occurrence (Gabbett et al., 2007; Lee & Garraway, 2000). Such findings might be attributed to a heat-induced decrease in match intensity and running load, which could mitigate muscular fatigue and decrease overall exposure to risky match situations, such as maximum sprints and opponent contacts. Importantly, both studies lacked data from matches played under extreme heat conditions (Gabbett et al., 2007; Lee & Garraway, 2000). In football, no study has yet directly examined whether environmental temperature is associated with injury occurrence. This is particularly concerning given that acute injuries continue to pose significant challenge for football clubs and players, affecting personal health and career success, as well as team performance and financial outcomes (Hägglund et al., 2013; Lu et al., 2021). The literature regarding potential relationship between environmental temperatures and acute injuries will be summarized in more detail in the introduction to Study 3 and Table 11.

B8. Exertional Heat Illnesses

At high exercise intensities, T_{core} can rise rapidly, leading to heat-related health adversities within an hour (Epstein et al., 1999). Such illnesses can range from mild symptoms like headaches, cramps, dizziness or nausea, to severe exertional heat stroke (EHS). Although more prevalent in hot conditions, EHS can occur even at ambient temperatures of 15 °C as it is linked to the exercise intensity rather than the climate alone (Epstein et al., 1999). It is characterized by a severe central nervous system disturbance, such as intensely irrational or confused behaviours, whole body seizures and finally partial or complete losses of consciousness at a T_{core} above 40 °C (Roberts et al., 2023). This is one of the three main causes of life-threatening events in athletes, alongside cardiac and cerebral events, sometimes referred to as the "3 H's": heart, head, and heat. EHS fatalities are especially tragic, as they are fully avoidable with proper awareness, prevention, recognition and treatment strategies. Interestingly, athletes can sometimes perform at a high level with T_{core} exceeding 40 °C without any visual impairments (Singh et al., 2023), raising questions, about why and when hyperthermia develops into a life-threatening condition in some cases but not others (Racinais et al., 2023). In football for instance, T_{core} exceeding 40 °C have been reported, but reports of EHS remain scarce.

The sport with the highest incidence of EHS is American football, recording more than 50 fatal cases between 2000 and 2020 (Eichner, 2019) and 7 cases just between 2020 and 2021 (Puga et al., 2022), resulting in 1.7-1.9 cases per year depending on the age group (Gamage et al., 2020). This is linked to the body composition of American Football players and the additional safety gear, limiting heat dissipation. However, in other sports, the incidence rate of less severe heat illnesses is increasing alongside the increased exposure to hot conditions due to global warming (Gamage et al., 2020). In football, the incidence rate of heat illness per 10.000 athletes exposures is 1.1 during pre-season and 0.7 during the season (Yeargin et al., 2019).

Summary Box 3: Signs and symptoms of exertional heat stroke.

Mild exertional heat illnesses	Headache; Nausea; Muscle cramp; Exceptional fatigue or weakness; Chills
Impaired coordination	Dizziness; Loss of balance; Unsteady walk; Ataxia
Impaired cognitive function	Missing assigned tasks; Personality changes; Mental status changes; Disorientation; Inappropriate behaviour; Aggressiveness; Erratic behaviour; Agitation
Spasms	Flaccid muscles or persistent rigidity; Convulsions; Seizure; Stool incontinence
Loss of consciousness	Delirium; Closed eyes; Coma
Physiological signs	Profuse sweating; High rectal temperature > 40°C; Weak or rapid pulse; Tachycardia; Systolic hypotension

(Laitano et al., 2019; Périard et al., 2022; Roberts et al., 2023)

If recognized correctly and early, intense and rapid cooling can, in almost all cases, prevent the death of an EHS patient. Survival rates decrease with the time needed to reduce T_{core} (Périard et al., 2021). A delayed response is often related to hyperthermia not being identified as the underlying condition, with sudden cardiac arrest or head injuries being suspected instead (Epstein & Yanovich, 2019). Therefore, a summary of symptoms to recognize EHS is presented in Summary Box 3. Coaches, athletes and especially medical staff should be aware of these symptoms and consider hyperthermia when risk factors (Summary Box 2) are present. If an EHS is suspected, immediate and intense cooling, preferably with cold water immersion, should be prioritized over hospital transport (Roberts et al., 2023).

B9. Heat Mitigation Strategies

In an ideal world, athletes will be protected from being exposed to extreme heat stress conditions. Meaning, when heat stress passes a certain threshold, a training or competition would be re-scheduled to the early morning, late evening or another day

(Bergeron, 2009; Gouttebarge et al., 2023; Hosokawa et al., 2018). However, in elite-level football, contractual obligations to fans and media outlets determine match starts. In lower-level football competitions, the venue, referee and even player availability often oppose a spontaneous match rescheduling. Given this inflexibility and the current trends in global warming, exposures to severe heat stress in football are set to become more prevalent (Nassis et al., 2024). If exposed to such conditions, multiple strategies exist to mitigate their effects on athlete health, wellbeing and performance.

Heat acclimatization, meaning deliberately seeking heat exposure is one of the most effective protective strategies. By slowly increasing the exercise intensity and therefore heat strain over 7 - 14 days, adaptations occur that eventually decrease the observed heat strain (Tyler et al., 2016). Ideally such an acclimatization protocol would involve living and training in hot conditions for one to two weeks, but even shorter exposures of less than seven days (Chalmers et al., 2014) a series of four training protocols in a heated room (Sunderland et al., 2010) and even passive heat exposures post-exercise such as hot baths or saunas (Casadio et al., 2017) have been shown to enable initial adaptations. Adaptations include a higher stroke volume, lower heart rate and expansion of blood plasma volume, which in turn enables an earlier onset of subcutaneous vasodilation and sweating (with lower sodium loss). These improvements in heat dissipation mechanisms result in a reduction in T_{core}, cardiovascular strain and oxygen consumption when exercising in the heat (Tyler et al., 2016). Investigations in football players have looked at acclimatization protocols between 5 and 8 days and showed plasma volume and sweat rate increases, sweat sodium concentration and heart rate reductions, and improvements in football-specific physical performance tests (Buchheit et al., 2016; Buchheit et al., 2011; Pethick et al., 2018; Racinais et al., 2012). However, in elite football, time to conduct such acclimatization protocols is scarce, as matches, seasons and tournaments are scheduled tightly. Even pre-season periods are determined by friendly matches used for marketing purposes (Buchheit et al., 2016). In lower-level football, other life obligations and high financial implications of performing heat acclimatization protocols oppose their implementation.

Ensuring adequate hydration is a simple, time- and cost-efficient method to improve heat tolerance. Even in temperate conditions, dehydration is associated with physical and cognitive performance impairments (Cheuvront & Kenefick, 2014). In hot conditions, these effects become amplified, through several mechanisms. Dehydration is associated with a lower blood plasma volume, which further decrease cardiac output and exacerbates the cardiovascular strain, which is already elevated, to meet the increased skin blood flow demands in the heat (Périard et al., 2021). Moreover, adequate hydration status is fundamental to sustain a proper sweat response and therefore heat dissipation (Périard et al., 2021). Hence, dehydrated individuals experience higher heat strain (Bernard et al., 2024). Despite these well-established associations between hydration, health and performance, athletes frequently begin training and competition with a less-than-optimal hydration. For example in two studies in football players 41 % (Aragón-Vargas et al., 2009) and 66% (Williams & Blackwell, 2012) were not optimally hydrated pre-exercise. Therefore, monitoring of the hydration status and education on the importance of it can be beneficial. To ensure ongoing hydration in team sports environments, frequent hydration opportunities should be presented and easily available, with different drinks catering to different tastes. However, in football matches, drinking opportunities are limited due to the continuous nature of the game and furthermore, the existing breaks (injuries, Video Replay, substitution) are rarely used for drinking (Wardenaar et al., 2022). During exercise in the heat, up to 4L/h of fluid loss can be experienced but sweat rates are highly variable between individuals (Mack & Nadel, 1996). In a football match this can result in sweat losses of up to 6 L per match, but this is highly individual (Aragón-Vargas et al., 2009). Even mean sweat losses per match are reported to be between 1.8 and 4.1 L, while only a portion of this can be replaced, resulting in a mean body mass loss of 1.6 - 2.3% (Duffield et al., 2013; Edwards & Clark, 2006; Mohr et al., 2012; Özgünen et al., 2010). Therefore, any opportunity should be used to re-hydrate. Introducing additional breaks presents a potential re-hydration opportunity, but how these contexts are used to improve heat mitigation remains under-reported and under-utilised.

Decreasing the exercise work rate can also mitigate the heat strain due to the direct link between work rate and metabolic heat production (Cramer & Jay, 2016).

In endurance sports, this typically results in athletes pacing themselves, thereby reducing the exercise intensity. Football players also display pacing behaviour, even in temperate conditions, as they aim to avoid excessive fatigue that could impair their performance (Bradley & Noakes, 2013). In hot conditions, pacing through reduced running volumes may help alleviate heat strain when environmental heat stress is elevated (Mohr et al., 2012). For instance in Australian Football it was shown that covering higher running distances, especially during the first half of play, was associated with developing higher T_{core} values (Duffield et al., 2009). However, in competitive matches, and even in training a certain exercise intensity is required to maintain performance and elicit training adaptations. Therefore, reducing the exercise intensity may not always be an optimal strategy in football. Existing research suggested that one pacing approach might be to reduce lower running intensities to maintain high-speed running (Duffield et al., 2009). However, factors associated with developing a high T_{core} in football matches remain to be identified.

Introducing additional breaks during the exercise in the heat, might be way of reducing the work rate whilst maintaining the performance in activity bouts. Even a passive rest in such breaks can lead to reductions in T_{core} opposed to a continuous exercise exposure (Brown et al., 2024; Chalmers, 2017). In football trainings, this can easily be implemented by allowing longer and more frequent breaks in-between drills. For football matches, this can be implemented by reducing the warm-up, and holding a break before the match, or by implementing additional drinking or cooling breaks per half. Such breaks not only reduce metabolic heat production, but further create an opportunity to implement other heat mitigation strategies, such as hydration and cooling (Brown et al., 2024; Chalmers et al., 2019). Introducing additional cooling breaks per half are the core of most heat policies used in football, which are presented in Summary Box 4. However, their effects on thermoregulatory, physiological and performance responses during actual football matches is yet to be investigated.

Using cooling applications has been shown to lower the heat strain and improve athletic performance using different methods (Bongers et al., 2015). For example, cooling can be applied prior to exercise (pre-cooling), increasing the heat storage

capacity. It can also be applied during exercise (per-cooling), mitigating the rise in T_{core}. Finally, it can be applied after, or in-between bouts of exercise, increasing the rate of heat loss (Bongers et al., 2017). A wide range of cooling methods and devices exist, ranging from simple and cost-effective (e.g., towels dipped in cold water, cold drinks, fans) to more advanced methods that need special equipment (e.g., cold-water immersions, cooling garments). They can be divided into external, meaning cooling the skin, or internal, meaning ingesting a cold fluid or ice (Bongers et al., 2015). In general, research has shown that the effects of cooling are dose-dependent (Minett et al., 2011). A higher cooling dose could be achieved by a colder cooling stimulus, a longer cooling duration, a bigger surface area exposed, or the combination of internal and external cooling methods (Bongers et al., 2015). Those bigger cooling doses lead to bigger, physiological benefits such as a reduced T_{core}, T_{skin}, heart rate or sweat loss. Alternatively, smaller cooling doses might deliver perceptual benefits such as reduced thermal sensations or levels of fatigue (Wegmann et al., 2012). Interestingly, both smaller and bigger cooling doses have shown to improve performance, as performance benefits were not associated with alterations of T_{core} or T_{skin} (Bongers et al., 2015; Wegmann et al., 2012). Even purely perceptual cooling methods, such as menthol mouth rinses have been shown to improve performance (Bongers et al., 2017). The performance benefits associated with cooling are mainly observed for endurance activities, followed by intermittent sprint performance, but not for pure sprint and explosive tasks (Wegmann et al., 2012). Furthermore, cooling has been effective in improving cognitive performance (Hemmatjo et al., 2017; Saldaris et al., 2019). In general, the beneficial effects of cooling are observed when a high heat strain is present. Meaning in studies with severe environmental conditions or intense and longer duration exercise protocols in non-acclimatized athletes. In observations where participants recorded an overall lower heat strain, cooling did not have beneficial effects on performance (Wegmann et al., 2012).

In football simulating treadmill running, cooling was also able to lower T_{core} (Aldous et al., 2019; Brown et al., 2025; Brown et al., 2024; Chalmers et al., 2019; Clarke et al., 2011; Drust et al., 2000; Parris & Tyler, 2018; Price et al., 2009) and improve running performance in the form of an increased time to exhaustion (Aldous et al.,

2019; Clarke et al., 2011; Zhang et al., 2022; Zhang et al., 2014). However, most of these observations, were derived from laboratory-based studies and applications to field based football settings might be difficult. The only field-based observation investigating cooling in actual football training and matches found that effects did not transfer to the field (Duffield et al., 2013). Other organisational, logistical and time constrains of a football match-day, make it difficult to deliver a high cooling dose close to the match start. Further, football performance depends on various factors, thereby improvements might not be captured as easily. Therefore, more field-based investigations are needed, with a higher emphasis on applicable rather than maximum-dose cooling methods (Bongers et al., 2015). Studies on the use of cooling in football are summarized in more detail in the introduction to Study 4 and Table 15.

Summary Box 4: Heat mitigation strategies in football.

Prevent exposure	reschedule training or matches to earlier morning or later evening; postpone to another day; cancel
Acclimatization	One-to-two-week heat acclimatization to gradually increase resistance to heat stress and lower heat strain
Hydration	Ensure adequate hydration pre-exercise (through monitoring and education); provide ample hydration opportunities during training and matches
Lower work rate / Additional breaks	Decrease exercise intensity or allow for more frequent and longer breaks (e.g., drinking and cooling breaks in matches).
Cooling	Implement internal (e.g., cold drinks, slush ice) or external cooling (e.g., cold towels, ice packs, cold water immersions, fans) before (pre-cooling) or during breaks (cooling breaks and halftime).

(Bongers et al., 2017; Gouttebarge et al., 2023; Maughan & Shirreffs, 2008; Nassis et al., 2024; Tyler et al., 2016)

B10. Heat Policies

Federations across different sports have adopted various heat policies to guide the implementation of such heat mitigation strategies. For example, in tennis additional breaks of play are introduced in severe heat (Racinais et al., 2023), the international

athletic federation might reschedule endurance events to the early morning or late evening (Sugawara et al., 2022) and in triathlon, the distance of the event may be reduced when high heat is present (World Triathlon, 2022).

Since the introduction of official cooling breaks during the 2014 FIFA World Cup, many football federations have followed to promote their own heat policies. While the health and safety risks associated with playing in the heat are widely acknowledged, the guidelines and thresholds for intervention vary substantially across federations (Gouttebarge et al., 2023). This variability is likely linked to the limited empirical evidence available and the inherent difficulty in defining a universal threshold suitable for diverse settings. Policymakers need to balance between designing a precise but overly complex policy which may not be practically applicable, or an oversimplified version that may lack sufficient detail.

A summary of current heat policies in football is presented in Summary Box 5. Additional cooling breaks are a central component of most existing policies, whilst some policies also include options for delaying, rescheduling or cancelling matches under extreme conditions. The International Football Association Board (IFAB) defines drinks breaks as < 1 min breaks and cooling breaks as 1.5 - 3-minute breaks. While the drinks breaks can be introduced more spontaneously by a referee during a match, cooling breaks must be communicated before the match to allow for the preparations needed to implement cooling strategies. Threshold for implementing cooling breaks range from 26 °C WBGT (Australian Football) to 32 °C WBGT (FIFA) and 30 °C T_{air} (German Federation) to 35°C T_{air} (UEFA). Break durations vary between 60 seconds and 4 minutes, typically scheduled at the 25th or 30th minute of each half. Match delays or cancellations are considered at thresholds starting from 28 °C WBGT (Australian Football), or 36 °C T_{air} (FIFPRO). Other countries, such as Argentina, may not specify explicit thresholds, but allow match postponements due to severe weather in their regulations. These postponements are frequently used to reschedule matches from the afternoon to the evening, when severe heat is forecasted. While many continental federations adopt FIFA's 32 °C WBGT threshold, fewer include FIFA's detailed recommendations regarding specific cooling equipment and procedures. For example,

it is mentioned that the match-day manager may implement cooling breaks already at a WBGT below 32 °C and decide to postpone or cancel the match in extreme heat. Further it is stated that, if cooling breaks are introduced, the organiser should provide 2 cooling boxes per team, 2 cold drinks and 2 ice-towels per player, as well as 3 persons to distribute towels and drinks. Notable exceptions include the US Soccer and the German Football Federation guidelines, which have developed more comprehensive and practically oriented recommendations to manage heat stress. Among the reviewed policies, the US Soccer guidelines are the only ones that include specific recommendations for football training, providing WBGT categories to guide breaks and cancellation for three climatic regions in the US, as well as information on acclimatization, hydration, cooling and heat illnesses.

Summary Box 5: Football federations match-day heat policies (around the world).

Organization	**Cooling breaks**		**Delay match**	
	T	**WBGT**	**T**	**WBGT**
FIFPRO	30 °C	26 °C	36 °C	28 °C
DFB (German Federation)	30 °C		35 °C	31.7 °C
Football Australia		26 °C		28 °C
UEFA (youth)	30 °C	28 °C	-	-
UEFA (senior)	35 °C	32 °C	-	-
US Soccer	-	32 °C	-	-
FIFA/ CONMEBOL/ AFC/ CAF/	-	32 °C	in severe heat	
AFA	-	-	in severe heat	

Above guidelines were accessed at August 8th 2025 under: (Fédération Internationale de Football Association (FIFA), 2015) {Football Emergency Medicine Manual}; (The International Football Association Board (IFAB), 2025) {Laws of the Game}; (FIFPRO - Football Players Worldwide, n.d.) {Guidelines and Mitigation Strategies for Hot Conditions in Professional Football}; (Union des associations européennes de football (UEFA), 2025) {Medical Regulations - Annex D}; (Asian Football Confederation (AFC), 2023) {Competitions Operations Manual}; (Confederación Sudamericana de Fútbol (CONMEBOL), 2024) {Protocolos Comisión Médica}; (Football Australia, n.d.) {Heat Policy}; (US Soccer, n.d.) {Heat Guidelines}; (Deutscher Fußball-Bund (DFB), 2024) {Empfehlungen der Medizinischen Kommission des Deutschen-Fußball-Bundes bei Hitze}; (Asociación del Fútbol Argentino (AFA), 2025) {Reglamento Torneos Proyección}.

The decision to implement heat mitigation strategies in football can be based on either fixed environmental thresholds or more flexible, stakeholder-led decisions. Both approaches offer distinct advantages and limitations:

Establishing fixed thresholds is inherently challenging, as the degree of heat stress and heat strain is co-influenced by situational, team-specific and individual factors (see Chapter B3 and B4). This is particularly difficult when policies aim to cover a wide range of populations, for instance with different playing or acclimatization levels. Consequently, frameworks solely based on environmental parameters, such as T or WBGT, may fail to adjust for varied physiological responses across individuals. Further, youth and amateur competitions arguably warrant more conservative thresholds, due to the limited availability of medical support in the event of serious incidents. Moreover, complex heat stress indices like WBGT may be impractical for implementation at grassroots levels, complicating policy implementation.

Alternatively, some federations allow certain stakeholders to take match-day decisions (e.g.: Deutscher Fußball-Bund (DFB), 2024; Fédération Internationale de Football Association (FIFA), 2015). In professional settings, match-day medical officers, team physicians and educated referees can assess the heat stress and interpret the individual risk based on situational and team specific factors. In contrast, at youth or amateur levels, this responsibility lies with referees and coaches, who may lack the required training or confidence to take and justify a decision. This underscores the need for referee education, but currently no data exists regarding referees' knowledge or decision making in this field.

Given the limitations of both fixed and flexible strategies, a hybrid approach may be most appropriate. Such a model would define mandatory interventions at certain thresholds, while still encouraging stakeholders to implement mitigation strategies below these levels based on individual risk factor assessments (see Summary Box 2). Additionally, distinct thresholds for professional and amateur levels may be useful, with the latter also including simpler temperature measures for practicality. Beyond this information heat policies should incorporate educational resources for medical staff, referees, coaches and players, to promote knowledge of the key contributors to heat strain in football (Summary Box 2) and possible mitigation strategies (Summary Box 4). This is critical to support informed decision-making and to empower stakeholders to act responsibly and independently. Policies should also

provide information on the recognition of early signs and symptoms of exertional heat stroke (Summary Box 3) and the adequate treatment, to ensuring preparedness for worst-case scenarios.

B11. Research Questions

When reviewing the background presented in this thesis, several gaps in the existing literature, regarding playing football in hot conditions, become apparent. Based on these gaps, and the previously outlined aims of this thesis (see Introduction), five research questions were developed. These research questions are addressed through the five original investigations presented in this thesis:

i) How do environmental temperatures affect match running performance in professional football leagues?

ii) How do environmental temperatures affect match-play characteristics in professional football leagues?

iii) How do environmental temperatures affect match injury occurrence in professional football leagues?

iv) What are the effects of pre-cooling and cooling breaks on thermoregulatory, physiological and performance responses during football?

v) What are T_{core} responses in football and which physiological and performance factors are associated with T_{core}?

STUDIES

Study 1: Football Running Performance in the Heat

S1.1 Introduction and Literature Summary

When exploring factors associated with elite football players, some physical performance aspects, such as a high aerobic capacity, but also high-speed and explosive movements are of importance (Walker et al., 2019). However, equivocal findings are reported on the relevance of overall and high-speed running distances for success in football matches, let alone those in hot conditions. In some observations higher total and high-speed distances were associated with ranking higher at the end of a season (Aquino et al., 2021), whilst in others they were not related to match outcomes i.e. win or loss (Plakias et al., 2025). The total distance and sprint distance covered whilst in ball possession was related to accumulating more points over the course of a season (Andrzejewski et al., 2022; Hoppe et al., 2015). When more specific context, high-speed and sprinting activities have been associated with goal scoring (Faude et al., 2012; Schulze et al., 2021). Therefore, it seems of interest, how different environmental conditions effect different running performance markers.

Several observational (Carling et al., 2011; Chmura et al., 2017; Chmura et al., 2021; Coker et al., 2020; Draper et al., 2023; Konefał et al., 2021; Link & Weber, 2015; Loxston et al., 2019; Nassis et al., 2015; Trewin et al., 2018; Zhou et al., 2019) and one experimental study (Mohr et al., 2012) have investigated the associations between heat stress and physical performance in male football. Only one study has investigated female players (Trewin et al., 2018). In general, they reported reductions in running distances, with variations evident for whether these reductions occur overall, or specifically in lower, moderate or high-speed activities (see Table 1). The different findings could be related to the sometimes-small number of matches analysed, often observed from a single league or tournament. Further, there is a tendency to report environmental parameters categorized into two to four heat stress classifications, which may result in an oversimplification of the associations. Lastly, also different definitions of speed zones and sprint activities may play a role in differential outcomes.

Therefore, Study 1 aimed at conducting a large, multi-league analysis, examining 1610 matches from four professional football leagues, while using continuous T_{air} (in the following just "T") and WBGT, rather than categorical classifications. This approach derives a more generalizable understanding of how heat influences physical performance in elite football.

Table 1: Literature review of studies investigating associations between running performance and environmental temperatures in football.

Study	Sample	Environmental Parameters	Physical Performance Parameters	Effects of Hotter Conditions
Özgünen et al., 2010	2 matches; experimental; 11 male semi-professional players	2x T, RH and HI: •M1: 34 °C + 38% = 35 HI •M2: 36 °C + 61% = 49 HI	TD, WD, LSD, MSD, HSD, SD	•reduced LSD & MSD, reduced second half TD •increased WD
Carling et al., 2011	80 matches; French Ligue1; 1 team; 9 male players	4 T categories: •≤5 °C •6-10 °C •11-20 °C •≥21 °C	TD; LSD (≤14.3 km/h); MSD (14.4-19.7 km/h); HSD (≥19.8 km/h)	•reduced TD vs. all others •reduced HSD vs. ≤ 5 °C in minute 30-45
Mohr et al., 2012	2 matches; experimental; 2 teams 17 male players	2 T + RH combinations •21 °C + 55% •43 °C + 12%	TD; HSD (>14 km/h), SD (>24 km/h); sprint frequency, speed & length; peak speed	•reduced TD & HSD •increased peak speed
Konefał et al., 2014	64 matches; FIFA World Cup 2014; all teams; male players	3 T categories: •<22 °C •22-28 °C •28 °C	TD; LSD (≤11-14 km/h); MSD (>11-≤14 km/h); HSD (> 14 km/h); sprints	•reduced MSD, HSD and Sprints •peak speed highest in 22-28 °C
Nassis et al., 2015	64 matches; FIFA World Cup 2014; all teams; male players	3 HS categories based on WBGT + RH (Gonzalez, 1995): Low, Mod, Hot	TD; LSD (< 11km/h); MSD (11-14 km/h); HSD (>14 km/h); SD (>25 km/h); sprints; peak speed	•reduced HSD and Sprints •increased LSD
Link & Weber, 2015	2426 matches; German Bundesliga1,2; all teams; male players	2 T categories: •Low: -4-13 °C •High: ≥ 14 °C	TD	•reduced TD
Chmura et al., 2017	64 matches; FIFA World Cup 2014; all teams; male players	6 T+ RH combinations: •<22 °C + < 60 % •<22 °C + > 60 % •22-28 °C + < 60% •22-28 °C + > 60% •>28 °C + <60% •>28 °C + >60%	TD; LSD (< 11km/h); MSD (11-14 km/h), HSD (>14 km/h); sprints (>25 kmh); peak speed	•reduce TD, MSD, HSD, Sprints, •increased LSD •high RH had a negative effect even in low T
Trewin et al., 2018	47 matches; National team games; 1 team; 45 female players	2 T categories •Low: < 21°C •High: ≥ 21 °C	TD; LSD (<4.58 m/s); HSD (>4.58 m/s); accelerations (>2.26m/s²); HS runs (>4.58 m/s); sprints (>5.55 m/s)	•reduced TD, LSD, HS runs, Accelerations,
Loxston et al., 2018	42 matches; Arabic Gulf League; 1 team; 9 male players	4 HS categories •based on WBGT + RH (Gonzalez, 1995): Low, Mod, Hot, Excess	TD; LSD (7.2-14.4 km/h); MSD (14.4-19.8 km/h); HSD (19.8-25.2 km/h); SD (>25.2 km/h); ED (>2 m/s²); sprints; peak speed	•reduced MSD, HSD, ED,

Abbreviations: ***Environmental conditions:*** *T = Temperature; °C = degree Celsius; HI = Heat Index; HS = Heat Stress; RH = Relative humidity; % = percentage (RH); WBGT = Wet-bulb globe temperature; UTCI = Universal thermal climate index; Mod = Moderate;* ***Performance:*** *TD = Total Distance; WD = Walking Distance; LSD = Low-speed Distance; MSD = Moderate-speed Distance; HSD = High-Speed Distance; SD = Sprint Distance; ED = Explosive Distance; HS Runs = High-speed Runs; km/h = kilometres per hour.*

Table 1 (continuation):

Study	Sample	Environmental Parameters	Physical Performance Parameters	Effects of Hotter Conditions
Zhou et al., 2019	240 matches; Chinese Super League; all teams; male players	T & RH continuous scale	TD; HSD (19.1-23 km/h); SD (>23 km/h); HS runs; sprints;	•Optimal T for high TD = 11.6°C; HSD = 12.0°C; HSR = 10.6°C; SD = 15.1°C, Sprints = 13.2°C:
Coker et al., 2020	12 matches; USA NCAA Division I; 1 team; 7 male players	3 HS categories •based on WBGT + RH (Gonzalez, 1995): Low, Mod, Hot	TD; LSD (0.2-17.99 km/h); HSD (>18 km/h); SD (>21.6 km/h)	•increased LSD vs. low HS
Konefał et al., 2021	64 matches; FIFA World Cup 2018; all teams; male players	2 UTCI categories No HS: 9-26 °C UTCI HS: > 26 °C UTCI	TD; HSD (20-25 km/h); sprints;	•reduced TD, HSD, Sprints,
Chmura et al., 2021	1530 matches; German Bundesliga1; all teams; male players	T, RH & WBGT continuous scale	TD; HS runs; sprints; peak speed	•reduced TD, HS runs, but only for higher T not WBGT or RH
Draper et al., 2023	126 matches; US MLS; 1 team; 37 male players	T & HI continuous scale	TD; HSD (> 20.2 km/h)	•reduced TD, HSD
Study 1	1610 matches; German Bundesliga1,2, Australian A-League, Spanish La Liga; all teams; male players	T & WBGT continuous scale	TD; HSD (definitions depending on league); HS runs; sprints; peak speed	•reduced TD, HSD, HS runs, Sprints, •increase in Peak speed

S1.2 Associations between Match Running Performance and Environmental Temperatures in 4 Professional Football Leagues

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Abstract

Purpose: This study investigated associations between environmental temperatures and match running performance in 4 professional football leagues. **Methods:** Running performance indicators including total, high-speed, and sprint distances were collated from 1610 matches from the German Bundesliga 1 and 2, Japanese J-League, and Turkish SüperLig. Environmental data for each of these matches were obtained for dry-bulb and wet-bulb globe temperatures (WBGT) retrospectively from public sources. Linear regressions were used to determine relationships between running performance indicators and both temperature and WBGT for individual leagues. Furthermore, linear mixed models were used to determine associations across all 4 leagues, accounting for differences between them as random effects. Bonferroni corrections were applied to account for multiple tests. **Results:** Overall, combined-league data showed that total distance (95% CI,–0.50 to 0.37; β:–0.36), number of high-speed runs (95% CI,–4.57 to 2.93; β:–0.29), high-speed distances (95% CI,–0.07 to 0.05; β:–0.28), number of sprints (95% CI,–2.72 to 2.07; β:–0.39), and sprint distances (95% CI,–0.05 to 0.03; β:–0.22) were all lower when WBGT was higher ($P < .001$), whereas the peak speed recorded per match (95% CI, 0.01 to 0.03; β: 0.18) was higher when WBGT was higher ($P < .001$). Models with temperature instead of WBGT derived similar results. **Conclusion:** Warmer environmental conditions were associated with lower total, high-speed, and sprint distances covered. These responses may result from an increased thermoregulatory load or indirectly from an adapted individual or team-tactical pacing strategy in warmer conditions. Teams should consider strategies to counter such effects to avoid lower distances covered at high intensities that are related to success in football.

Introduction

There is a growing concern from football federations, teams, and players about matches being held in warm to hot conditions (Gouttebarge et al., 2023; Nassis et al., 2024). An important aspect of football match play in such conditions is the running performance of players, as high-speed distances covered have been associated with match outcomes and creating goal-scoring opportunities (Aquino et al., 2021; Faude et al., 2012; Schulze et al., 2021). Although it has been shown that playing in the heat can be detrimental to running performance, findings from observations of competitive football matches have been from small samples and with inconsistent findings, especially regarding high-speed activities, which are relevant to goal scoring outcomes (Draper et al., 2023; Maughan et al., 2010). Further understanding of the relationship between environmental temperatures and match running is important to football federations and teams to support player health and performance in hotter conditions.

During exercise, thermoregulatory processes are enabled to dissipate endogenously produced heat. In hot and humid conditions, the efficacy of these mechanisms becomes reduced (i.e., lower convective heat loss and decreased evaporation of sweat) and therefore they need to be increased to reach sufficient levels of heat dissipation, attempting to prevent excessive increases in core temperatures (Bergeron et al., 2012). The increased dilation of peripheral blood vessels and increased sweating lead to reduced central blood and stroke volumes and in turn increased heart rate and higher cardiovascular strain when temperatures are high (Bergeron et al., 2012). This is accompanied by the earlier onset of fatigue in warmer environmental conditions, which impairs endurance and intermittent sprint performance (Nybo et al., 2014). Collectively, these responses can result in reduced physical or technical football performance and, hence, are of importance for ensuring optimal player outcomes in the heat.

Running demands are critical in football, and total match running distance (although not necessarily linked to match success) is an often-reported performance

indicator (PI) in football. In hotter temperatures, match running is reported to be reduced due to players managing rising core temperatures, earlier onset of fatigue, and potential for heat illnesses. Although most studies report a reduction in match total distances in hotter temperatures (Chmura et al., 2017; Chmura et al., 2021; Konefał et al., 2021; Link & Weber, 2015; Loxston et al., 2019; Mohr et al., 2012; Özgünen et al., 2010; Trewin et al., 2018), one study (Nassis et al., 2015) reported no change. However, high-speed running activities have been found to be more important for success in football (Faude et al., 2012; Schulze et al., 2021), though the influence of hotter temperatures on high-speed activities remains less clear (Draper et al., 2023). High-speed running was found to be reduced in hotter conditions in some studies (Chmura et al., 2017; Loxston et al., 2019; Mohr et al., 2012; Nassis et al., 2015), but not all (Özgünen et al., 2010), and the number of sprints was also found to be reduced in some investigations (Chmura et al., 2017; Konefał et al., 2021; Nassis et al., 2015). Elite players might reduce running distances to maintain tactical and technical elements of the game, but this needs further investigation.

Differing outcomes regarding the association between environmental conditions and running PIs in football are potentially due to different methodological approaches, whereby different definitions of high-speed and sprint activities, as well as different arbitrary thresholds for “hot” conditions, are reported. Further, although most studies use a dichotomous categorization of heat stress (comparing “hot matches” vs “temperate matches”) (Konefał et al., 2021; Link & Weber, 2015; Mohr et al., 2012; Özgünen et al., 2010; Trewin et al., 2018), others used 3 (Chmura et al., 2017; Nassis et al., 2015) or 4 (Loxston et al., 2019) categories. The hottest category in these studies ranged from >14 °C (Link & Weber, 2015) to >43 °C (Mohr et al., 2012). As temperature is a linear variable, it makes sense that a more recent publication attempted to treat temperature as such and found that the relation- ship between temperature and physical performance parameters in football seemed to be linear (Chmura et al., 2021). However, these publications vary in their approach (observational vs experimental), number of matches observed (n= 2–1530), type of measurements (global positioning system vs optical tracking system), competition

setting (experimental matches vs World Cup matches), level of players (amateur vs elite), regional settings, and the gender of participants.

To better understand the relationship between environmental conditions and match running, we investigated data from 4 professional football leagues, both per league and in combination. We aimed to include large data sets from multiple leagues and settings, investigating total running distances and high-speed activities. We further aimed to include 2 different environmental conditions, comparing the associations between temperature (T) and wet-bulb globe temperature (WBGT) on running PIs, while treating them as linear variables as opposed to temperature categories. We hypothesized that match running PIs would be reduced in hotter environmental conditions.

Methods

This study observed 1610 matches from 4 professional male football leagues across Germany, Turkey, and Japan. The German data consists of all 612 matches from one season (2021–2022) of first (BL1) and second Bundesliga (BL2) and includes match locations, kick-off times, and match running statistics from official match reports that were shared from the league organization (Deutsche Fußball Liga GmbH, DFL). Data from the Turkish SüperLig (SL) were collated from the official SL performance data for 312 matches of the 2021–2022 season, including basic match information (time, location, and teams) and running performance data. Sixty-eight remaining matches of the SL were missing due to no performance data (50) or unavailable weather conditions (Nassis et al., 2015). Finally, all match data for 2 seasons (2021–2022) of Japanese J-League (JL) were collated from their website (jleague.co), including basic match information (time, location, and teams) and running performance, resulting in 686 matches. All leagues used optical tracking to generate physical performance data but used different parameters and cutoff values to characterize physical performance. In total, 7 PIs were available for BL1 and BL2, 10 for SL, and 2 for the JL, which are summarized with definitions in Table 2. The definitions and threshold values of PIs are based on those defined by the respective leagues. In total, 7 PIs overlapped in at least 3 leagues and were included in a combined analysis including all observed matches. The total distance and number of

sprints were the only available PIs available across all 4 leagues, although the definition of a sprint and high-speed run differed. Prior to analysis, all individual team information was removed from the data set, and data were analysed as PI per match for both teams, including goalkeepers. For example, if the 2 teams involved in a match performed 200 and 205 sprints, respectively, this was summed to a single metric (405 sprints) to describe the overall sprint volume for that match. Ethical approval was granted by the ethics committee of the Faculty for Human and Business Sciences of Saarland University (Ref No.: 23-14).

For all observed matches, dry-bulb T and WBGT were linked retrospectively. T is the commonly known and easily accessible ambient air temperature, whereas WBGT is a more inclusive heat index, adding the influence of relative humidity, wind, and solar radiation for a more detailed interpretation of the observed heat stress (Lemke & Kjellstrom, 2012; Liljegren et al., 2008). The use, advantages, and disadvantages of WBGT have been described extensively in previous research (Brocherie & Millet, 2015). This study included both indexes to understand potential differences in their use as predictors for running performance changes and to provide further insight for using these indexes in heat policies and guidelines. Environmental data were obtained from Meteostat.net, which is an open-source service that provides hourly meteorological data to most given geographical locations. The service estimates T, relative humidity, dew point, wind-speed, air-pressure, total precipitation, and descriptive weather condition (i.e., rain, cloudy, sunny, etc) based on a weighted interpolation of up to 4 weather stations, considering their distance and elevation difference to the actual location. Further, solar radiation was estimated using the solar angle at the time and location of the match. With this data, WBGT can be estimated by a validated and reliable method (Patel et al., 2013) developed by Liljegren et al. (2008) and implemented into R-code by Casanueva (Casanueva, 2019) in 2019. Overall, environmental conditions ranged from–8.8 to 45.4 °C T (mean [SD]:15.7 [8.4]) and–8.1 to 29.7 °C WBGT (mean [SD]: 13.6 [8.0]), including matches within a 54.2 °C T and 37.8 °C WBGT range. The environmental conditions observed in each league are presented in Table 3.

Table 2: Definitions of performance indicators (PIs) per league.

Performance indicator	Definition
Bundesliga 1 & 2	
total distance	Total distance covered by all players throughout the match.
number of sprints	Number of times a player is running faster than 4m/s for at least 2 seconds and during this time surpasses the threshold of 6.3 m/s at least once.
sprint distance	Distance covered as sprints by all players throughout the match.
number of high-speed runs	Number of times a player is running faster than 4m/s for at least 2 seconds and during this time surpasses the threshold of 5 m/s at least once, but not 6.3 m/s.
high-speed run distance	Distance covered as high-speed runs by all players throughout the match.
maximal speed	Single highest speed recorded throughout the match (fastest player).
ball in play	Minutes the ball is actually in play. Playing time, minus the time the match is stopped.
SüperLig	
total distance	Total distance covered by all players throughout the match.
number of sprints	Number of times a player is running faster than 7 m/s.
sprint distance	Distance covered at higher than 7 m/s.
number of high-speed runs	Number of times a player is running faster than 5.5 m/s but not 7 m/s.
high-speed run distance	Distance covered between 5 m/s and 7 m/s.
distance in speed zones (including high-speed run & sprint distance)	Distances covered in 5 different speed zones: - SZ1: < 2 m/s - SZ2: 2.01 – 4 m/s - SZ3: 4.01 – 5.5 m/s - SZ4: 5.51 – 7 m/s (high-speed run distance) - SZ5: > 7 m/s (sprint distance)
maximal speed	Average of each player's highest speed recorded throughout the match.
ball in play	Minutes the ball is actually in play. Total playing time, minus the time the match is stopped.
J-League	
total distance	Total distance covered by all players throughout the match.
number of sprints	Number of times a player is running faster than 6.667 m/s (24 km/h).

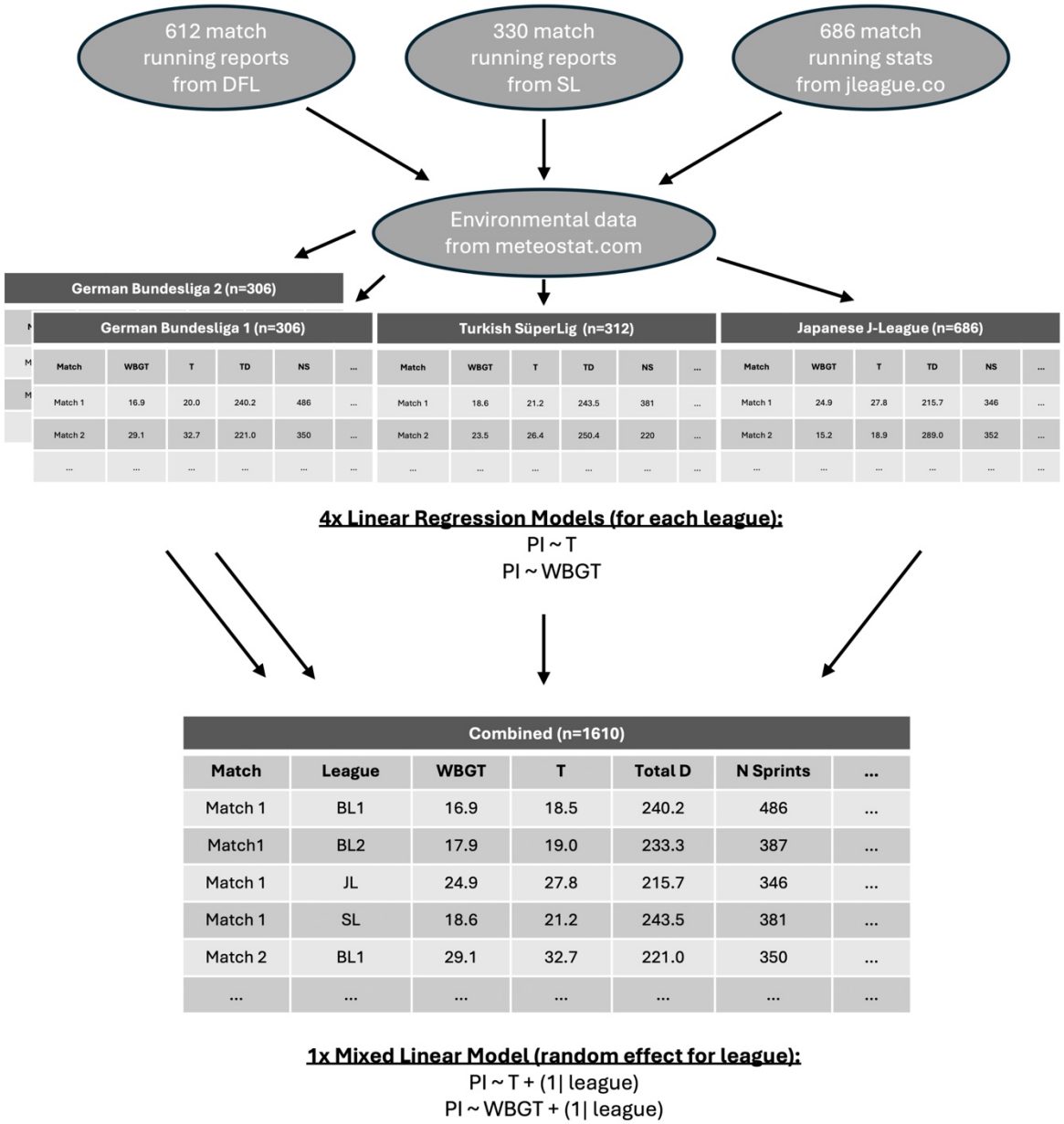
Abbreviations: SZ = speed zone; m/s = meters per second

Table 3: Environmental conditions in degree Celsius (°C), including mean and standard deviation (mean ± sd), minimum (min) and maximum (max) temperature and wet-bulb globe temperature.

	Temperature (in °C)			Wet-bulb globe temperature (in °C)		
	mean ± sd	min	max	mean ± sd	min	max
BL1	11.2 ± 7.1	-1.7	29.8	8.9 ± 6.2	-2.0	25.1
BL2	11.5 ± 7.3	0.4	29.4	9.9 ± 6.6	-1.6	25.4
JL	20.5 ± 6.6	-3.2	45.4	18.2 ± 7.0	-4.6	29.7
SL	13.9 ± 8.7	-8.8	33.7	11.7 ± 7.5	-8.1	28.0
Combined	**15.7 ± 8.4**	**-8.8**	**45.4**	**13.6 ± 8.0**	**-8.1**	**29.7**

Abbreviations: BL1 = Bundesliga 1; BL2 = Bundesliga 2; JL = J-League; SL = SüperLig; Combined = all four leagues; sd = standard deviation; min = minimum; max = maximum

Figure 1: Visualization of data structure and analysis. BL1 indicates Bundesliga 1; BL2, Bundesliga 2; DFL, Deutsche Fußball Liga; JL, J-League; NS, number of sprints; SL, SüperLig; T, temperature; TD, total distance; WBGT, wet-bulb globe temperature.



For each individual league, linear regressions were performed to investigate relationships between PIs and T or WBGT, respectively. To interpret the relationship, the estimate and 95% confidence interval (95% CI), standardized estimate (β) and 95% CI, explained variance (marginal R2), and P value were determined. Depending on β, effects can be categorized into small (0.10–0.29), medium (0.30–0.49), and large (>0.50), and R2 can be interpreted as small (.02–.12), medium (.13–.25), and

large (>.26). Further, to detect effects present across all 4 leagues, all matches were also combined into 1 large multileague data set, including the PIs and environmental conditions for all 1609 matches. To account for differences in data sources, PI definitions, and environmental conditions throughout the leagues, we performed mixed linear models and included the leagues as a random effect, resulting in the following models:

1. ***Model_0:*** *PI~ 1 + (1|league)*
2. ***Model_T:*** *PI~ T + (1|league)*
3. ***Model_WBGT:*** *PI~ WBGT + (1|league)*

The structure of the analysis is visualized in Figure 1. For the presentation of the full results in Table 4, the results of the combined leagues are also presented as "per player per 10 °C T or WBGT increase," to allow for an easy interpretation of the outcomes for individual performances. This value is derived by dividing the estimate for a 1 °C change in all players by 22 and multiply it by 10. Analysis and visualization were performed with R Studio 2022.07.1 using R version 4.2.1 stats, lme4, ggplot2, and jtools libraries. Statistical significance was defined at a level of 5% or less for the α-error ($P < .05$). As for each league, the series of relationships were observed, Bonferroni corrections were performed, and P values were adjusted depending on the number of tested PIs per data set (BL1 and BL2: $P < .0029$; JL: $P < .025$; SL: $P < .00417$; Combined: $P < .00714$).

Results

Bundesliga 1

The total distance covered by players decreased by 0.4 km (95% CI,–0.5 to–0.2; $P < .001$) for each 1 °C T and 0.4 km (95% CI,–0.6 to–0.3; $P < .001$) for each 1 °C WBGT was higher, resulting in a moderate effect (β: 0.32–0.33). Further, the number of sprints was lower by a moderate sized effect (β: 0.39–0.40) for 1 °C T (–2.8 sprints; 95% CI,–3.6 to–2.1; $P < .001$) and 1 °C WBGT (–3.3 sprints; 95% CI,–4.2 to–2.5; $P < .001$), whereas sprint distance was also lower per 1 °C T (–0.06 km; 95% CI,–0.07 to–0.04; $P < .001$), or WBGT (–0.07 km; 95% CI,–0.09 to–0.04; $P < .001$) was higher. Large effect sizes (β: 0.54 to 0.55) were detected for the association between the

number of high-speed runs, being lower by 6.2 runs (95% CI,–7.3 to–5.1; P < .001) for each 1 °C T and 7.0 runs (95% CI,–8.3 to–5.8; P < .001) for each 1 °C WBGT, which resulted in a lower high-speed distance covered per 1 °C T (–0.09 km; 95% CI,–0.11 to–0.07; P < .001), or WBGT (–0.10 km; 95% CI,–0.12 to–0.08; P < .001) was higher. Further, the peak speed recorded per match was higher by 0.03 km/h (95% CI, 0.01 to 0.04; P < .001) for each 1 °C T, and 0.03 km/h (95% CI, 0.01 to 0.05; P < .001) for each 1 °C WBGT was higher, resulting in small effect sizes (β: 0.21–0.23).

Bundesliga 2

The distance players covered during matches was lower by 0.3 km (95% CI,–0.4 to–0.2; P < .001) for each 1 °C T or 0.4 km (95% CI, –0.6 to–0.3; P < .001) for each 1 °C WBGT, resulting in a small effect of both T and WBGT (β: 0.29). Further, players performed less sprints per 1 °C T (–1.8 sprints; 95% CI,–2.5 to–1.1; P < .001), or WBGT (–1.9 sprints; 95% CI,–2.7 to–1.1; P < .001) was higher, and sprint distance was also lower per 1 °C T (–0.04 km; 95% CI,–0.06 to–0.02; P < .001), or WBGT (–0.04 km; 95% CI,–0.06 to–0.02; P < .001) was higher. Moderate effect sizes (β: 0.40–0.43) were also present for the relationship between a lower number of high-speed runs per 1 °C T (–5.2 runs; 95% CI,–6.4 to–4.0; P < .001) and WBGT (–5.7 runs; 95% CI, –7.0 to–4.3; P < .001) and lower high-speed distances covered per 1 °C higher T (–0.07 km; 95% CI,–0.09 to–0.06; P < .001) and WBGT (–0.08 km; 95% CI,–0.10 to–0.06; P < .001). Finally, the peak speed recorded per match was higher per 1 °C T (0.03 km/h; 95% CI, 0.02 to 0.04; P < .001) and WBGT (0.03 km/h; 95% CI, 0.02 to 0.05; P < .001), resulting in a small effect (β: 0.27–0.28).

J-League

The total distance players covered was lower per 1 °C T (–0.6 km; 95% CI,–0.7 to–0.5; P < .001) or WBGT (–0.6 km; 95% CI,–0.7 to–0.5; P < .001), resulting in moderate effect sizes (β: 0.34–0.39). In additional, the number of sprints was lower by 2.7 sprints (95% CI,–3.3 to–2.1; P < .001) and 3.1 sprints (95% CI,–3.6 to–2.5; P < .001) for each 1 °C higher in T or WBGT, resulting in a moderate effect (β: 0.34–0.40).

SüperLig

The total distance players covered during matches was not associated with changes in either temperature measurement after Bonferroni corrections were applied ($P > .01$). By contrast, the number of sprints performed per match was lower with a small effect size (β: 0.16) for each 1 °C higher in T (–0.7 sprints; 95% CI,–1.1 to–0.2; P= .003) and WBGT (–0.8 sprints; 95% CI,–1.3 to–0.2; P= .002) but was not after Bonferroni corrections were applied ($P > .02$). When observing distances covered in different speed zones, only the distance in speed zone 3 (2.01–4 m/s) was lower ($P < .001$) when either temperature measure was higher. All other speed zones showed small reductions, but after Bonferroni corrections, nonsignificant reductions ($P > .01$), when T or WBGT, was higher, except speed zone 1 (0–2 m/s), which was conversely but also not significantly affected ($P > .02$).

Combined Leagues

When combining all match data, a reduction of total distance covered was associated with each 1 °C higher in T (–0.4 km; 95% CI,–0.4 to –0.3; $P < .001$) and WBGT (–0.4 km; 95% CI,–0.5 to–0.4; $P < .001$) per match, resulting in a moderate sized effect (β: 0.32–0.36). Figure 2 shows the association between total distance and T and WBGT for each individual league, as well as the number of sprints, which was also lower with moderate effect sizes (β: 0.34–0.39) per 1 °C higher in T (–2.0 sprints; 95% CI,–2.3 to–1.7; $P < .001$) and WBGT (–2.4 sprints; 95% CI,–2.7 to–2.1; $P < .001$). This resulted in the sprint distance covered being lower by 0.03 km (95% CI,–0.04 to–0.02; $P < .001$) for each 1 °C higher in T and 0.04 km (95% CI,–0.05 to –0.03; $P < .001$) for each 1 °C higher in WBGT. Similarly, high-speed runs were lower by 3.4 runs (95% CI,–4.2 to–2.7; $P < .001$) per 1 °C T, and 3.8 runs (95% CI,–4.6 to–2.9; $P < .001$) per 1 °C WBGT was higher, and accordingly, the high-speed runs distance was reduced per 1 °C higher T (–0.05 km; 95% CI,–0.06 to–0.04; $P < .001$) and WBGT (–0.06 km; 95% CI,–0.07 to–0.05; $P < .001$), resulting in small to moderate effects on high-speed running (β: 0.28–0.30). Figure 3 shows the association between sprint distance and high-speed distance with T and WBGT for each individual league.

Further, there were small effects (β: 0.18–0.19) on peak speed, which increased at 0.02 km/h (95% CI, 0.01–0.02; P < .001) per 1 °C higher in T and 0.02 km/h (95% CI, 0.01 to 0.02; P < .001) per 1 °C higher in WBGT. Finally, there were marginal to small effects on the minutes the ball was in play (β: 0.09–0.10), which was 0.05 minutes (95% CI, –0.09 to–0.02; P= .003) lower for each 1 °C higher in T and 0.06 minutes (95% CI,–0.10 to–0.02; P= .006) lower for each 1 °C higher in WBGT. Table 4 summarizes all results for each PI per league and in the combined data set.

Table 4: Association between running PIs and environmental conditions.

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	Estimate (95% CI)	β (95% CI)	R^2 marg.	p-value	Estimate (95% CI)	β (95% CI)	R^2 marg.	p-value
total distance (in km)									
BL1	230.3 ± 8.0	-0.36 (-0.47,-0.24)	-0.32 (-0.43,-0.22)	0.10	<0.001*	-0.43 (-0.56,-0.29)	-0.33 (-0.44,-0.23)	0.11	<0.001*
BL2	230.4 ± 8.1	-0.32 (-0.44,-0.20)	-0.29 (-0.40,-0.18)	0.08	<0.001*	-0.36 (-0.49,-0.23)	-0.29 (-0.40,-0.18)	0.08	<0.001*
JL	228.1 ± 11.2	-0.57 (-0.70,-0.46)	-0.34 (-0.41,-0.27)	0.12	<0.001*	-0.63 (-0.74,-0.52)	-0.39 (-0.46,-0.33)	0.15	<0.001*
SL	226.9 ± 8.6	-0.16 (-0.30,-0.09)	-0.06 (-0.17,-0.05)	0.02	0.01	-0.15 (-0.32,0.13)	-0.05 (-0.16,0.06)	0.01	0.02
Combi	228.7 ± 9.7	-0.37 (-0.43,-0.31)	-0.32 (-0.38,-0.27)	0.10	<0.001*	-0.44 (-0.5,-0.37)	-0.36 (-0.42,-0.31)	0.12	<0.001*
Reduction per player (in m):		*-168 m per 10° C T higher (CI95: -195,-141)*				*-200 m per 10° C WBGT higher (CI95: -227,-168)*			
number of sprints (count)									
BL1	438.6 ± 56.4	-2.81 (-3.56,-2.06)	-0.39 (-0.49,-0.29)	0.15	<0.001*	-3.34 (-4.20,-2.48)	-0.4 (-0.51,-0.30)	0.16	<0.001*
BL2	418.9 ± 48.1	-1.77 (-2.49,-1.06)	-0.27 (-0.38,-0.16)	0.07	<0.001*	-1.93 (-2.73,-1.13)	-0.26 (-0.37,-0.15)	0.07	<0.001*
JL	348.7 ± 53.2	-2.69 (-3.25,-2.12)	-0.34 (-0.41,-0.27)	0.11	<0.001*	-3.06 (-3.58,-2.54)	-0.40 (-0.47,-0.33)	0.16	<0.001*
SL	190.3 ± 35.1	-0.68 (-1.11,-0.19)	-0.16 (-0.27,-0.05)	0.03	0.003*	-0.81 (-1.30,-0.24)	-0.16 (-0.27,-0.05)	0.03	0.002*
Combi	352.4 ± 102.5	-1.99 (-2.30,-1.67)	-0.34 (-0.40,-0.29)	0.02	<0.001*	-2.39 (-2.72,-2.07)	-0.39 (-0.44,-0.34)	0.02	<0.001*
Reduction per player (count):		*-0.9 sprints per 10° C T higher (CI95: -1.0,-0.8)*				*-1.1 sprints per 10° C WBGT higher (CI95: -1.2,-0.9)*			

Abbreviations: SD = standard deviation; Estimate 95% CI = estimate and 95% confidence interval; ß 95% CI = standardized Estimate (effect size) and 95% confidence interval; R^2 marg. = marginal r squared (explained variance); BL1 = Bundesliga 1; BL2 = Bundesliga 2; JL = J-League; SL = SüperLig; Combined = all four leagues; * = significant after Bonferroni correction

Table 4 (continued):

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	Estimate (95%CI)	β (95%CI)	R^2 (marg.)	p-value	Estimate (95%CI)	β (95%CI)	R^2 (marg.)	p-value
sprint distance (count)									
BL1	8.7 ± 1.3	-0.06 (-0.07,-0.04)	-0.30 (-0.41,-0.20)	0.09	<0.001*	-0.07 (-0.09,-0.04)	-0.31 (-0.42,-0.21)	0.10	<0.001*
BL2	8.3 ± 1.2	-0.04 (-0.06,-0.02)	-0.23 (-0.34,-0.12)	0.05	<0.001*	-0.04 (-0.06,-0.02)	-0.23 (-0.34,-0.12)	0.05	<0.001*
SL	3.3 ± 0.7	-0.01 (-0.02,0.00)	-0.11 (-0.22,0.00)	0.01	0.03	-0.01 (-0.02,0.00)	-0.12 (-0.23,-0.01)	0.01	0.02
Combi	6.9 ± 2.8	-0.03 (-0.04,-0.02)	-0.22 (-0.28,-0.15)	0.01	<0.001*	-0.04 (-0.05,-0.03)	-0.22 (-0.29,-0.16)	0.01	<0.001*
Reduction per player (in m):		*-14 m per 10° C T higher (CI95: -18,-9)*				*-18 m per 10° C WBGT higher (CI95: -23,-14)*			
number of high-speed runs (count)									
BL1	942.9 ± 94.2	-6.21 (-7.28,-5.14)	-0.55 (-0.64,-0.45)	0.30	<0.001*	-7.03 (-8.28,-5.79)	-0.54 (-0.63,-0.44)	0.29	<0.001*
BL2	921.4 ± 101.9	-5.17 (-6.39,-3.95)	-0.43 (-0.53,-0.33)	0.18	<0.001*	-5.66 (-7.03,-4.3)	-0.42 (-0.53,-0.32)	0.18	<0.001*
SL	1077.6 ± 99.4	-0.21 (-1.67,1.24)	-0.02 (-0.13,0.09)	0.00	0.77	0.11 (-1.59,1.8)	0.01 (-0.10,0.12)	0.00	0.90
Combi	989.4 ± 0.1	-3,40 (-4.15,-2.73)	-0.3 (-0.36,-0.24)	0.05	<0.001*	-3.8 (-4.57,-2.93)	-0.29 (-0.35,-0.22)	0.04	<0.001*
Reduction per player (count):		*-1.6 sprints per 10° C T higher (CI95: -1.9,-1.2)*				*-1.7 sprints per 10° C WBGT higher (CI95: -2.1,-1.3)*			
high speed distance (in km)									
BL1	13.3 ± 1.3	-0.09 (-0.11,-0.07)	-0.49 (-0.59,-0.40)	0.24	<0.001*	-0.10 (-0.12,-0.08)	-0.48 (-0.58,-0.39)	0.23	<0.001*
BL2	13.2 ± 1.4	-0.07 (-0.09,-0.06)	-0.40 (-0.51,-0.30)	0.16	<0.001*	-0.08 (-0.10,-0.06)	-0.40 (-0.50,-0.29)	0.16	<0.001*
SL	16.5 ± 1.6	-0.03 (-0.04, 0.00)	-0.11 (-0.22,-0.01)	0.01	0.06	-0.03 (-0.05,0.00)	-0.09 (-0.20,0.02)	0.01	0.10
Combi	14.4 ± 2.1	-0.05 (-0.06,-0.04)	-0.29 (-0.35,-0.23)	0.03	<0.001*	-0.06 (-0.07,-0.05)	-0.28 (-0.34,-0.22)	0.03	<0.001*
Reduction per player (in m):		*-23 m per 10° C T higher (CI95: -27,-18)*				*-27 m per 10° C WBGT higher (CI95: -32,-23)*			
peak speed (in km/h)									
BL1	34.0 ± 0.9	0.03 (0.01,0.04)	0.23 (0.12,0.34)	0.05	<0.001*	0.03 (0.01,0.05)	0.21 (0.10,0.32)	0.04	<0.001*
BL2	33.6 ± 0.8	0.03 (0.01,0.04)	0.28 (0.17,0.39)	0.08	<0.001*	0.03 (0.02,0.05)	0.27 (0.17,0.38)	0.07	<0.001*
SL	29.5 ± 0.6	0.01 (-0.01,0.03)	0.05 (-0.07,0.16)	0.00	0.42	0.01 (-0.02,0.04)	0.04 (-0.07,0.16)	0.00	0.43
Combi	32.5 ± 2.3	0.02 (0.01,0.02)	0.19 (0.12,0.25)	0.00	<0.001*	0.02 (0.01,0.03)	0.18 (0.12,0.25)	0.00	<0.001*
Increase per player (in km/h)		*+0.2 km/h per 10° C T higher (CI95: 0.1,0.2)*				*+0.2 km/h per 10° C WBGT higher (CI95: 0.1,0.3)*			

Abbreviations: SD = standard deviation; Estimate 95% CI = estimate and 95% confidence interval; ß 95% CI = standardized Estimate (effect size) and 95% confidence interval; R^2 marg. = marginal r squared (explained variance); BL1 = Bundesliga 1; BL2 = Bundesliga 2; JL = J-League; SL = SüperLig; Combined = all four leagues; * = significant after Bonferroni correction

Discussion

This study investigated the relationship between environmental temperatures (T and WBGT) and running PIs in 4 professional football leagues. When combining match data of all leagues, a lower total running distance was observed when environmental temperatures were higher. Further, a lower number of sprints and high-speed runs, as well as distances covered at these speeds, were observed when T or WBGT were

higher. However, a higher peak speed was observed in matches with higher T or WBGT.

The total distance covered during football matches is an often- reported PI, though its usefulness as a predictor for success is questionable (Aquino et al., 2021; Hoppe et al., 2015; Rampinini et al., 2009). Although some studies found teams with higher running distances to be more successful (Aquino et al., 2021), more often, the less successful teams are found to run more, whereas successful teams only run more when in ball possession (Hoppe et al., 2015; Rampinini et al., 2009).

Figure 2: Relationship of total distance and number of sprints with temperature and WBGT across all 4 leagues. BL1 indicates Bundesliga 1; BL2, Bundesliga 2; JL, J-League; TSL, Turkish SüperLig; WBGT, wet-bulb globe temperature.

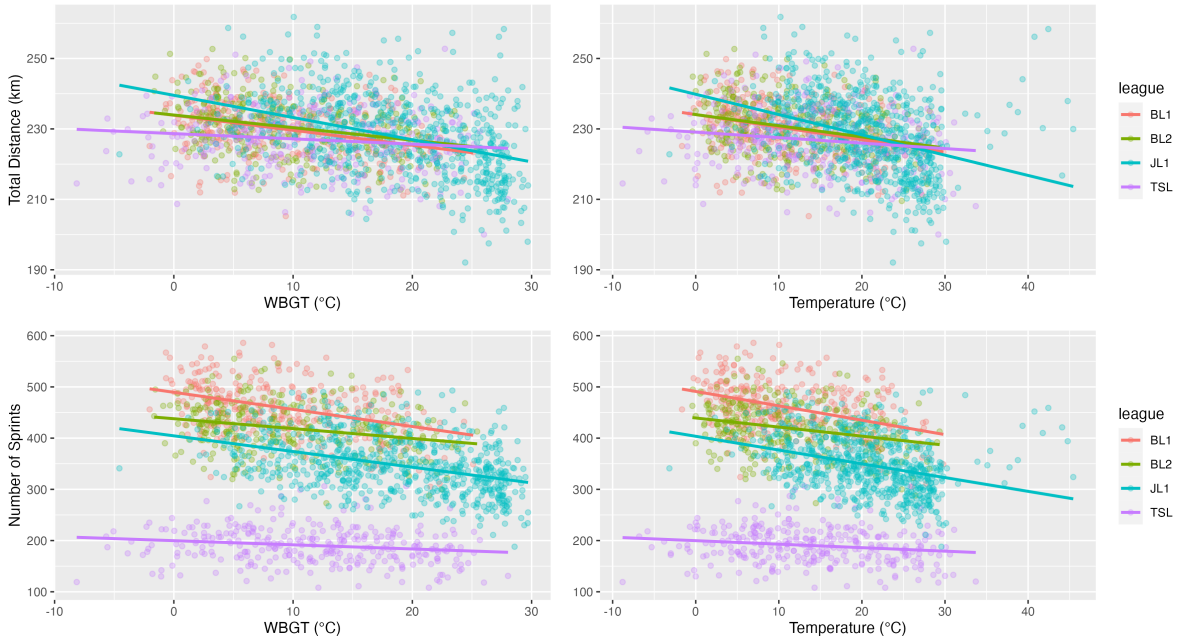
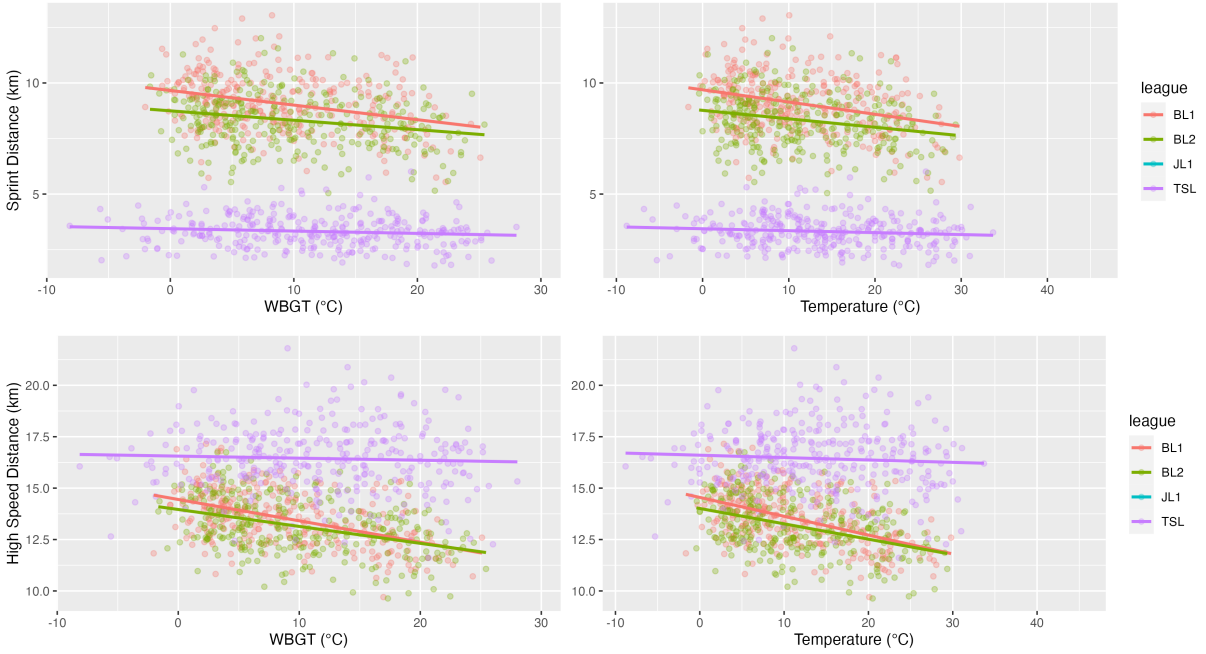


Figure 3: Relationship of total distance and number of sprints with temperature and WBGT across all 4 leagues. BL1 indicates Bundesliga 1; BL2, Bundesliga 2; JL, J-League; TSL, Turkish SüperLig; WBGT, wet-bulb globe temperature.



In our study, total distance was clearly lower when T or WBGT were higher in the BL1, BL2, JL, and the combined match data of all 4 leagues, which is in line with previous research (Konefał et al., 2021; Loxston et al., 2019; Mohr et al., 2012). Although speculative, these findings could result from increased player thermoregulatory and cardiovascular strain, leading to earlier onset of fatigue as part of a preventive measure against an elevated core temperature (Bergeron et al., 2012; Nybo et al., 2014). Furthermore, a conscious pacing strategy, in which players try to avoid elevated levels of fatigue to maintain their overall quality of playing, could be another underlying reason (Skein et al., 2012). Such pacing and tactical strategies exist even in nonthermoregulatory challenging matches, but they are especially important in the heat, aiming to manage fatigue throughout the match and enabling high physical efforts when most critical (Schulze et al., 2021).

The distance covered at a high speed, especially when in ball possession, is associated with successful match outcomes in football (Andrzejewski et al., 2022; Chmura et al., 2018; Rampinini et al., 2009). For example, increased high intensity distances and straight-line sprinting were the most frequent actions leading to goal scoring opportunities (Faude et al., 2012; Schulze et al., 2021). The current study

found that less sprints were attempted in all 4 leagues and that the number of high-speed runs, as well as the sprint and high-speed distance, was lower when T or WBGT were higher in the BL1, BL2, and when combining all match data, in line with previous studies (Chmura et al., 2017; Chmura et al., 2021; Konefał et al., 2021; Loxston et al., 2019; Mohr et al., 2012; Nassis et al., 2015; Trewin et al., 2018). Nevertheless, research has not shown that goals or shots are reduced in hotter temperatures (Chmura et al., 2021; Nassis et al., 2015). Although speculative, this might again result from players pacing strategies, persevering thermoregulatory state, preventing heat-related illnesses, and managing fatigue by performing high-speed actions only when most needed.

A player's ability to perform high maximum speeds and outrunning an opponent might aid in creating or preventing scoring opportunities. This study found a small effect for a higher peak speed in BL1, BL2, and the combined match data when T or WBGT were higher. This is in line with thermoregulatory theory, arguing that higher muscle temperatures in hot conditions are related to increased maximum velocities (Nybo et al., 2014). Accordingly, previous research has shown markers of muscle damage to be reduced after a match in hot compared with temperate conditions, which may result from a combination of less muscle damage in warmer muscles and a reduced running volume in warmer conditions (Nybo et al., 2013).

In this investigation there was no difference between model outcomes for T or WBGT as a predictor for running PIs. Although it is suggested that WBGT is better in describing athletes heat stress by including the effects of humidity, solar radiation, and wind, the measure is also less accessible, especially to lower league clubs, who would need to invest in equipment and trained personnel to monitor WBGT. Therefore, when considering the implementation of heat guidelines, the use of T should not be neglected.

Limitations

The approach of this study, including a large number of observations from 4 different leagues, was able to identify robust findings of environmental conditions on

running performance but is also subject to some limitations. Although we accounted for differences in data sources and PI thresholds by including the leagues as a random effect in the mixed models, a more standardized data collection would be preferable. Similarly, measuring environmental conditions directly at match venues would improve accuracy of the observed temperatures. Nevertheless, the ability to combine multiple leagues and geographical settings and increases in the number of observations lead to an increased external validity of the findings. Finally, although our data represented a large range of environmental conditions, it can be argued that the ratio of observations in very hot conditions was low, especially in the German leagues. Only 24 matches were held in >30 °C T, 17 of these in the JL, 7 in the SL, and none in BL1 or BL2. The same number of matches were held in >28 °C WBGT, with one of these in the SL and the rest in the in the JL. It must be assumed that hotter conditions could further increase the effects observed in this study, though examining more matches in such environments would be needed to better understand this relationship.

Practical Applications

Football teams should be aware of the associations between environmental conditions and running performance to adjust their playing styles and tactical approaches accordingly. Performing a reduced warm up or applying cooling might help to mitigate some effects of hotter conditions (Gouttebarge et al., 2023; Nassis et al., 2024). Football federations should further monitor environmental conditions and their effects on players as the observations of the current study were made in only moderately challenging conditions but may become more pronounced in more severe heat. Heat mitigating policies might be implemented to protect players from being exposed to hotter conditions in the future (Gouttebarge et al., 2023; Nassis et al., 2024).

Conclusion

Higher temperature or wet-bulb globe temperature was associated with lower physical performance in football matches. This was observed not only for total distances covered but, notably, also for high-speed and sprinting activities, though

peak speed was higher in warmer climates. The reductions may be a conscious or subconscious reaction to the increased heat stress observed by players aiming to manage fatigue, preserve thermoregulatory state, and prevent heat illnesses.

Study 2: Football Match Play Characteristics in the Heat

S2.1 Introduction and Literature Summary

Technical and tactical match play characteristics are strong determinates for success in football. For instance, a higher number of shots, (Lepschy et al., 2020; Rampinini et al., 2009), passes (Bostanci et al., 2018; Broich et al., 2014; Chmura et al., 2021; Liu et al., 2015), short passes (Rampinini et al., 2009), passes into the final third (Rein et al., 2017), ball touches (Broich et al., 2014; Liu et al., 2015; Rampinini et al., 2009) and tackles (Rampinini et al., 2009) have all been associated with success in football. As cognitive abilities decrease in hotter conditions, it has been hypothesized that match play characteristics may also be altered when playing in hotter conditions (Nassis et al., 2024). Next to the direct influence of heat on cognition, and thus the execution of technical activities, the changes in match running associated with higher temperatures may also call for an adaptation of the tactical match approach.

Multiple observational (Chmura et al., 2021; Konefał et al., 2021; Loxston et al., 2019; Nassis et al., 2015; Zhou et al., 2019) and one experimental (Mohr et al., 2012) study have investigated associations between heat stress and match play characteristics and found mainly an increase in the success rate of passes and a decrease in lost balls (see Table 5). This has been proposed to result from a lower opponent pressure, due to the decreased match intensity and running (Mohr et al., 2012; Nassis et al., 2015). However, many of these studies analysed small samples from individual competition settings and categorized environmental parameters instead of investigating them as continuous factors. Finally, some studies only looked at a very limited number of match play parameters.

Therefore, Study 2 aimed at examining associations between T and WBGT and 17 different performance indicators (PIs), in a large dataset including 1585 matches, across four different professional football leagues. This approach enables a more

detailed and robust understanding of associations between heat and match play characteristics in football.

Table 5: Literature review of studies investigating associations between match play characteristics and environmental temperatures in football.

Study	Sample	Environmental Parameters	Physical Performance Parameters	Effects of Hotter Conditions
Mohr et al., 2012	2 matches; experimental; 2 teams; 17 male players	2 T + RH combinations •21 °C + 55% •43 °C + 12%	passes; pass%; crosses; cross%; forward passes; forward pass %; pass and cross length; gain and loss of ball possession; challenges; duels	•increased pass%, forward pass% and cross% •reduced gain and loss of ball possession, challenges and duels
Nassis et al., 2015	64 matches; FIFA World Cup 2014; all teams; male players	3 HS categories based on WBGT + RH (Gonzalez, 1995): Low, Mod, Hot	goals; passes; pass%; cards; total playing time	•increased pass% •Increase red cards
Loxston et al., 2018	42 matches; Arabic Gulf League; 1 team; 9 male players	4 HS categories based on WBGT + RH (Gonzalez, 1995): Low, Mod, Hot, Excess	passes; pass%; short passes; medium passes; long passes; tackles; interceptions (in opposition half); balls lost (in own half); fouls	•reduced balls lost
Zhou et al., 2019	240 matches; Chinese Super League; all teams; male players	T & RH continuous scale	shots (on target); possession (in attaching half); passes; pass %; forward passes; forward pass%; crosses; corners; offsides; opponent entry in 35m and penalty box; 50-50 challenges won; fouls; cards	•increased pass% and forward pass%
Konefal et al., 2021	64 matches; FIFA World Cup 2018; all teams; male players	2 UTCI categories No HS: 9-26 °C UTCI HS: > 26 °C UTCI	shots; passes; pass%	•reduced passes (when training and playing in hot vs. training but not playing in hot)
Chmura et al., 2021	1530 matches; German Bundesliga1; all teams; male players	T, RH & WBGT continuous scale	shots; passes; crosses; duels; duel%	•no effects
Study 2	1585 matches; German Bundesliga1,2, Australian A-League, Spanish La Liga; all teams; male players	T & WBGT continuous scale	goals; shots; passes; pass%; short passes; long passes; pass distance; key passes; final third passes; touches; offensive touches; take-ons; take-on%; turnovers; tackles; fouls; cards	•reduced passes, short passes, passes into final third, touches, offensive touches, take-ons, turnovers •increased pass%

Abbreviations: ***Environmental conditions:*** *T = Temperature; °C = degree Celsius; HS = Heat Stress; RH = Relative humidity; % = percentage (RH); WBGT = Wet-bulb globe temperature; UTCI = Universal thermal climate index; Mod = Moderate;* ***Performance:*** *Parameter = Number of parameter; Parameter% = success rate of parameter.*

S2.2 Associations between Match Play Characteristics and Environmental Conditions in 4 Professional Football Leagues

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Abstract

This study investigated the association between environmental temperature and match-play characteristics (shooting, passing, dribbling and defending) in four professional football leagues. Twenty-seven performance indicators (PI's) were collated from 1585 matches from the German Bundesliga 1 and 2, Spanish La Liga and Australian A-League. Environmental data were obtained for dry-bulb temperature (T) and wet-bulb globe temperature (WBGT) retrospectively from public sources. For each league, linear regressions were used to determine relationships between PI's and T and WBGT and linear mixed models were used to determine those associations across all four leagues. Individual leagues showed varying associations between a collection of PI's and environmental measures. When combining the four leagues' match data, 8 of the 17 investigated parameters were associated with T and WBGT ($p < 0.002$). Passes, especially short passes, were reduced in higher T (–2.3[–3.1,–1.5] and $p < 0.001$) and WBGT (–3.1 [–4.0,–2.1] and $p < 0.001$), alongside an increase in the success rate of passes (0.06[0.02,0.09]and $p \leq 0.001$).The number of passes into the opponent's final third was reduced for both T(–0.18[–0.25,–0.05] and $p = 0.001$) and WBGT (–0.17[–0.28,–0.05] and $p = 0.002$), but the number of key passes leading to a shot or goal was not associated with T or WBGT ($p \geq 0.67$). The number of touches, take-ons and turnovers were reduced in higher T and WBGT (all $p < 0.001$). Accordingly, in higher heat stress, match actions, especially those performed at high volumes, are reduced. Therefore, teams should expect a possibly altered match play and may consider adapting tactical or heat-mitigating strategies to counter these effects.

Introduction

Football matches played in hot conditions are of growing concern to football federations, clubs and players (Gouttebarge et al., 2023; Nassis et al., 2024). Although it is known that competing in hot environmental conditions can have implications for physical and cognitive performance and health, most football literature focusses on either thermoregulatory function or running demands (Draper et al., 2022; Maughan et al., 2010). However, research on the effects on football match play (i.e., number of match actions and success rates of technical parameters) remains lacking, especially given its importance to overall match performance (Broich et al., 2014; Chmura et al., 2021; Rampinini et al., 2009). Understanding match-play characteristics in changing environmental temperatures can inform players and staff on expected technical and tactical performance changes and inform federations on the overall game style for viewing audiences.

During exercise, thermoregulatory function alleviates metabolic heat production. In environments where the air and mean radiant temperature are higher than an athlete's skin temperature, heat dissipation occurs predominantly through sweating (evaporative heat loss). However, in hot environments with high humidity or in adequate wind flow, evaporation of sweat is impaired and heat loss decreases (Bergeron et al., 2012). When heat gain exceeds loss, this can lead to increasing core temperatures linked to health adversities (Cramer & Jay, 2016; Nybo et al., 2014). Nevertheless, among athletic populations high-core temperatures are often sustained without negative health implications but are associated with performance changes (Racinais et al., 2023). In football, this typically translates into a reduced running performance (Draper et al., 2022; Schwarz et al., 2024). However, running is only one part of football, and whether higher environmental temperatures also result in deteriorations of other match actions (e.g., passes, touches and tackles) is yet to be investigated using a large multi league sample. The increased or earlier manifestation of fatigue due to hot conditions can result in alterations of cognitive and motor skill performance, such as the impairment of complex tasks namely decision-making, working memory, recognition and problem-solving (Schmit et al., 2017), which are slower or worse in hotter temperatures (Coehoorn et al., 2020; Syndicus et al., 2018).

These effects on cognitive function, alongside observed alterations to pacing strategies (Racinais et al., 2015; Skein et al., 2012), may affect player's technical engagement, and thus affect team performance and match style. Hence, playing football in hot conditions could result in a lower playing quality, with players performing more errors (cognitive performance decrease) or reducing the quantity of match actions (team tactical or individual pacing approaches). On the other hand, playing football in colder conditions has not been found to affect performance (Carling et al., 2011).

Only five observational studies have investigated changes to football match characteristics based on environmental conditions. These studies reported minor changes in performance indicators (PI's), such as passing (total passes and pass rates), shooting (goals scored and shots taken) and defending (number of duels) parameters. These investigations included environmental measurements of dry-bulb temperature (T), relative humidity (RH), wet-bulb globe temperature (WBGT) or universal thermal climate index (UTCI) (Chmura et al., 2021; Konefał et al., 2021; Nassis et al., 2015; Zhou et al., 2019). A higher pass rate was found during the 2014 FIFA World Cup in Brazil when environmental stress was ‘high’ compared to ‘low’ (Nassis et al., 2015). A similar small effect (β= 0.27) for increased pass rates in higher T was reported in Chinese first-division football (Zhou et al., 2019). This was hypothesised to be linked to less opponent pressure caused by lower running distances in hotter conditions (Nassis et al., 2015; Zhou et al., 2019). However, other investigations have not observed this relationship (Chmura et al., 2021; Konefał et al., 2021), instead reporting fewer passes performed above 26° UTCI at the 2018 FIFA World Cup in Russia. Although these descriptions are useful, they investigated a small number of PI's during singular tournament settings, that is, the 64 matches of a single FIFA World Cup (Konefał et al., 2021; Nassis et al., 2015), or data from a single league (Chmura et al., 2021; Zhou et al., 2019).The different findings from these studies suggest that the influence of higher temperatures on match characteristics can vary between different locations and competition settings. Future research could investigate different settings and aim to include more factors (e.g., player

acclimatisation and fitness, playing styles and competition structures) to identify potential reasons for such differences.

Many heat policies and guidelines exist to support players and staff in hot environments and limit possible health complications whilst maintaining performance (Gouttebarge et al., 2023; Nassis et al., 2024). Such heat policies commonly rely on WBGT as the underlying heat stress index and vary between federations. For example, the Fédération Internationale de Football Association (FIFA) suggests additional drinking breaks when WBGT exceeds 32°C, whereas Football Australia implements them at 26°C WBGT (Gouttebarge et al., 2023). Although widely used, WBGT has been criticised for its difficulty to measure and potentially underestimating the risk in humid conditions (Brocherie & Millet, 2015). Although the purpose of these policies is to reduce heat-illness risk, from a performance perspective, it is important to understand expected changes in match characteristics. Hence, this study aimed to investigate the relationship between environmental conditions and match PI's across four professional football leagues. We hypothesised that in higher WBGT or T, there would be significantly lower volumes of shooting, passing, dribbling and defending PI's, whilst performance quality metrics would be maintained.

Materials and Methods

This study observed 1585 matches (all played on natural grass) from four professional male football leagues across Germany, Spain and Australia. The German data were obtained over one season (2021–2022) of the first (BL1) and second (BL2) Bundesliga. The 306 matches, including match locations, kick-off times and 143 match play PI's, were obtained through an open-source website (FBREF) for each German league. For the Spanish league, match PI's from two seasons (2021–2023) of Spain's first division, La Liga (LL), were collected through the same website (FBREF), resulting in a total of 520 matches, with 67 PI's aligned to each match. Finally, data from Australia were provided for four seasons (2016–2020) of the Australian first division A-League (AL), sharing match information for 453 matches and 109 PI's aligned with each match. All match-play data were generated using ‘Opta’ (STATS PERFORM), an optical tracking service using a combination of human annotation, computer vision

and artificial intelligence modelling. Prior to analysis, all individual player or team information was removed, and data were analysed as PI per match for both teams in that match. For example, in any match, if the two teams performed 500 and 400 passes, respectively, this was summed to a single metric (900 passes) to describe the passing volume for that match. After scanning all available PI's, a total of 17 PI's were deemed as relevant based on use in previous research and appropriateness to the topic, of which 15 were available across all four leagues, with two markers (passing distance and final third passes) not being available for the AL. Table 6 summarises all PI's in four categories: shooting, passing, dribbling and defending and gives detailed definitions of how each PI was defined. The ethical approval was granted by the Ethics Committee of the Faculty for Human and Business Sciences of Saarland University (Ref No.: 23-14).

Table 6: Definitions of Performance Indicators (PI's).

Performance Indicator	Definition
Shooting	
Goals	Number of goals scored
Shots	Number of shots taken
Passing	
Passes	Overall number of pass attempts (successful & unsuccessful)
Pass success rate	Percentage of pass attempts being successful
Short passes	Number of short passes (In BL1, BL2 and LL: shorter than 15 yards ≈ 13.7 meter)
Long passes	Number of long passes (In BL1, BL2 and LL: longer than 30 yards ≈ 27.4 meter)
Passing distance	Total distance (in meter) that completed passes have travelled in any direction
Key passes	Passes that directly lead to a shot
Final third passes	Passes that enter the third of the pitch closest to the opponent's goal
Dribbling	
Touches	Overall number of touches
Offensive touches	Number of touches in the offensive third
Take-ons	Number of take-ons
Take-on success rate	Percentage of take-ons being successful.
Defending	
Turnovers	Total number of turnovers including unsuccessful pass attempts, unsuccessful take-ons, or other unsuccessful touches/mis-controls resulting in loss of possession
Tackles	Number of tackles
Fouls	Number of fouls committed
Cards	Number of yellow and red cards

Abbreviations: BL1 = Bundesliga 1; BL2 = Bundesliga 2; LL = La Liga.

Environmental conditions in the form of T and WBGT were obtained retrospectively and aligned to each match based on the location and kick-off times. T is the commonly reported ambient air temperature, whereas WBGT is an index developed to monitor human heat stress in hot thermal environments, adding the influence of RH, wind and solar radiation. The use, advantages and disadvantages of WBGT have been described extensively in previous research (Brocherie & Millet, 2015; Budd, 2008; Lemke & Kjellstrom, 2012; Liljegren et al., 2008).We included both T and WBGT to refine the understanding of the differences between these measures and their associations with match-play, to provide insights on the future use of these measures. For BL1, BL2 and LL matches, environmental data were obtained from Meteostat.net (Meteostat.net), an open-source service providing hourly meteorological data for most geological locations. They collate environmental data from the four closest weather stations to the stadium whilst considering elevation differences and provide the following data: T, RH, dew point, wind speed, air pressure, total precipitation and the descriptive weather condition (i.e., cloudy and sunny), based on a weighted interpolation considering the distance and elevation difference of the weather stations to the stadium. Due to concerns about the accuracy of the wind speed inside the stadiums, airflow was set to 1 m/s to represent a minimum airflow generated by the movement of players, standardising this between matches. Further, the maximum solar radiation was estimated using the solar angle at the time and location of the match. With this data, WBGT can be estimated using a validated and reliable method (Patel et al., 2013) developed by Liljegren et al. (2008) (Liljegren et al., 2008) and implemented into R-code by Casanueva (2019) (Casanueva, 2019). For AL matches, as some locations were not accessible through Meteostat.net, environmental conditions were obtained from the commercial provider UBIMET GmbH (UBIMET GmbH). Similarly to Metoestat.net, they collect data from multiple weather stations, radar and satellite data to estimate meteorological data at given ground locations and provide measurements of T, RH and WBGT. As an internal validation of the WBGT data based on Meteostat.net data, the WBGT estimation method used for the BL1, BL2 and LL data was performed with the AL data as well and then compared to the WBGT reported from the commercial provider UBIMET.com, resulting in a very good linear association (correlation coefficient r = 0.93). Although data from both

providers aligns, there might be differences between the retrospectively fitted data and the actual conditions in the stadium, as wind speed and solar radiation might change locally (Chalmers et al., 2020; Racinais et al., 2023). Fewer local variations exist for T and RH, which yield the most weight in the used WBGT estimations. Therefore, the standardised use of minimal airflow and maximum solar radiation may result in a small over estimation of WBGT. As this would be a systematic overestimation, this should influence the intercept but not the direction and slope of the association between WBGT and PI's. To display the exposure to hot environments in each of the presented leagues, matches were categorised into no (< 18.3°CWBGT), low(18.4°C–22.2°CWBGT), moderate (22.3°C–25.6°C WBGT), high (25.7°C–27.8°C WBGT) and extreme (> 27.9°C WBGT) risk of sustaining exertional heat illness (Roberts et al., 2023). For the analysis, T and WBGT were not categorised but instead treated as continuous variables.

For each individual league, linear regression models were used to investigate relationships between each PI and T or WBGT, respectively. To interpret the relationship, the estimate (Est)and 95% confidence interval (95% CI) and standardised estimate (β) and 95% confidence interval (β-95% CI) explained variance (marginal $R2$) and p-value (p) were determined. Significant associations between PI's and environmental temperatures are presented as per 1°C T or WBGT increase. Depending on β, effects can be categorised into small (0.10–0.29), medium (0.30–0.49) and large (> 0.50), whereas $R2$ can also be interpreted as small (0.02–0.08), medium (0.09–0.24) and large (> 0.25) (Cohen, 1988). Additionally, to determine effects present across the four leagues, all matches were also combined into one large multileague dataset, including the 17 PI's and environmental conditions for all 1585 matches. Due to potential differences in data sources and PI definitions and environmental conditions throughout the leagues, we performed mixed linear models and included the leagues as a random effect, resulting in the following models:

a. ***Model_0:*** *PI ~ 1* þ*(1|league)*
b. ***Model_T:*** *PI ~ T* þ*(1|league)*
c. ***Model_WBGT:*** *PI ~ WBGT* þ*(1|league)*

Statistical significance was defined at a level of 5% or less for the α-error ($p < 0.05$). As 17 different PI's were investigated, a Bonferroni correction was performed and the level of statistical significance adjusted to $p < 0.00294$. Analysis and visualisation were performed with R Studio 2023.12.1 using R version 4.3.2 (R Core Team, 2023) stats (R Core Team, 2023), lme4 (Bates et al., 2015), ggplot2 (Wickham, 2016) and jtools (Long, 2022) libraries. Results are first reported for each individual league and then for the combined data.

Results

Environmental conditions across all leagues ranged from –1.7°C to 37.1°C T and–2.0°C to 29.6°C WBGT, with the AL having the warmest average conditions (T: 21.0 ± 5.3°C and WBGT: 18.1 ± 4.3°C), followed by the Spanish LL (T: 18.8 ± 6.8°C and WBGT: 15.5 ± 5.6°C) and then the two German leagues (BL1: T: 11.2 ± 7.1°C and WBGT: 8.9 ± 6.1°C and BL2: T: 11.5 ± 7.3°C and WBGT: 9.8 ± 6.6°C). In the A-League, 1% of matches were held at extreme, 1% were held at high, 16% were held at moderate and 34% were held at a low heat risk. In Bundesliga 1 and 2, no matches were held at extreme or high risk, 1% and 3% were held at moderate and 8% and 11% were held at a low-heat risk. In La Liga, no matches were held at extreme, 1% were held at high, 11% were held at moderate and 22% were held at a low-heat risk. Overall, 8 out of the 17 investigated PI's were associated with T and WBGT across three categories: passing, dribbling and defending ($p < 0.002$). Shooting was the only category in which no significant association existed for all leagues ($p > 0.04$). All detailed results for each individual league and the combined dataset are summarised in Tables 7 – 10, and in the following sections, changes are presented as per 1°C T or WBGT increase.

A-League

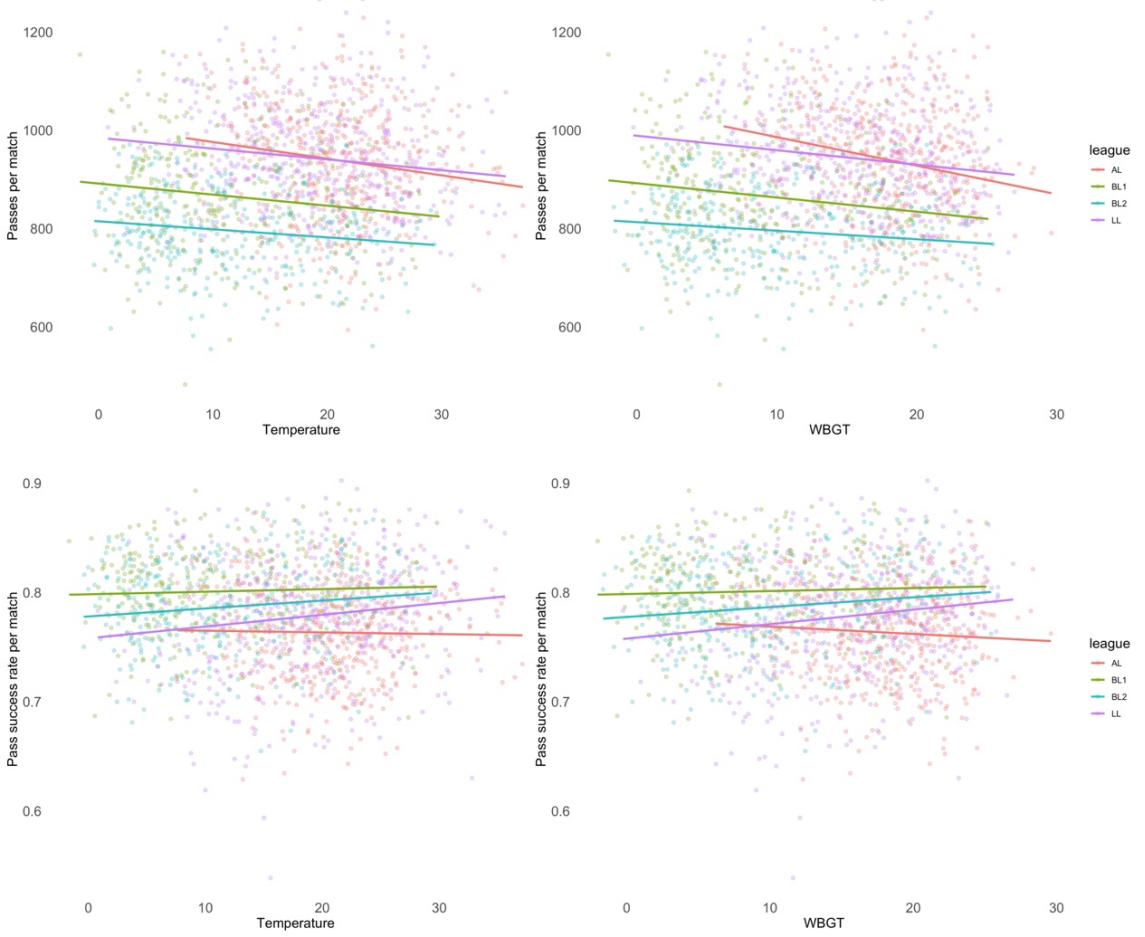
A small effect (β: 0.15 – 0.21) existed for lower passing volume in higher T (3.4 passes; 95% CI: –5.4 to –1.4 and $p = 0.002$) and WBGT (5.8 passes; 95% CI: –5.4 to–1.4 and $p = 0.002$). This reduction was present in short passes for both T (–3.3 passes; 95% CI: –5.4 to –1.2 and $p= 0.002$) and WBGT (–5.9 passes; 95% CI: –8.4 to–3.3 and $p < 0.001$) but not long passes for neither T (–0.21 passes; 95% CI: –0.53

–0.11 and $p = 0.19$)nor WBGT(–0.09 passes; 95% CI:–0.48 – 0.31and $p = 0.67$).There was a small effect for lower overall touches (β: 0.15 – 0.21) in higher T (–4.3 touches; 95% CI:–6.3 to–2.4 and $p < 0.001$) and WBGT (–6.9 touches; 95% CI:–9.3 to –4.5 and $p < 0.001$), though this association was not significant for touches in the offensive third for neither T (–0.54 touches; 95% CI:–1.39 to –0.31 and $p = 0.21$) nor WBGT (–1.33 touches; 95% CI:–2.38 to –0.28 and $p = 0.01$).The number of take-ons was also not associated with neither T (–0.17 take-ons; 95% CI:–0.32 to –0.01and $p = 0.03$) nor WBGT (–0.25 take- ons; 95% CI:–0.44 to–0.06 and $p = 0.01$), but the rate of successful take-ons was higher by 0.3% (95% CI: 0.2%–0.5% and $p < 0.001$) and 0.4% (95% CI: 0.2%–0.6% and $p < 0.001$) when T and WBGT were higher, resulting in a small effect (β: 0.16 – 0.18). The overall number of turnovers was lower by 1.3 turnovers (95% CI: –1.5 to –1.0 and $p < 0.001$) and 1.4 turnovers (95%CI: –1.8to –1.2 and $p < 0.001$) when T and WBGT were higher, resulting in a small effect (β: 0.14 – 0.15).

Bundesliga 1

There were fewer small effect There were fewer short passes when T (–2.0 passes; 95% CI: –3.0 to –1.0 and p = 0.001) or WBGT (–2.4 passes; 95% CI: –3.6 to –1.2 and p = 0.001) were higher, resulting in a small effect (β: 0.21 – 0.28). No association was evident for the number of long passes for T (+0.13 passes; 95% CI: –0.24 – 0.50 and p = 0.48) or WBGT (+0.15 passes; 95% CI: –0.29 – 0.58 and p= 0.49). There was a small effect (β: 0.17 – 0.18) for fewer passes into the final third of the opponent in higher T (–0.3 passes; 95% CI: –0.4 to –0.1 and p = 0.001) and WBGT (–0.3 passes; 95% CI: –0.5 to –0.1 and p = 0.002). The volume of touches was lower by 3.2 touches (95% CI: –5.1 to–1.4 and p = 0.001) per degree T was higher and 4.0 touches (95% CI: –6.1 to–1.8 and p= 0.001) per degree WBGT was higher, resulting in a small effect (β: 0.20 – 0.26). Touches in the final third were lower in higher T (–1.1 touches; 95% CI: –1.7 to –0.5 and p < 0.001) or higher WBGT (–1.3 touches; 95% CI: –2.0 to –0.6 and p < 0.001). The overall number of turnovers was lower by 1.1 turnovers (95% CI: –1.7 to –0.6 and p < 0.001) with each degree higher in T or 1.3 turnovers (95% CI: –2.0 to–0.7 and p < 0.001) with each degree higher in WBGT, resulting in a small effect (β: 0.22 – 0.23).

Figure 4: The relationship of passes and pass-success rate with temperature and wet-bulb globe temperature across all four leagues.

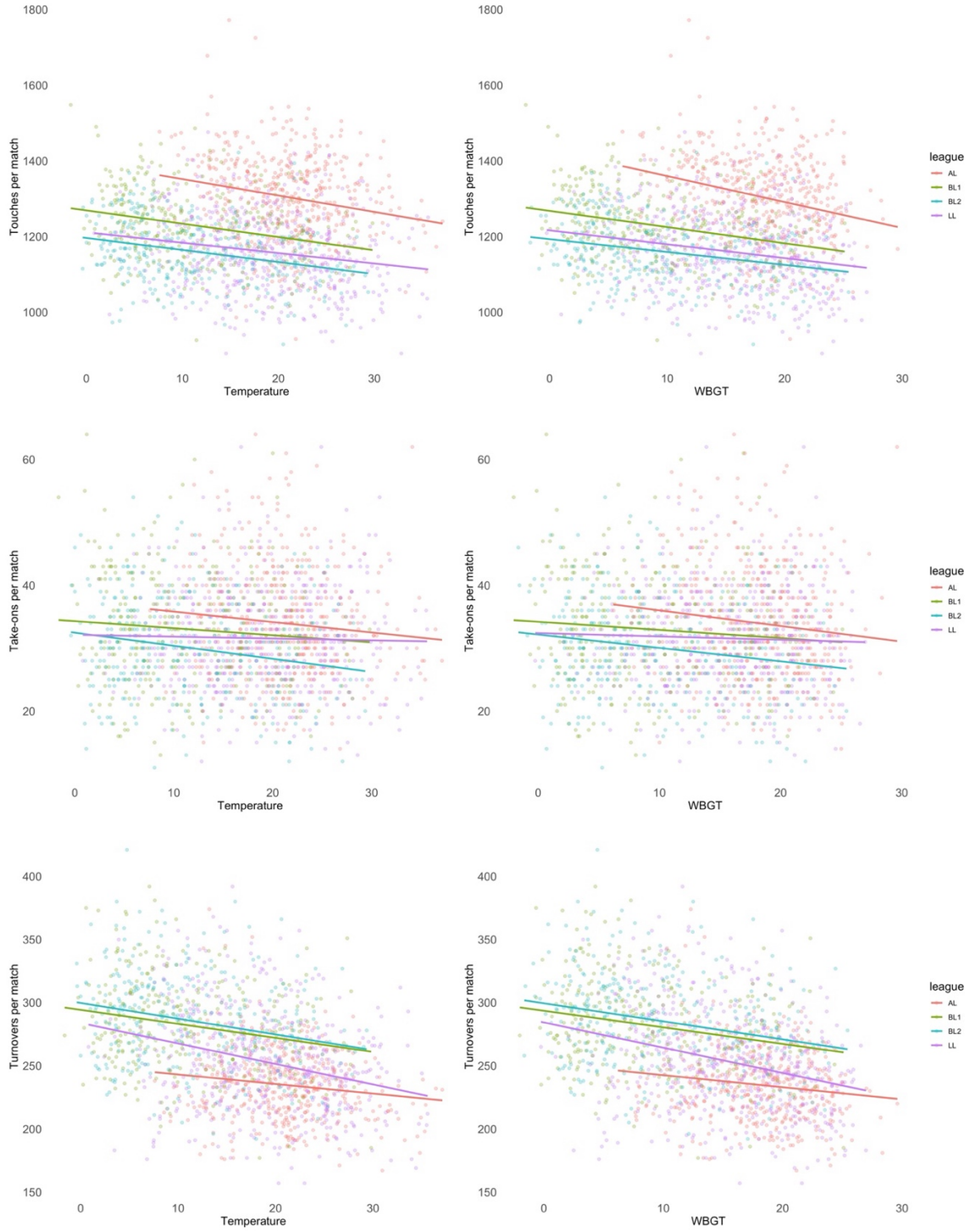


Bundesliga 2

There were fewer short passes associated with higher T (–1.8. passes; 95% CI: –2.5 to–1.1 and p < 0.001) and WBGT (–2.0 passes; 95% CI: –2.7 to–1.2 and p < 0.001), resulting in a small effect for both T and WBGT (β: 0.28), but no effects on long passes was observed for T (+0.34 passes; 95% CI: 0.03 – 0.65 and p = 0.03) or WBGT (+0.40 passes; 95% CI: 0.05 – 0.75 and p = 0.02). There were fewer touches associated with higher T (–3.2 touches; 95% CI: –4.02 to –1.46 and p < 0.001) and WBGT (–3.4 touches; 95% CI: –4.8 to –2.1 and p< 0.001), touches in the offensive third with higher T (–1.4 touches; 95% CI:–2.0 to–0.9; p < 0.001) and WBGT (–1.6 touches; 95% CI: – 2.2 to –1.0 and p < 0.001) as well as take ons with higher T (–0.2 take-ons; 95%CI:–0.3 to–0.1and p < 0.001) and WBGT (–0.2 take-ons; 95% CI: –0.4 to–0.1 and p= 0.001), resulting in small to moderate effects (β: 0.18–0.30). The overall number of turnovers was lower by 1.3 turnovers (95% CI: –1.8 to–0.7 and p < 0.001)

per degree T and 1.4 turnovers (95% CI: –2.1 to–0.9 and p < 0.001) per degree WBGT was higher, resulting in a small effect for both T and WBGT (β:0.26).

Figure 5: The relationship of touches, take-ons and turnovers with temperature and wet-bulb globe temperature across all four leagues.



LaLiga

The total number of passes was lower by 2.2 passes (95% CI: –3.5 to–0.9; p < 0.001) per degree T and 2.9 passes (95% CI: –4.5 to–1.4; p < 0.001) per degree WBGT was higher, resulting in a small effect (β: 0.14–0.16). This effect was not evident in short passes for T (–0.93 passes; 95% CI: –1.83 – 0.04 and p = 0.04) or WBGT (–1.24 passes; 95% CI: –2.31 to –0.16; p = 0.02) but was evident for long passes for both T (–0.5 passes; 95% CI: –0.8 to–0.3 and p < 0.001) and WBGT (–0.8 passes; 95% CI:–1.1 to –0.4 and p < 0.001). The pass-success rate was higher with higher T (0.1%; 95% CI: 0.0–0.2 and p < 0.001) and WBGT (0.1%; 95% CI: 0.0–0.2 and p= 0.001), resulting in a small effect (β: 0.14 – 0.15). There was a small effect (β: 0.18 – 0.20) for less overall touches with each degree higher in T (–2.7 touches; 95% CI: –4.0 to–1.5 and p < 0.001) and WBGT (–3.7 touches; 95%CI: –5.2 to–2.1 and p< 0.001). There ate of successful take-ons was lower with higher T (–0.4%; 95% CI: –0.5 – 0.2 and p < 0.001) and WBGT (–0.5%; 95% CI: –0.6 – 0.3 and p < 0.001). The number of turnovers was lower by 1.6 turnovers (95% CI: –2.1 to –1.1 and p< 0.001) per degree T and 2.0 turnovers (95% CI: –2.6 to–1.4; p < 0.001) per degree WBGT was higher, resulting in a small effect for both T and WBGT (β: 0.28).

Table 7: Association between Shooting PI's and Environmental Conditions.

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**
Goals									
AL	3.0 ± 1.8	0.03 (-0.00,0.06)	0.09 (-0.01,0.18)	0.01	0.07	0.04 (0.00,0.08)	0.1 (0.01,0.19)	0.01	0.03
BL1	3.1 ± 1.8	0.00 (-0.03,0.02)	-0.02 (-0.13,0.10)	0.00	0.77	0.00 (-0.03,0.03)	0.00 (-0.11,0.11)	0.00	1.0
BL2	2.9 ±1.5	0.00 (-0.03,0.02)	-0.03 (-0.15,0.08)	0.00	0.6	-0.01 (-0.03,0.02)	-0.03 (-0.14,0.08)	0.00	0.55
LL	2.5 ± 1.7	0.00 (-0.02,0.02)	0.00 (-0.09,0.09)	0.00	1.0	0.00 (-0.03,0.02)	-0.01 (-0.14,0.08)	0.00	0.8
Combi	2.8 ± 1.7	0.00 (-0.01,0.01)	0.007 (-0.05,0.07)	0.00	0.79	0.003 (-0.01,0.02)	0.01 (-0.05,0.07)	0.00	0.69
Shots									
AL	26.8 ± 6.9	0.12 (-0.00,0.24)	0.09 (0.00,0.18)	0.01	0.06	0.08 (-0.07,0.23)	0.05 (-0.04,0.14)	0.00	0.29
BL1	25.6 ± 5.8	-0.07 (-0.16,0.02)	-0.08 (-0.20,0.03)	0.00	0.15	-0.06 (-0.17,0.04)	-0.07 (-0.18,0.04)	0.00	0.23
BL2	27.6 ± 5.5	-0.06 (-0.14,0.03)	-0.08 (-0.19,0.04)	0.00	0.18	-0.06 (-0.15,0.04)	-0.07 (-0.18,0.05)	0.00	0.24
LL	23.5 ± 5.2	0.00 (-0.06,0.06)	0.003 (-0.08,0.09)	0.00	0.93	-0.02 (-0.10,0.06)	-0.-02 (-0.11,0.07)	0.00	0.64
Combi	29.0 ± 8.5	-0.007 (-0.05,0.04)	-0.01 (-0.07,0.05)	0.06	0.78	-0.02 (-0.08,0.03)	-0.03 (-0.09,0.03)	0.00	0.37

Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant after Bonferroni correction; AL = A-League; BL1 = Bundesliga 1; BL2 = Bundesliga 2; LL = La Liga; Combi = combined data set including data from all 4 leagues.

Combined League Effects

When combining all data, players performed 2.3 passes (95% CI: –3.1 to –1.5 and $p < 0.001$) less per degree T and 3.1 passes (95% CI: –4.0 to–2.1 and $p < 0.001$) less per degree WBGT was higher, resulting in small effects (β: 0.17–0.19). This was also evident in short passes, which were lower in higher T (–1.8 passes; 95% CI:–2.4 to–1.8 and $p < 0.001$) and WBGT (–2.5 passes; 95% CI:–3.2 to–1.7 and $p < 0.001$), but not in long passes for neither T (–0.12 passes; 95% CI:–0.28–0.03 and p= 0.13) nor WBGT (–0.14 passes; 95% CI:–0.32–0.05 and p= 0.15). The rate of successful passes was slightly higher when T (0.1%; 95% CI:0.0–0.1 and p= 0.002) or WBGT (0.1%; 95% CI: 0.0–0.1 and p= 0.001) was higher (Figure 4). The number of passes into the final third was lower in higher T (–0.2 passes; 95% CI:–0.3to–0.1 and p= 0.001) or WBGT (–0.2 passes; 95% CI:–0.3 to–0.1 and p= 0.002), but the number of key passes resulting in a shot or goal was not associated with T (0.00 passes; 95% CI: –0.03 – 0.04 and p= 0.83) or WBGT (–0.01 passes; 95% CI: –0.05 – 0.03 and p= 0.65). There were 3.3 (95% CI: –4.1 to –2.4 and $p < 0.001$) fewer touches per degree higher in T and 4.2 (95% CI: –5.2 to–3.3 and $p < 0.001$) fewer touches per degree higher in WBGT, resulting in small effects (β: 0.23–0.26). Touches in the offensive third were lower in higher T (–0.9 touches; 95% CI: –1.2 to–0.6 and $p < 0.001$) or WBGT (–1.2 touches; 95% CI: –1.6to–0.8 and $p< 0.001$) and the number of take-ons was lower when T (–0.1 take-ons; 95% CI:–0.2 to–0.1 and $p < 0.001$) or WBGT (–0.1 take-ons; 95% CI:–0.2 to–0.1 and $p < 0.001$) was higher (Figure 5). Finally, there were no associations found for the number of tackles (T: –0.03 tackles; 95% CI:–0.08 – 0.03 and p = 0.30 and WBGT:–0.03 tackles; 95% CI: –0.10 – 0.03 and p = 0.32), fouls (T:–0.02 fouls; 95% CI: –0.06–0.03 and p= 0.45 and WBGT: –0.00 fouls; 95%CI: –0.05–0.04 and p= 0.90) and cards (T: +0.01 cards; 95% CI:–0.01–0.03 and p= 0.33 and WBGT: + 0.02 cards; 95% CI: –0.00 – 0.04 and p= 0.08), but turnovers were lower for each degree T (–1.3 turnovers; 95% CI: –1.5 to –1.0 and $p < 0.001$) or WBGT (–1.5 turnovers; 95% CI: –1.8 to–1.2 and $p < 0.001$) was higher, resulting in small effects (β: 0.28 – 0.29).

Table 8: Association between Passing PI's and Environmental Conditions.

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**
Passes									
AL	938.8 ± 118.0	-3.38 (-5.42,-1.35)	-0.15 (-0.24,-0.06)	0.02	0.002*	-5.81 (-8.32,-3.31)	-0.21 (-0.30,-0.12)	0.04	<0.001*
BL1	867.7 ± 117.7	-2.35 (-4.13,-0.56)	-0.15 (-0.26,-0.04)	0.02	0.01	-3.00 (-5.05,-0.95)	-0.16 (-0.27,-0.05)	0.02	0.004
BL2	795.9 ± 81.8	-1.64 (-2.88,-0.39)	-0.15 (-0.26,-0.03)	0.02	0.01	-1.74 (-3.13,-0.35)	-0.14 (-0.25,-0.03)	0.02	0.01
LL	943.4 ± 104.2	-2.19 (-3.50,-0.89)	-0.14 (-0.23,-0.06)	0.02	<0.001*	-2.94 (-4.51,-1.36)	-0.16 (-0.24,-0.07)	0.02	<0.001*
Combi	898.8 ± 121.4	-2.27 (-3.05,1.46)	-0.17 (-0.22,-0.11)	0.02	<0.001*	-3.05 (-3.97,-2.11)	-0.19 (-0.25,-0.13)	0.02	<0.001*
Short passes									
AL	768.7 ± 120.3	-3.28 (-5.36,-1.20)	-0.14 (-0.24,-0.05)	0.02	0.002*	-5.88 (-8.44,-3.33)	-0.21 (-0.30,-0.12)	0.04	<0.001*
BL1	379.8 ± 67.1	-2.0 (-3.04,-0.96)	-0.21 (-0.32,-0.10)	0.04	<0.001*	-2.39 (-3.59,-1.19)	-0.22 (-0.33,-0.11)	0.04	<0.001*
BL2	340.9 ± 46.0	-1.79 (-2.47,-1.11)	-0.28 (-0.39,-0.18)	0.08	<0.001*	-1.99 (-2.74,-1.23)	-0.28 (-0.39,-0.17)	0.08	<0.001*
LL	377.4 ± 70.8	-0.93 (-1.83,-0.04)	-0.09 (-0.18,0.00)	0.01	0.04	-1.24 (-2.31,-0.16)	-0.10 (-0.18,-0.01)	0.01	0.02
Combi	482.7 ± 200.0	-1.81 (-2.43,-1.81)	-0.17 (-0.23,-0.11)	0.00	<0.001*	-2.47 (-3.20,-1.74)	-0.20 (-0.26,-0.14)	0.00	<0.001*
Long passes									
AL	120.7 ± 182.4	-0.21 (-0.53,0.11)	-0.06 (-0.15,0.03)	0.00	0.19	-0.09 (-0.48,0.31)	-0.02 (-0.11,0.07)	0.00	0.67
BL1	159.3 ± 23.4	0.13 (-0.24,0.50)	0.04 (-0.07,0.15)	0.00	0.48	0.15 (-0.29,0.58)	0.04 (-0.07,0.15)	0.00	0.49
BL2	166.8 ± 20.4	0.34 (0.03,0.65)	0.12 (0.01,0.23)	0.01	0.03	0.40 (0.05,0.75)	0.13 (0.02,0.24)	0.01	0.02
LL	159.1 ± 22.4	-0.54 (-0.82,-0.26)	-0.16 (-0.25,-0.08)	0.03	<0.001*	-0.77 (-1.11,-0.44)	-0.20 (-0.28,-0.11)	0.04	<0.001*
Combi	149.7 ± 28.1	-0.12 (-0.28,0.03)	-0.05 (-0.10,0.01)	0.00	0.13	-0.14 (-0.32,0.05)	-0.04 (-0.10,0.02)	0.00	0.15
Pass success rate									
AL	76.33 ± 4.16	-0.02 (-0.08,0.06)	-0.02 (-0.11,0.07)	0.00	0.67	-0.07 (-0.15,0.02)	-0.07 (-0.16,0.02)	0.00	0.14
BL1	81.75 ± 3.77	0.05 (-0.01,0.11)	0.09 (-0.02,0.2)	0.01	0.11	0.06 (-0.01,0.13)	0.1 (-0.02,0.21)	0.01	0.09
BL2	79.68 ± 3.95	0.06 (0.00,0.12)	0.12 (0.01,0.23)	0.01	0.04	0.08 (0.01,0.15)	0.13 (0.02,0.24)	0.01	0.02
LL	77.83 ± 5.15	0.11 (0.04,0.17)	0.14 (0.06,0.23	0.02	0.001*	0.13 (0.05,0.21)	0.15 (0.06,0.23)	0.02	0.001*
Combi	77.99 ± 4.62	0.06 (0.02,0.09)	0.10 (0.04,0.16)	0.01	0.001*	0.06 (0.02,0.10)	0.09 (0.03,0.15)	0.01	0.002*
Key passes									
AL	17.9 ± 5.4	0.08 (-0.02,0.17)	0.08 (-0.01,0.17)	0.00	0.10	0.05 (-0.07,0.16)	0.04 (-0.05,0.13)	0.00	0.41
BL1	18.9 ± 4.8	-0.02 (-0.10,0.05)	-0.04 (-0.15,0.08)	0.00	0.54	-0.02 (-0.10 - 0.07)	-0.02 (-0.14,0.09)	0.00	0.7
BL2	20.1 ± 4.5	0.01 (-0.06,0.08)	0.01 (-0.10,0.13)	0.00	0.80	0.01 (-0.07 - 0.08)	0.01 (-0.10,0.12)	0.00	0.86
LL	17.6 ± 4.6	-0.03 (-0.07,0.05)	-0.01 (-0.10,0.07)	0.00	0.35	-0.01 (-0.1 - 0.37)	-0.04 (-0.13,0.05)	0.00	0.74
Combi	18.4 ± 4.9	0.00 (-0.03,0.04)	0.01 (-0.05,0.06)	0.00	0.83	-0.01 (-0.05 - 0.03)	-0.01 (-0.07,0.04)	0.00	0.65

Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant after Bonferroni correction; AL = A-League; BL1 = Bundesliga 1; BL2 = Bundesliga 2; LL = La Liga; Combi = combined data set including data from all 4 leagues.

Table 8 (continued):

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**
Passes into final third									
BL1	54.9 ± 10.6	-0.27 (-0.44,-0.11)	-0.18 (-0.29,-0.07)	0.03	0.001*	-0.3 (-0.49,-0.11)	-0.17 (-0.29,-0.06)	0.03	0.002*
BL2	54.2 ± 10.7	-0.20 (-0.36,-0.03)	-0.13 (-0.25,-0.02)	0.01	0.02	-0.20 (-0.38,-0.02)	-0.12 (-0.23,-0.01)	0.01	0.03
LL	57.2 ± 12.6	-0.08 (-0.24,0.08)	-0.04 (-0.13,-0.04)	0.00	0.35	-0.08 (-0.27,0.12)	-0.03 (-0.12,0.05)	0.00	0.43
Combi	55.8 ± 11.6	-0.18 (-0.25,-0.05)	-0.11 (-0.17,-0.04)	0.01	0.001*	-0.17 (-0.28,-0.05)	-0.10 (-0.16,-0.03)	0.01	0.002*
Pass distance									
BL1	12.5 ± 1.6	-7.25 (-32.99,18.48)	-0.03 (-0.14,0.08)	0.00	0.58	-10.63 (-40.35,19.10)	-0.04 (-0.15,0.07)	0.00	0.48
BL2	12.7 ± 1.5	10.3 (-12.97,33.56)	0.05 (-0.06,0.16)	0.00	0.38	14.89 (-11.03,40.81)	0.06 (-0.05,0.18)	0.00	0.26
LL	13.3 ± 1.8	-9.6 (-32.97,13.77)	-0.04 (-0.12,0.05)	0.00	0.42	-17.58 (-45.8,10.65)	-0.05 (-0.14,0.03)	0.00	0.22
Combi	12.1 ± 1.6	-1.96 (-15.09,11.25)	-0.01 (-0.08,0.06)	0.00	0.77	-3.90 (-19.24,11.44)	-0.02 (-0.08,0.05)	0.00	0.62

Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant after Bonferroni correction; AL = A-League; BL1 = Bundesliga 1; BL2 = Bundesliga 2; LL = La Liga; Combi = combined data set including data from all 4 leagues.

Table 9: Association between Dribbling PI's and Environmental Conditions.

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**
Touches									
AL	1304.0 ± 113.5	-4.34 (-6.28,-2.39)	-0.2 (-0.29,-0.11)	0.04	<0.001*	-6.87 (-9.25,-4.49)	-0.26 (-0.35,-0.17)	0.06	<0.001*
BL1	1276.5 ± 118.7	-3.21 (-5.06,-1.36)	-0.19 (-0.30,-0.08)	0.03	<0.001*	-3.95 (-6.08,-1.82)	-0.20 (-0.32,-0.09)	0.04	<0.001*
BL2	1243.8 ± 149.7	-3.18 (-4.39,-1.98)	-0.29 (-0.39,-0.18)	0.08	<0.001*	-3.4 (-4.76,-2.06)	-0.27 (-0.38,-0.17)	0.17	<0.001*
LL	1148.4 ± 102.5	-2.74 (-4.02,-1.46)	-0.18 (-0.27,-0.1)	0.03	<0.001*	-3.65 (-5.18,- 2.11)	-0.2 (-0.29,-0.12)	0.04	<0.001*
Combi	1212.8 ± 126.2	-3.25 (-4.05,-2.44)	-0.23 (-0.29,-0.17)	0.04	<0.001*	-4.22 (-5.15,-3.27)	-0.26 (-0.32,-0.20)	0.04	<0.001*
Touches offensive									
AL	271 ± 48.7	-0.54 (-1.39,-0.31)	-0.06 (-0.15,0.03)	0.00	0.21	-1.33 (-2.38,-0.28)	-0.12 (-0.21,-0.02)	0.01	0.01
BL1	263.4 ± 38.8	-1.13 (-1.73,-0.52)	-0.21 (-0.32,-0.10)	0.04	<0.001*	-1.33 (-2.03,-0.64)	-0.21 (-0.32,-0.10)	0.04	<0.001*
BL2	266.2 ± 35.4	-1.44 (-1.95,-0.92)	-0.3 (-0.41,-0.19)	0.09	<0.001*	-1.61 (-2.18,-1.03)	-0.30 (-0.41,-0.19)	0.09	<0.001*
LL	277.9 ± 46.2	-0.68 (-1.26,-0.10)	-0.1 (-0.19,-0.01)	0.01	0.02	-0.84 (-1.54,-0.14)	-0.10 (-0.19,-0.02)	0.01	0.02
Combi	270.9 ± 44.0	-0.9 (-1.21,-0.56)	-0.16 (-0.22,-0.10)	0.02	<0.001*	-1.20 (-1.57,-0.80)	-0.18 (-0.24,-0.13)	0.03	<0.001*

Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant after Bonferroni correction; AL = A-League; BL1 = Bundesliga 1; BL2 = Bundesliga 2; LL = La Liga; Combi = combined data set including data from all 4 leagues.

Table 9 (continued):

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**
Take-ons									
AL	34.0 ± 8.7	-0.17 (-0.32,-0.01)	-0.1 (-0.19,-0.01)	0.01	0.03	-0.25 (-0.44,-0.06)	-0.12 (-0.21,-0.03)	0.01	0.01
BL1	32.9 ± 8.6	-0.1 (-0.25,0.04)	-0.08 (-0.19,0.03)	0.00	0.15	-0.12 (-0.29,0.04)	-0.08 (-0.19,0.03)	0.00	0.15
BL2	34.2 ± 8.4	-0.22 (-0.34,-0.10)	-0.2 (-0.31,-0.09)	0.04	<0.001*	-0.22 (-0.36,-0.09)	-0.18 (-0.30,-0.07)	0.03	0.001*
LL	31.6 ± 7.9	-0.03 (-0.13,0.07)	-0.03 (-0.11,0.06)	0.00	0.57	-0.05 (-0.17,0.07)	-0.04 (-0.12,0.05)	0.00	0.38
Combi	32.3 ± 8.4	-0.11 (-0.17,-0.05)	-0.10 (-0.16,-0.05)	0.01	<0.001*	-0.14 (-0.21,-0.06)	-0.11 (-0.17,-0.05)	0.01	<0.001*
Take-on rate									
AL	52.76 ± 9.64	0.33 (0.16,0.49)	0.18 (0.09,0.27)	0.03	<0.001*	0.37 (0.16,0.58)	0.16 (0.07,0.25)	0.02	<0.001*
BL1	54.35 ± 9.96	0.06 (-0.10,0.22)	0.04 (-0.07,0.16)	0.00	0.44	0.07 (-0.11,0.26)	0.05 (-0.07,0.16)	0.00	0.43
BL2	52.10 ± 9.79	0.01 (-0.14,0.16)	0.007 (-0.11,0.12)	0.00	0.90	0.04 (-0.13,0.21)	0.03 (-0.09,0.14)	0.00	0.63
LL	52.61 ± 12.65	-0.35 (-0.51,-0.20)	-0.19 (-0.28,-0.11)	0.03	<0.001*	-0.46 (-0.65,-0.27)	-0.2 (-0.29,0.12)	0.04	<0.001*
Combi	52.86 ± 10.90	-0.05 (-0.12,0.02)	-0.04 (-0.09,0.02)	0.00	0.18	-0.06 (-0.15,0.02)	-0.04 (-0.10,0.01)	0.00	0.14

Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant after Bonferroni correction; AL = A-League; BL1 = Bundesliga 1; BL2 = Bundesliga 2; LL = La Liga; Combi = combined data set including data from all 4 leagues.

Table 10: Association between Defending PI's and Environmental Conditions.

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**
Tackles									
AL	35.1 ± 8.0	-0.1 (-0.24,0.04)	-0.06 (-0.16,0.03)	0.00	0.17	-0.08 (-0.26,0.09)	-0.05 (-0.14,0.05)	0.00	0.34
BL1	32.2 ± 7.7	-0.06 (-0.18,0.06)	-0.06 (-0.17,0.06)	0.00	0.33	-0.07 (-0.21,0.07)	-0.06 (-0.17,0.05)	0.00	0.31
BL2	30.1 ± 6.8	-0.04 (-0.16,0.04)	-0.07 (-0.18,0.05)	0.00	0.42	-0.05 (-0.19,0.04)	-0.07 (-0.18,0.04)	0.00	0.36
LL	31.4 ± 7.3	0.02 (-0.07,0.12)	0.02 (-0.06,0.11)	0.00	0.60	0.02 (-0.09,0.13)	0.02 (-0.07,0.10)	0.00	0.69
Combi	32.2 ± 7.7	-0.03 (-0.08,0.03)	-0.03 (-0.09,0.03)	0.00	0.30	-0.03 (-0.10,0.03)	-0.03 (-0.09,0.03)	0.00	0.32
Fouls									
AL	27.6 ± 6.3	-0.15 (-0.26,-0.04)	-0.13 (-0.22,-0.04)	0.01	0.01	-0.11 (-0.25,0.02)	-0.08 (-0.17,0.01)	0.00	0.1
BL1	22.7 ± 5.4	0.04 (-0.05,0.12)	0.05 (-0.07,0.16)	0.00	0.41	0.04 (-0.06 -0.14)	0.05 (-0.07,0.16)	0.00	0.42
BL2	22.1 ± 5.2	0.03 (-0.05,0.11)	0.04 (-0.07,0.15)	0.00	0.48	0.02 (-0.07,0.11)	0.03 (-0.08,0.14)	0.00	0.62
LL	26.5 ± 5.7	-0.02 (-0.09,0.06)	-0.02 (-0.11,0.07)	0.00	0.66	-0.01 (-0.09,0.08)	0.01 (-0.09,0.08)	0.00	0.86
Combi	25.2 ± 6.1	-0.02 (-0.06,0.03)	-0.02 (-0.08,0.04)	0.00	0.45	-0.00 (-0.05,0.04)	-0.00 (-0.06,0.06)	0.00	0.9

Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant after Bonferroni correction; AL = A-League; BL1 = Bundesliga 1; BL2 = Bundesliga 2; LL = La Liga; Combi = combined data set including data from all 4 leagues.

Table 10 (continued):

		Temperature				Wet-bulb globe temperature			
	Mean ± SD	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**	**Estimate (95%CI)**	**β (95%CI)**	**R^2 marg.**	**p-value**
Cards									
AL	4.1 ± 1.9	0.00 (-0.04,0.03)	0.01 (-0.10,0.09)	0.00	0.88	0.02 (-0.02,0.06)	0.04 (-0.05,0.14)	0.00	0.35
BL1	3.5 ± 1.9	0.02 (-0.01,0.05)	0.06 (-0.05,0.18)	0.00	0.27	0.02 (-0.01,0.05)	0.07 (-0.05,0.18)	0.00	0.25
BL2	4.1 ± 2.0	0.02 (-0.01,0.05)	0.06 (-0.06,0.17)	0.00	0.32	0.02 (-0.02,0.05)	0.06 (-0.05,0.17)	0.00	0.29
LL	5.6 ± 2.8	0.01 (-0.03,0.04)	0.02 (-0.07,0.10)	0.00	0.71	0.02 (-0.02,0.06)	0.04 (-0.05,0.12)	0.00	0.84
Combi	4.5 ± 2.4	0.01 (-0.01,0.03)	0.03 (-0.03,0.09)	0.00	0.33	0.02 (-0.00,0.04)	0.05 (-0.01,0.11)	0.00	0.08
Turnovers									
AL	234.8 ± 27.8	-0.76 (-1.24,-0.28)	-0.14 (-0.24,-0.05)	0.02	0.002*	-0.96 (-1.56,-0.36)	-0.15 (-0.24,-0.06)	0.02	0.002*
BL1	281.8 ± 35.6	-1.11 (-1.66,-0.56)	-0.22 (-0.33,-0.11)	0.05	<0.001*	-1.31 (-1.95,-0.68)	-0.23 (-0.34,-0.12)	0.05	<0.001*
BL2	285.4 ± 36.8	-1.25 (-1.83,-0.74)	-0.26 (-0.36,-0.15)	0.06	<0.001*	-1.43 (-2.08,-0.86)	-0.26 (-0.37,-0.15)	0.06	<0.001*
LL	253.4 ± 39.8	-1.62 (-2.11,-1.14)	-0.28 (-0.36,-0.20)	0.08	<0.001*	-2.00 (-2.58,-1.41)	-0.28 (-0.37,-0.20)	0.08	<0.001*
Combi	259.7 ± 40.7	-1.27 (-1.53,-1.02)	-0.28 (-0.34,-0.22)	0.06	<0.001*	-1.53 (-1.84,-1.23)	-0.29 (-0.35,-0.23)	0.07	<0.001*

Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant after Bonferroni correction; AL = A-League; BL1 = Bundesliga 1; BL2 = Bundesliga 2; LL = La Liga; Combi = combined data set including data from all 4 leagues.

Discussion

This study investigated the relationship of environmental conditions (T and WBGT) on match play PI's in four professional football leagues. Although definitions of PI's were sometimes different across the leagues (Table 6), overall trends were evident. In general, shooting PI's were not associated with changes in either T or WBGT but passing, dribbling and defending PI's were. A significantly lower number of passes, particularly short passes, and a slightly higher pass rate were associated with higher T and WBGT. Noteworthy was also a lower number of passes into the offensive final third of the pitch, although key passes - leading to a shot or goal - were not associated with T or WBGT. Further, the number of touches (touches in the final third), take-ons and turnovers were also lower in higher T and WBGT. Therefore, the hypothesis is partially accepted: some PI-volumes were significantly reduced (passes, short passes, passes into the final third, touches, touches in the final third, take-ons and turnovers), while others were not (goals, shots, long passes, key passes, tackles and fouls cards) and performance quality metrics were maintained (take-on success rate and pass distance) or increased (pass-success rate). Generally, T and WBGT only described a small amount of PI variance, and the standardised estimates show only small effects.

The number of shots is an important PI associated with success in football matches (Lepschy et al., 2020; Rampinini et al., 2009). In this investigation, the number of shots and goals were not associated with either T or WBGT, which is in line with previous research (Chmura et al., 2021). Hence, although other football actions (running, passing and ball involvements) were reduced in hotter conditions, this may enable players to manage fatigue and maintain the ability to create goal-scoring opportunities (Mohr et al., 2012; Nassis et al., 2015).

Passing has been found to be increased in matches won (Broich et al., 2014; Chmura et al., 2021), in more successful teams (Liu et al., 2015), and to be associated with scoring more goals (Bostanci et al., 2018). Our study found that the number of passes was lower in hotter T or WBGT in the AL and LL but not in BL1 and BL2. Estimates and effect sizes in BL1 and BL2 were similar, but relationships were nonsignificant after post hoc corrections. When combining the data from all four leagues, this resulted in a small effect, comparable to other research (Konefał et al., 2021). Pass-success rates were not significantly associated with either T or WBGT in the AL, BL1 and BL2 individually but were higher in warmer conditions in the LL and when combining all match data, which were also found in previous research (Mohr et al., 2012; Nassis et al., 2015; Zhou et al., 2019). Increased pass rates may result from lower opponent pressure, possibly due to lower running distances covered at high intensities in hotter conditions, which were reduced by 4%–6% when WBGT increased by 10°C (Schwarz et al., 2024). Novel findings of this study include the reduction of short passes (evident in AL, BL1, BL2 and combined) rather than long passes (evident in LL) and the observation of a lower number of passes into the final third in higher T or WBGT. This is especially important, as a higher number of short passes has been associated to with more successful football teams (Rampinini et al., 2009) and passes into the opponent's final third have been found to be most effective in creating goal scoring opportunities (Rein et al., 2017). However, the number of key passes, leading to a shot or goal is not associated with changes in either T or WBGT. The overall findings on reduced passing volumes may depict a more static and slower match play, which is possibly a reaction to the assumed increased heat strain and confirms the findings of

the only experimental study, which came to a similar conclusion, comparing a match in hot versus neutral temperatures (Mohr et al., 2012). Similar to a reduced physical performance in the heat (Draper et al., 2022; Schwarz et al., 2024), this might be part of a pacing strategy, where players reduce the overall amount of passing activity, whilst maintaining key passes, pass quality and the overall distance passes cover. Whether this occurs subconsciously, because of elevated fatigue in the heat (Nybo et al., 2014) or consciously in the form of prospectively applied match tactical strategies (Mohr et al., 2012) remains in question.

It has been shown that ball contacts are an important parameter for winning football matches (Broich et al., 2014) and more successful teams have more ball touches and attempt more dribbling take-ons (Liu et al., 2015; Rampinini et al., 2009). This study showed a lower number of touches in each of the observed leagues when T or WBGT was higher. Importantly, this reduction was also evident in the offensive third in BL1, BL2 and when combining all match data. Also, the number of dribbling take-ons was reduced in BL2 and when combining all match data. This has not been previously investigated but is in line with the observed reductions in passing PI's and further describes a lower amount of technical activity and match actions performed in hotter conditions, again possibly due to the pacing of game involvements.

Defensive qualities are an equally important factor in football performance. For example, a higher number of tackles was found to be performed by more successful teams in the Italian Serie A (Rampinini et al., 2009). Our study observed no associations between environmental conditions and the number of tackles, fouls and cards. Although speculative, the maintenance of these events may result from adjustments of other gameplay aspects in the heat, observed in this study, as these PI's might be critical in preventing goal scoring opportunities. Nevertheless, the number of turnovers was lower in warmer conditions in each of the observed leagues, which is in line with previous studies suggesting a lower opponent pressure in matches held under hot environmental conditions (Mohr et al., 2012; Nassis et al., 2015). The data of this study suggest further that this reduction in turnovers could also be linked to the lower number of attempted passes, touches and take-ons.

Exercising in hot conditions is a concern for sporting and football organisations, which have been introducing various heat policies and guidelines, including different thresholds and indexes for their recommendations (Gouttebarge et al., 2023; Nassis et al., 2024). In this investigation, there was no difference in whether T or WBGT was used as the independent variable in the models but WBGT was estimated. A measurement of WBGT, including actual air flow and mean radiant temperature at the athletes' field of play may be necessary, albeit unlikely in research with large datasets (Racinais et al., 2023). Nevertheless, when considering the implementation of heat guidelines and policies, the use of T should not be neglected. Especially in lower competition levels, using WBGT is not feasible due to its high financial and organisational demand, which might present a barrier to implementing guidelines. Although the observed effects in this study remained small, football federations should be aware of the possible detrimental effects on football match play, which was found whilst the data contained only a small number of matches in hot environmental conditions. With an expected increase in exposure to hotter conditions in the future, these effects may become more pronounced. Therefore, environmental conditions and their associations with performance and health aspects of football players should be monitored further and federations could consider the preventive implementation of heat mitigating policies to maintain a low exposure to heat stress and consequently the quality of play (Gouttebarge et al., 2023).

Although the outcomes of this study are important to fill an existing gap in knowledge, there remain some limitations that could be addressed in future investigations. By including the leagues as random effects in the mixed models, we tried to ac- count for differences in data sources for match characteristics and environmental conditions and aimed to detect universal effects across different geographical settings and football competitions. A more standardised line of data collection would be preferable, though the advantages of combining multiple leagues and increasing the external validity of the investigation might outweigh the limitations of a less standardised data collection. Additionally, measuring environmental conditions directly at the match venues would improve the accuracy of the heat stress observed by players (Chalmers et al., 2020;

Racinais et al., 2023), but the chosen retrospective approach is appropriate for investigating performance markers and enables the inclusion of a large sample of matches. Furthermore, the presented data were analysed at a level per match, disregarding the influence of each team or even individual players. Future research could aim at including individual teams and try to link observed effects to match outcomes. Further, including physical performance data alongside match-play characteristics would describe the effect of hot conditions more holistically. Future studies should also aim to investigate these associations in a female cohort. Finally, although our data represented a wide range of environmental conditions, it can be argued that the number of observations in hot conditions is low, with only 3 matches at extreme, 10 matches at high, 142 matches at moderate and 331 matches at a low heat risk, whereas there were 1099 matches at no heat risk (Roberts et al., 2023). This might be a reason for effect sizes remaining small, as hotter conditions could potentially increase the observed effects (Schmit et al., 2015). More matches in such environments would be needed to better understand the effects of very hot conditions.

Conclusion

In conclusion, across four different football leagues, a higher T or WBGT led to alterations in match play. Mainly, small effects on lower amounts of (short) passes, touches and take-ons were observed, depicting a more static and slower match play. Critically, this involves passes into and touches in the final third. Football teams should be aware of these associations, possibly alter match tactical approaches or consider applying heat-mitigating strategies. Methods, such as adequate hydration, cooling before and during the half-time of matches or performing shorter warm-ups, have been suggested; however, their effectiveness in the field is yet to be proven (Gouttebarge et al., 2023; Nassis et al., 2024). This is also true for recent investigations of in-play cooling breaks, which have been introduced by football organisations (Brown et al., 2024; Chalmers et al., 2019). As these associations were found in a dataset containing a relatively low number of matches in hot conditions, football federations could consider this information for implementing and updating existing heat policies to prevent exposure to hotter matches, which may exaggerate the observed effects.

Study 3: Football Match Injuries in the Heat

S3.1 Introduction and Literature Summary

Injuries, due to their implications for player health and careers, are a big concern in football (Ekstrand et al., 2011). Additionally they are associated with high financial costs and have a negative impact on team performance (Hägglund et al., 2013; Lu et al., 2021). Although it remains a challenge to predict injury, there are various external and internal factors associated with injury risk (Dvorak et al., 2000). Environmental conditions have been proposed as one such external risk factor, and different underlying factors have been discussed (Chang et al., 2017; Distefano et al., 2013; Dvorak et al., 2000; Schmit et al., 2017).

It is hypothesised that the higher levels of fatigue associated with exercising in hot conditions may increase injury risk by impairing lower limb biomechanics (Brazen et al., 2010; Tsai et al., 2009). Further, the effects of heat stress and hyperthermia itself are associated with altered cognitive function (Schmit et al., 2017). Heat stress can result in riskier behaviour (Chang et al., 2017; Syndicus et al., 2018) and impair balance and landing abilities (Distefano et al., 2013; Mtibaa et al., 2018). Indeed, in various occupational settings (Fogleman et al., 2005; Martínez-Solanas et al., 2018; Spector et al., 2019) and the general public (Otte im Kampe et al., 2016) it has been found that injuries were increased in higher temperatures.

However, in epidemiological observations of athletic setting this has not been confirmed. For example in Rugby, no clear relationship of temperature and injury occurrence was found (Gabbett et al., 2007; Lee & Garraway, 2000), and in track athletes injury occurrence was even lower in higher temperatures (Edouard et al., 2025). Studies in football have mainly focussed on differences between geographical settings and some have found higher injury rates in teams located in warmer regions (Orchard & Seward, 2002), while others found the opposite (Jacobson & Tegner, 2006; Waldén et al., 2013). However, as these observations were not focused on investigating the influence of heat stress and do not include any match-day weather conditions, the influence of temperature on the injury rates can only be speculated.

The influence of other regional differences such as different playing styles, different training and competition habits, different medical support systems or a combination of factors is likely to big to allow conclusions on the influence of heat stress.

A potential relationship between heat stress and injury risk in football, could be mediated by other factors. For instance higher muscle temperatures and thus better contractile functions are associated with hotter temperatures and it has been shown that markers of muscle damage were reduced after competing in hotter conditions (Nybo et al., 2013). This could also be linked to the reduced physical performance and lower intensity of play when competing in the heat (Gabbett et al., 2007). The reduced running performance (Schwarz et al., 2024), as well as the proposed reduced opponent pressure (Mohr et al., 2012) could mitigate effects of heat stress on injury rates by simply lowering exposure to risky situations (i.e., high-speed activities and tackles). Furthermore, other factors, such as the stage of the season and the ground conditions could also influence associations of heat and injury occurrence. For example, softer pitches are associated with less injuries and also with hot and humid conditions (Gabbett et al., 2007). However, it remains elusive what happens to this association in severe heat stress (see Table 11), as previous studies rarely contain hot observations. In Lee & Garraway (2000) the “hottest” category was still below 22.2 °C and in Gabbett et al. (2007), the hottest match was held in 29.6 °C.

A better understanding of whether heat stress affects injury rates in football is crucial for player safety, especially as global temperatures continue to rise, and more frequent and extreme exposures to heat become likely (Gouttebarge et al., 2023). Hence, Study 3 aimed to conduct a large-scale, multi-league study, analysing 2612 matches using continuous T and WBGT data in two professional football leagues. This approach describes initial evidence about the associations between heat and injury occurrence in football.

Table 11: Literature review of studies investigating associations between injury occurrence and environmental temperatures in rugby and football.

Study	Sample	Environmental Parameters	Physical Performance Parameters	Effects of Hotter Conditions
Lee & Garraway, 2000	605 matches; Scottish Borders District Rugby League; all teams; male players	4 T categories: -15 - 4.9 °C 5.0 - 7.1 °C 7.2 - 11°C 11.1 - 22.2 °C + weather and ground conditions	overall injuries	• effects of T and weather possible but unclear
Gabbett et al., 2007	137 matches; Australian semi-professional Rugby League; all teams; male players	T, RH continuous scales + yearly rainfall and ground conditions	overall injuries; injury location; injury mechanism; injury type; injury severity	• heat associated with fewer injuries, but not after adjusting for ground conditions • softer ground reduced injuries, high T and RH associated with softer ground
Study 3	2612 matches; German Bundesliga1, Australian A-League; all teams; male players	T & WBGT as continuous scales	overall injuries; injury location; injury mechanism; injury type;	• no relationship in Bundesliga • small increase in injuries in higher WBGT in A-League

Abbreviations: *T = Temperature; °C = degree Celsius; RH = Relative humidity; % = percentage (RH); WBGT = Wet-bulb globe temperature.*

S3.2 Associations between Injury Occurrence and Environmental Conditions in the German and Australian Professional Football Leagues

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Abstract

A cross-sectional analysis was performed to investigate associations between environmental temperatures and injury occurrence in two professional male football (soccer) leagues. Data from seven seasons of the German Bundesliga (2142 matches) and four seasons of the Australian A-League (470 matches) were included. Injuries were collated via media reports for the Bundesliga and via team staff reports in the A-League and comprised injury incidence, mechanisms (contact, noncontact), locations (e.g., ankle, knee, and thigh), and types (e.g., muscle and tendon, joint and ligament). Weather data included ambient air temperature (temperature or T) and wet-bulb globe temperature (WBGT), which were collected from online sources retrospectively. Generalized linear mixed models were analyzed to examine associations between temperature or WBGT and injury occurrence for each league, respectively. Additionally, matches were grouped into categories of 5°C temperature steps to compare for injury occurrence. Results showed no relationship existed between either temperature or WBGT and any injury occurrence, mechanisms, locations or types for the Bundesliga ($P > 0.10$). A trend for an increase in injury occurrence in higher WBGT existed in the A-League ($P = 0.05$). Comparisons between 5°C temperature categories showed no significant differences for injury occurrence for either temperature or WBGT in either League ($P > 0.05$). Within the observed temperature ranges (–11.2 to 37.1°C T; –12.2 to 29.6°C WBGT) environmental temperature had no relationship with the rate or type of injury occurrence in professional football. Nevertheless, the number of matches at extreme heat within this

study was limited and other factors (e.g., playing intensity, season stage, ground conditions) likely co-influence the relationship with injuries.

Introduction

Injuries in football (soccer) are common and remain the biggest concern for player health and performance, as well as for team performance (Hägglund et al., 2013; Lu et al., 2021). The risk of injury is generally higher in football compared to other workforces and occupational health and safety strategies need to focus on reducing this risk and explore associated factors (Drawer & Fuller, 2002). The risk of injury is generally influenced by both intrinsic (e.g., joint flexibility, previous injury, muscular fatigue) and extrinsic (e.g., environmental conditions, pitch surface, playing schedule, fouls) risk factors (Dvorak et al., 2000). Although environmental conditions have been proposed as an external risk factor for injury (Dvorak et al., 2000), the relationship between injury occurrence and environmental temperature lacks epidemiological insight in football. Nevertheless, initial concerns have led to the Fédération Internationale de Football Association (FIFA) and other professional leagues to introduce heat policies (Brown et al., 2024).

Recently, there are growing concerns around playing football in hot environmental conditions (Gouttebarge et al., 2023; Nassis et al., 2024). Exercising in hotter temperatures leads to an earlier onset and higher levels of fatigue (Nybo et al., 2014), which in football typically translates to a reduction in running performance (Draper et al., 2022). Alongside physical performance changes, there are expected impairments to cognitive function (Schmit et al., 2017) and technical match play when football is played in the heat (Chmura et al., 2021; Zhou et al., 2019). The earlier onset of fatigue and reduced physical and cognitive performance in higher temperatures are hypothesized to lead to an increased susceptibility to injury (Distefano et al., 2013; Schmit et al., 2017; Spector et al., 2019). In the general public as well as in different occupational fields, this has resulted in an increased number of acute and unintentional injuries in hotter environmental temperatures, although the potential mechanisms of this relationship are still under investigation (Martínez-Solanas et al., 2018; Otte im Kampe et al., 2016; Spector et al., 2019). It was hypothesized that a

number of factors associated with hotter conditions, such as changes in cognitive performance, impaired balance, more risky behaviour, increased muscle fatigue, dehydration, and poorer sleep quality, could influence the increased injury occurrence (Fogleman et al., 2005; Spector et al., 2019). In laboratory studies, hyperthermia-induced fatigue decreased attention and increased errors in complex tasks (Gaoua, Grantham, et al., 2011), potentially leading to errors in planning and performing movement strategies, such as, tackles or landings in football. Furthermore, there is an impaired coordination, especially proprioception (Ingersoll et al., 1992), dynamic and static postural stability, and balance (Distefano et al., 2013; Mtibaa et al., 2018). For example, a combination of hypohydration and hyperthermia has been shown to lead to more landing and balance errors and higher center-of-pressure and elliptical sways during a dynamic balance test (Distefano et al., 2013). Finally, there is also a tendency to take more risky decisions in hotter temperatures (Syndicus et al., 2018). Despite the hypothesized nature of these mechanisms insights from larger epidemiological investigations on this relationship of environmental temperature with injury in football remain scarce. While football federations and teams are concerned about the effect of environmental conditions on match technical and physical performance(Draper et al., 2022; Zhou et al., 2019), there should also be a concern about the injury risk in such conditions (Gouttebarge et al., 2023).

The few existing epidemiological studies investigating the relationship between environmental conditions and injuries in football have shown different injury rates in teams located in warmer compared to those in colder regions (Jacobson & Tegner, 2006; Orchard & Seward, 2002; Waldén et al., 2013). A study in Swedish women's football found a higher prevalence of injuries in colder regions (Jacobson & Tegner, 2006). In European professional men's football, a similar overall trend was observed, though anterior cruciate ligament injuries were more frequent in warmer regions (Waldén et al., 2013). In contrast, overall injuries were higher in teams based in hotter environments in Australian Rules football (Orchard & Seward, 2002). As these varying results are based on a dichotomous regional categorization, and no actual weather data was recorded, the differences observed could be resulting from different competition structures, differences in training and nutritional habits, different playing

styles and levels, different medical support systems, as well as the different climates, or a combination of factors (Jacobson & Tegner, 2006; Orchard & Seward, 2002; Waldén et al., 2013). Due to this methodology, previous studies rarely describe the relationship between environmental temperature and injury rates and further investigation as an extrinsic injury risk factor is required. Although in the general public, injury occurrence seems to increase with higher environmental temperatures (Martínez-Solanas et al., 2018; Otte im Kampe et al., 2016; Spector et al., 2019), this association was reversed in track and field athletes, especially regarding muscle injuries in sprint disciplines (Edouard et al., 2025). In team sports, only two studies in rugby have reported match and training temperatures alongside injury occurrence (Gabbett et al., 2007; Lee & Garraway, 2000). Both reported no significant relationships between injuries and the recorded weather conditions, which ranged from ambient air temperature (temperature or "T") and relative humidity to wind chill temperature. None of these studies has investigated wet-bulb globe temperature (WBGT) a "feels-like temperature" combining the influence of temperature and relative humidity but also solar radiation and wind speed, that is often used in sport federations heat policies.28 These previous studies in Rugby suggested playing style and match intensity, as well as ground conditions, as potential extrinsic risk factors of greater importance than the environmental conditions (Gabbett et al., 2007; Lee & Garraway, 2000). Furthermore, physical demands change in different parts of the playing season, while climatic conditions change according to the seasons. Therefore, suggesting that multiple factors could all influence injury occurrence and more data on environmental and contextual aspects (e.g., stage of the season, congested periods, playing styles, match characteristics) were required to investigate a possible influence on injury risk based on environmental temperature (Gabbett et al., 2007; Lee & Garraway, 2000). Accordingly, this study aimed to explore relationships between match environmental temperatures and injury occurrence in football (soccer), by analyzing a large number of observations from two professional leagues from different continents, representing a range of different climates. We hypothesize that injury occurrence increases when match temperature is higher.

Methods

Data of 2612 matches of male professional football (soccer) were obtained. This included all 2142 matches, over seven seasons (2014–2021) of the German “Bundesliga” (BL), and 470 of 624 matches, over four seasons (2016–2020) of the Australian “A-League” (AL). In the AL, one team was located outside Australia, in Wellington, New Zealand. The BL dataset was built on open-source data used in previous research (aus der Fünten et al., 2023; Krutsch et al., 2022). It involved scouting multiple online and social media sources to detect and describe injuries. The injury definition for the BL data was based on Fuller et al. (2006) (Fuller et al., 2006) when a player could not fully participate in at least 1 day of training or competition. If a player had to stop exercise because of injury but returned the next day, this counted as a time loss of zero days and was not included, as these types of injury were insufficiently reported by media and clubs (aus der Fünten et al., 2023; Krutsch et al., 2022). The AL data set was based on anonymized data used in previous research (Lu et al., 2022). In the AL, injuries were defined as “any physical complaint requiring medical attention resulting in a missed AL match” (also adopted from (Fuller et al., 2006)) and had been obtained based on injury surveillance system within the league, where injury data was collected from team medical staff on a weekly basis. Due to the different data sources, leagues were analyzed separately, and no grouped analysis was performed, though using two available data sources from different leagues and continents provides larger and wider insights on the influence of temperature on injury occurrence. Ethical approval was granted by the Ethics Committee of the Faculty for Human and Business Sciences of Saarland University (Ref No.: 23-14). Injuries for both leagues were further classified by mechanism (contact versus noncontact), where contact injuries resulted from physical contact with another player or object, and non-contact injuries occurred without any interaction with outside forces (Alentorn-Geli et al., 2009). Injury locations and types were classified according to the Orchard Sports Injury Classification System (OSICS(Fuller et al., 2006)). Grouping the head and neck, upper limbs, and trunk injuries, and adding heat illnesses, this resulted in nine distinct injury locations (head and neck, upper limbs, trunk, hip/groin, thigh, knee, lower leg/Achilles tendon, ankle, foot/toe), six different injury types (muscle and tendon, joint [nonbone] and ligament, contusions, fractures and bone stress, lacerations and skin

lesions, central/peripheral nervous system), as well as heat illnesses. Injuries were aggregated to overall counts and by sub-groups (mechanism, location, and type) across both leagues for each match and reported as injuries per match. Although reporting injuries per 1000 match-hours is the more common, the data was reported as injuries occurring per match per team, due to the lack of specific player exposure data. The limitations associated with this method should be recognized (Stoviz & Shrier, 2012).

Environmental conditions in the form of temperature and WBGT were collated retrospectively for each match. The use, advantages, and disadvantages of WBGT have been described extensively in previous research (Brocherie & Millet, 2015; Lemke & Kjellstrom, 2012; Liljegren et al., 2008). Despite its widespread use, the black globe temperature (radiative heat gain) and natural wet-bulb temperature (evaporative heat loss) measurements are criticized as not representing human thermoregulation, thereby underestimating heat stress in many settings (Blazejczyk et al., 2012; Brocherie & Millet, 2015). It should also be mentioned that WBGT is a heat stress index and is not validated for colder conditions. Therefore, to interpret the effects of colder environments on injury occurrence, temperature was also used in our analyses. Although more modern and sophisticated thermal indexes exist (Blazejczyk et al., 2012; Jendritzky et al., 2012), WBGT remains widely used, especially in sports federation heat policies. Specifically, this index is also used in the heat policy introduced by FIFA, which recommends the use of drinking breaks at 32°C WBGT (Brown et al., 2024).

For BL matches, weather data were obtained from Meteostat.net (Meteostat.net). This is an open source service, providing hourly meteorological data for any given coordinates. Data is obtained as a weighted interpolation depending on the distance and elevation difference from the four closest weather stations to a geological location. They provide the following data: temperature, relative humidity, dew point, wind speed, air pressure, total precipitation, and the current weather condition. Based on this, WBGT can be estimated in a variety of ways according to previous research (Lemke & Kjellstrom, 2012). We used the estimation developed by Liljegren et al. (2008)

(Liljegren et al., 2008). This is validated and reliable in different environmental settings and is described as the best estimate for WBGT from different methods (Patel et al., 2013). The R code needed to implement these calculations has been provided and used in previous research (Casanueva, 2019). Wind speed was assumed to be a minimum of 1 m/s, as moving players generate airflow of at least equivalent to that. Solar radiation was estimated using the solar angle at the time and location of the match (Duffie & Beckman, 2013). As Meteostat.net provides hourly data, two time points (the kick-off time and one hour later) were used per match and averaged. If the match did not start at a full hour but at 15 or 30 minutes past the hour, the previous full hour was used as a starting point and the following hour as a second time point. For AL matches, environmental conditions were provided by UBIMET.com (UBIMET GmbH). This commercial provider uses artificial intelligence and data input from multiple weather stations, radar, and satellite data to estimate meteorological data at given ground locations. They provide temperature, relative humidity, solar radiation, and WBGT measurements for the starting times of the first and second half, which were then averaged to create one value per match. To validate the WBGT data based on Meteostat.net data, the WBGT estimation method used for the BL data was also performed with the AL data. As internal validation, results were then compared to the WBGT reported from UBIMET.com. There was a very good linear association (correlation coefficient $r = 0.93$).

Both temperature and WBGT were used for the analysis. They were treated as continuous variables to investigate relationships between environmental conditions and injury occurrence. Additionally, matches were categorized into groups of 5°C temperature increments, resulting in nine WBGT groups (from –15 to 30°C) and 10 temperature groups (–15 to 35°C) in the BL and five WBGT groups (5–30°C) and six temperature groups (5–35°C) in the AL.

Statistical analyses were performed separately for each league due to the different injury definitions and data sources (media collation vs. team reports) used. Any over- or underreporting of injuries by one given reporting method would influence all matches regardless of the environmental conditions and there- fore not alter the

relationship between temperature and injuries within a league. Further, separate analyses do not conflate acclimatization and local exposures of the players given the different temperature ranges regularly encountered by players in their respective leagues. To analyze the relationship of environmental conditions and injury, generalized linear mixed effects models (GLMM) were used, with specified zero-inflated Poisson distribution of the injury data and a random effect of the observed match. Additionally, for the separate temperature categories in 5 °C steps, differences between categories were determined by one-way analysis of variance (ANOVA) with Tukey's Honest Significant Difference post-hoc test. Analysis was performed with R Studio 2022.07.1 using R version 4.2.1 stats, jtools, glmmTMB, MuMIn & performance libraries. Statistical significance was defined at a level of 5% or less for the α-error ($P < 0.05$).

Results

As outlined in Table 12, 2101 injuries (BL: n = 1779, AL: n = 322) were reported from 2612 matches, resulting in 0.83 ± 0.97 injuries per match in the BL and 0.68 ± 0.86 injuries per match in the AL. Contact (BL: n = 881 [49.5%]; AL: n = 148 [46.1%]) and noncontact injuries (BL: n = 898 [50.5%]; AL: n = 174 [54.2%]), are similarly distributed within both leagues. The lower limbs are the most common injury location (BL: n = 1417 [79.7%]; AL: n = 264 [82.2%]). Muscle and tendon injuries are the most frequent injury type (BL: n = 855 [48.1%]; AL: n = 140 [43.6%]). Data on specific injury mechanisms, locations and types per match are reported in Table 12 for each league separately. Table 12 also shows the environmental conditions for both leagues. Although maximum values are similar, a larger proportion of the BL matches is played in colder conditions. The number of matches above thresholds implemented by respective governing bodies is minimal in both leagues, with 27 matches (11 in BL, 16 in AL) above 26°C WBGT or 31°C T, two matches (zero in BL, two in AL) above 28°C WBGT and none above 32°C WBGT).

Table 12: Descriptive summary of environmental conditions and injury-occurrences per match in 4 seasons of A-League and 7 seasons of Bundesliga.

Variable	A-League	Bundesliga
Number of Matches	470	2142
Number of Seasons	4	7
Mean Temperature (°C)	21.0 ± 5.3	11.0 ± 7.2
Temperature range (°C)	7.6 – 37.1 (Δ29.5)	-11.2 – 34.3 (Δ45.5)
Mean WBGT (°C)	18.1 ± 4.	9.4 ± 6.0
WBGT range (°C)	6.2 – 29.6 (Δ23.4)	-12.2 – 26.3 (Δ38.5)
Total Number of Injuries	322	1779
Number of Injuries per Match	0.68 ± 0.86	0.83 ± 0.97
Non-Contact	0.36 ± 0.61	0.42 ± 0.68
Contact	0.32 ± 0.58	0.41 ± 0.69
Muscle and Tendon	0.29 ± 0.54	0.38 ± 0.67
Joint (non-bone) and Ligament	0.16 ± 0.43	0.16 ± 0.40
Contusion	0.04 ± 0.20	0.15 ± 0.40
Fractures and Bone stress	0.04 ± 0.21	0.04 ± 0.21
Laceration and Skin lesion	0.00 ± 0.07	0.01 ± 0.11
Central/Peripheral Nervous System	0.06 ± 0.28	0.04 ± 0.21
Heat Illness	0.01 ± 0.08	0.00 ± 0.00
Head and Neck	0.05 ± 0.25	0.06 ± 0.26
Upper Limbs	0.02 ± 0.16	0.03 ± 0.17
Trunk	0.04 ± 0.20	0.05 ± 0.23
Hip/Groin	0.06 ± 0.25	0.08 ± 0.28
Thigh	0.22 ± 0.47	0.21 ± 0.48
Knee	0.12 ± 0.35	0.11 ± 0.34
Lower Leg/Achilles Tendon	0.07 ± 0.25	0.08 ± 0.28
Ankle	0.06 ± 0.28	0.12 ± 0.37
Foot/Toe	0.03 ± 0.18	0.05 ± 0.23
Lower Limbs (overall)	0.57 ± 0.79	0.66 ± 0.87

Abbreviations: Δ (delta) = range; °C = degree Celcius; WBGT = wet-bulb globe temperature

Bundesliga

In BL there is no significant relationship between temperature or WBGT and injury occurrence (Figure 6; $P > 0.83$). Table 13 shows the GLMMs using temperature or WBGT to predict injury occurrence. There are only marginal differences in the outcomes of using temperature and WBGT. Second, the 'null-hypothesis model' (i.e., injuries occur randomly) performs similar, indicating that the random model is equally successful in predicting injuries than models using temperature or WBGT as predictors. When reported based on injury subcategories of mechanism, type, or location, no significant relationship ($P \geq 0.10$) is evident for any GLMM with either temperature or WBGT. Results of the GLMMs for overall injuries and subcategories are presented in Table 14, with no significant differences ($P \geq 0.37$) in overall injury occurrence or any injury subcategories existing for either of the temperature or WBGT categories (Figure 7). As the trends of the subcategories followed those of the overall injuries, their results are not specifically displayed or visualized here. Of note, no heat illness events are reported in the data set.

Table 13: Performance of the generalized linear mixed effects models (GLMMs), comparing the 'Null'-model to models using WBGT or T as independent factor to predict overall injury occurrence.

	Coeff	AIC	BIC	Deviance	RMSE	LL	marg. R^2	p-value
Bundesliga								
Inj ~ 1 + (1 | Match)		5230.4	5247.4	5224.4	0.83	-2612.2		
Inj ~ T + (1 | Match)	0.00	5232.4	5255.0	5224.4	0.83	-2612.2	0.00	0.97
Inj ~ WBGT + (1 | Match)	0.00	5232.3	5255.0	5224.3	0.83	-2612.2	0.00	0.81
A-League								
Inj ~ 1 + (1 | Match)		1044.3	1056.8	1038.3	0.76	-519.2		
Inj ~ T + (1 | Match)	0.02	1043.8	1060.4	1035.8	0.76	-517.9	0.008	0.11
Inj ~ WBGT + (1 | Match)	0.03	1042.4	1059.0	1034.4	0.76	-517.2	0.009	0.05

Abbreviations: Coeff = Coefficient; AIC = Akaike information criterion, BIC = Bayesian information criterion , RMSE = Root mean squared error; LL = ; Log-likelihood; marg. R2 = marginal R squared; Inj = Injuries, T = Temperature; WBGT = wet-bulb globe temperature

A-League

In the AL there are 0.03 (95 CI = 0.00, 0.06) more injuries per 1 °C WBGT increase, though it is only describing a small effect (estimated coefficient [β] = 0.12, 95 CI = 0.00, 0.24; P = 0.05) and a neglectable amount of explained variance (R2 = 0.01). This association is not significant and lower when temperature is used as a predictor for injuries, which then increases by 0.02 per 1 °C temperature increase (95 CI = 0.00, 0.04; R2 = 0.01; β = 0.10, 95 CI = –0.02, 0.21; P = 0.11). A similar tendency toward more injuries in higher WBGT is observed for all lower body injuries combined (0.03; 95 CI = 0.00, 0.06; R2 = 0.01; β = 0.13, 95 CI = –0.00, 0.27; P = 0.06) and thigh injuries specifically (0.05; 95 CI = 0.00, 0.10; R2= 0.01; β = 0.20, 95 CI = –0.01, 0.42; P = 0.06). Further, small effect sizes are observed for noncontact (β = 0.13), hip and groin (β = 0.16), and injuries of the lower leg and Achilles tendon (β = 0.17) that occur more often when WBGT is higher, but none of these effects are significant (P > 0.05; Figure 8). Similar findings exist for temperature in the models, with GLMM outcomes for overall injuries and selected subcategories reported in Table 14. Finally, there are three heat illnesses in the data set, occurring at 22 °C, 25 °C, and 29 °C WBGT.

Figure 6: Results of generalized linear mixed models between wet-bulb globe temperature (WBGT) specific injury subcategories in the A-League. Each dot represents one match, while the black line shows the regression line, with the 95% CI (gray band). A, overall lower body injuries. B, noncontact injuries. C, thigh injuries. D, lower leg and achilles tendon injuries.

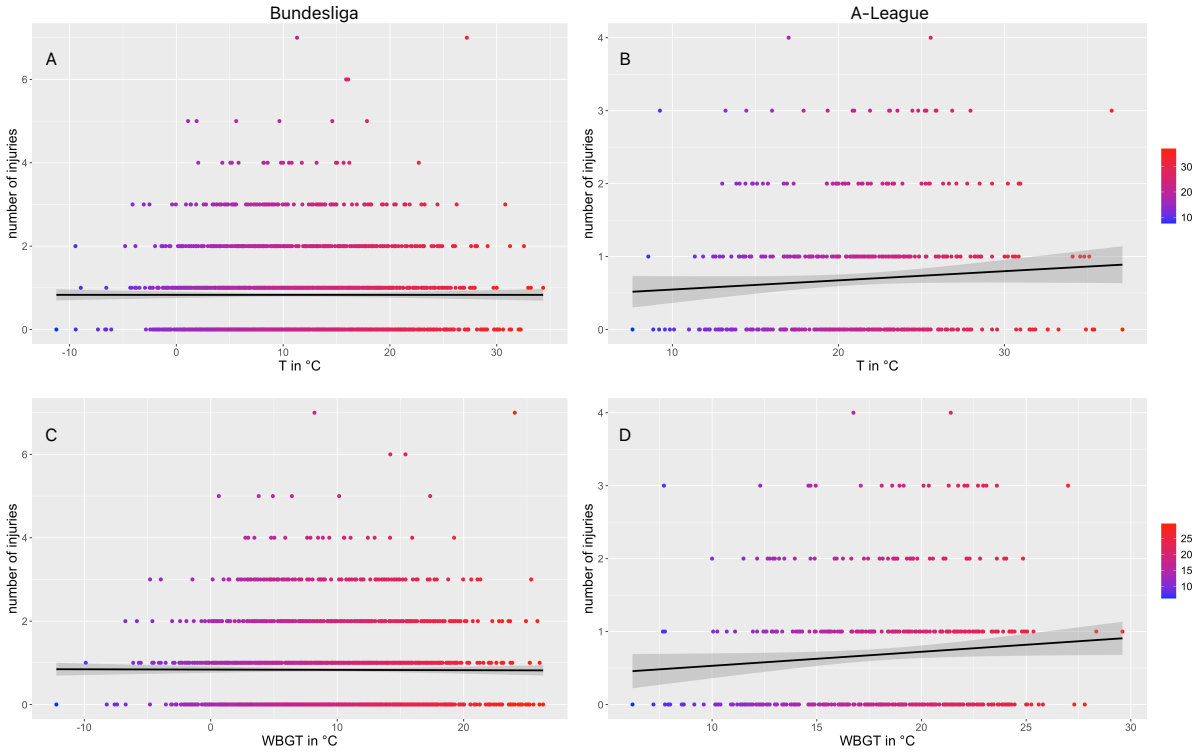


Table 14: Association between injuries (overall and selected subcategories) and environmental conditions.

			Temperature			Wet-bulb globe temperature			
	Mean ± SD	Estimate (95%CI)	β (95%CI)	R^2 marg.	p-value	Estimate (95%CI)	β (95%CI)	R^2 marg.	p-value
OVERALL INJURIES									
Overall									
BL	0.83 ± 0.97	-0.00 (-0.01,0.01)	-0.00 (-0.05,0.05)	0.00	0.98	-0.00 (-0.01,0.01)	-0.00 (-0.06,0.04)	0.00	0.81
AL	0.68 ± 0.87	0.02 (-0.00,0.04)	0.10 (-0.02,0.21)	0.01	0.11	0.03 (0.00,0.06)	0.12 (0.00,0.24)	0.01	0.05*
MECHANISM									
Contact									
BL	0.41 ± 0.69	0.01 (-0.01,0.02)	0.04 (-0.04,0.11)	0.00	0.35	0.00 (-0.01,0.02)	0.02 (-0.05,0.10)	0.00	0.55
AL	0.32 ± 0.58	0.01 (-0.02,0.05)	0.07 (-0.10,0.24)	0.00	0.44	0.02 (-0.02,0.06)	0.09 (-0.08,0.26)	0.00	0.32
Non-Contact									
BL	0.42 ± 0.68	-0.01 (-0.02,0.01)	-0.04 (-0.11,0.03)	0.00	0.29	-0.01 (-0.02,0.01)	-0.04 (-0.11,0.04)	0.00	0.32
AL	0.36 ± 0.61	0.02 (-0.01,0.05)	0.10 (-0.06,0.26)	0.00	0.23	0.03 (-0.01,0.07)	0.13 (-0.04,0.29)	0.01	0.13

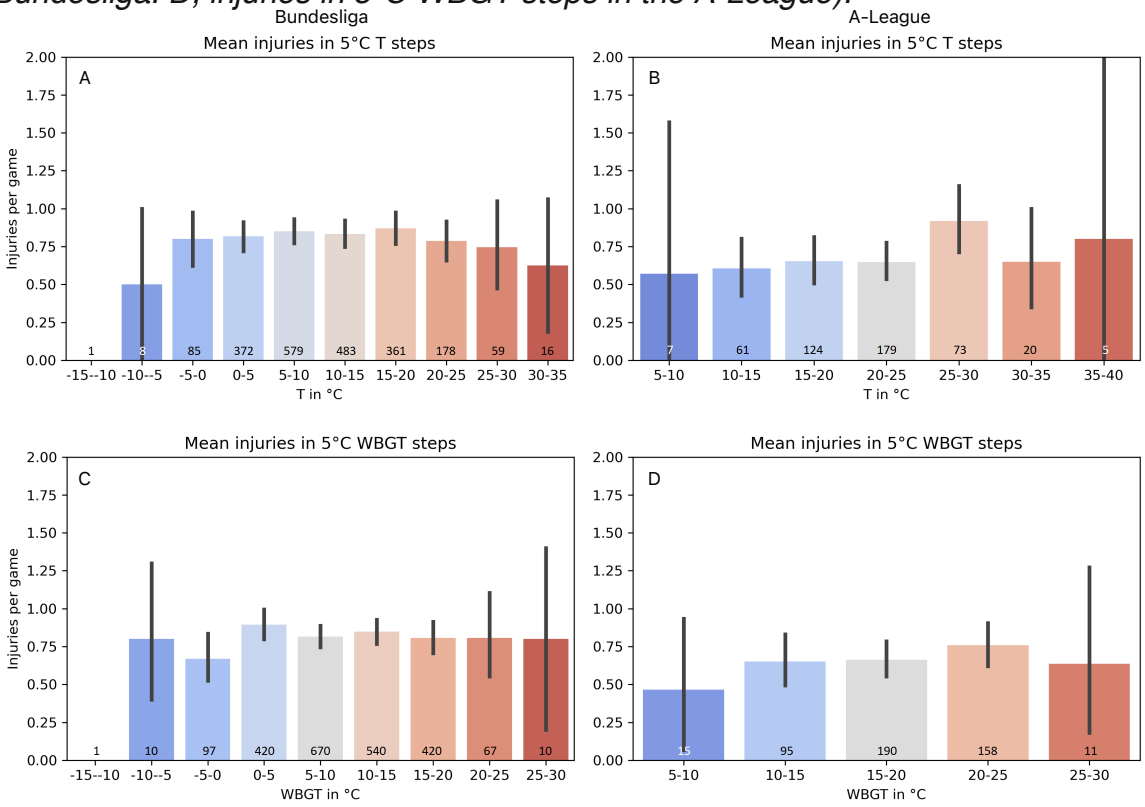
Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant; BL = Bundesliga; AL = A-League;

Table 14 (continued):

	Mean ± SD	Temperature				Wet-bulb globe temperature			
		Estimate (95%CI)	β (95%CI)	R^2 marg.	p-value	Estimate (95%CI)	β (95%CI)	R^2 marg.	p-value
TYPE OF INJURY									
Muscle and Tendon									
BL	0.40 ± 0.67	-0.01 (-0.02,0.00)	-0.05 (-0.12,0.03)	0.00	0.21	-0.01 (-0.02,0.00)	-0.05 (-0.12,0.03)	0.00	0.23
AL	0.29 ± 0.54	0.01 (-0.02,0.05)	0.07 (-0.09,0.24)	0.00	0.39	0.02 (-0.02,0.06)	0.09 (-0.08,0.26)	0.00	0.30
Joint (non-bone) and Ligament									
BL	0.16 ± 0.40	0.01 (-0.01,0.02)	0.06 (-0.05,0.16)	0.00	0.30	0.01 (-0.01,0.03)	0.05 (-0.05,0.16)	0.00	0.30
AL	0.16 ± 0.43	-0.01 (-0.06,0.03)	-0.06 (-0.31,0.18)	0.00	0.61	0.00 (-0.05,0.06)	0.01 (-0.23,0.26)	0.00	0.92
LOCATION OF INJURY (lower limbs)									
Lower Limbs overall									
BL	0.66 ± 0.87	0.00 (-0.01,0.01)	0.00 (-0.06,0.06)	0.00	0.96	-0.00 (-0.01,0.01)	0.00 (-0.06,0.05)	0.00	0.84
AL	0.57 ± 0.79	0.02 (-0.01,0.04)	0.10 (-0.03,0.23)	0.00	0.15	0.03 (-0.00,0.06)	0.13 (-0.00,0.27)	0.01	0.06
Hip/Groin									
BL	0.08 ± 0.28	0.01 (-0.03,0.04)	0.04 (-0.21,0.30)	0.00	0.73	0.01 (-0.03,0.05)	0.05 (-0.21,0.31)	0.00	0.70
AL	0.06 ± 0.25	0.03 (-0.10,0.16)	0.15 (-0.55,0.85)	0.00	0.67	0.04 (-0.13,0.21)	0.16 (-0.56,0.88)	0.00	0.66
Thigh									
BL	0.21 ± 0.48	-0.01 (-0.02,0.00)	-0.08 (-0.19,0.02)	0.00	0.13	-0.01 (-0.03,0.00)	-0.09 (-0.19,0.02)	0.00	0.10
AL	0.22 ± 0.47	0.03 (-0.01,0.07)	0.15 (-0.05,0.36)	0.01	0.14	0.05 (-0.00,0.10)	0.20 (-0.01,0.42)	0.01	0.06
Knee									
BL	0.11 ± 0.34	0.01 (-0.01,0.03)	0.08 (-0.08,0.24)	0.00	0.32	0.01 (-0.01,0.03)	0.07 (-0.09,0.23)	0.00	0.38
AL	0.12 ± 0.35	-0.01 (-0.07,0.06)	-0.04 (-0.36,0.29)	0.00	0.83	0.02 (-0.06,0.09)	0.07 (-0.25,0.40)	0.00	0.65
Lower Leg/ Achilles Tendon									
BL	0.08 ± 0.28	-0.01 (-0.04,0.02)	-0.07 (-0.27,0.13)	0.00	0.30	-0.01 (-0.05,0.02)	-0.08 (-0.28,0.12)	0.00	0.46
AL	0.07 ± 0.25	0.03 (-0.04,0.09)	0.14 (-0.21,0.48)	0.00	0.44	0.04 (-0.11,0.19)	0.17 (-0.47,0.82)	0.00	0.60
Ankle									
BL	0.07 ± 0.28	0.01 (-0.03,0.05)	0.07 (-0.21,0.35)	0.00	0.64	0.01 (-0.04,0.06)	0.07 (-0.21,0.35)	0.00	0.64
AL	0.06 ± 0.28	0.02 (-0.13,0.17)	0.09 (-0.70,0.89)	0.00	0.82	0.02 (-0.18,0.20)	0.06 (-0.75,0.87)	0.00	0.88
Foot/ Toe									
BL	0.05 ± 0.23	0.03 (-0.02,0.08)	0.22 (-0.14,0.59)	0.00	0.23	0.03 (-0.03,0.09)	0.20 (-0.17,0.57)	0.00	0.30
AL	0.03 ± 0.18	-0.01 (-0.22,0.20)	-0.06 (-1.18,1.05)	0.00	0.91	-0.03 (-0.29,0.23)	-0.14 (-1.24,0.96)	0.00	0.80

Abbreviations: Mean ± SD = mean and standard deviation; Estimate (95%CI) = estimate and 95% confidence interval; β (95%CI) = standardized estimate and 95% confidence interval; R^2 marg. = marginal R^2: explained variance of the fixed effects; p-value (*) = significant; BL = Bundesliga; AL = A-League;

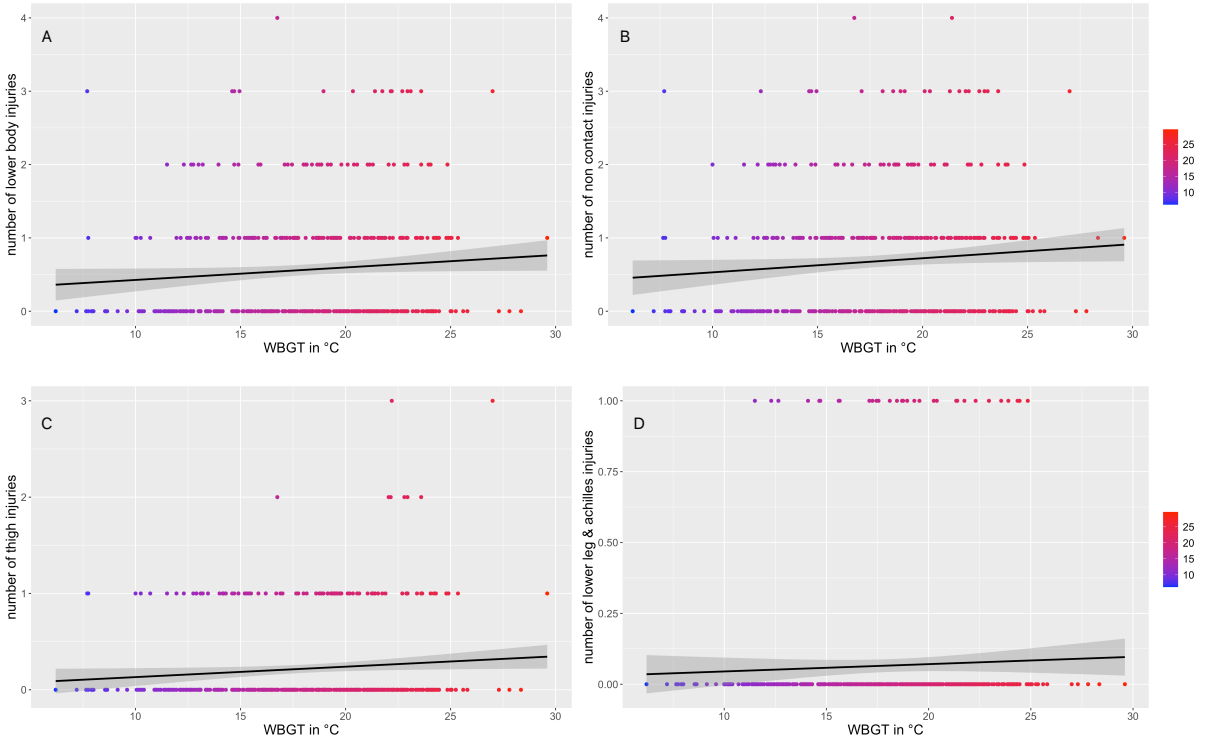
Figure 7: Mean injury-occurrence per match (gray bar) and 95% confidence interval (black line) in different temperature (T) and wet-bulb globe temperature (WBGT) zones (The small number on the bars indicating the number of observed matches in each category. A, injuries in 5°C temperature steps in the Bundesliga. B, injuries in 5°C temperature steps in the A-League. C, injuries in 5°C WBGT steps in the Bundesliga. D, injuries in 5°C WBGT steps in the A-League).



Discussion

This study was the first to investigate the relationship of environmental match temperatures (T and WBGT) on injury occurrence in professional football. Regardless of whether temperature or WBGT was considered, environmental temperatures were largely unrelated to the overall number of injuries, injury mechanism, location or type; however, there was a tendency toward a small effect of more injuries occurring in higher WBGT in the AL. When comparing matches in classification of 5 °C temperature or WBGT increments there were no differences between any of the injury subcategories in either league.

Figure 8: Results of generalized linear mixed models between wet-bulb globe temperature (WBGT) specific injury subcategories in the A-League. Each dot represents one match, while the black line shows the regression line, with the 95% CI (gray band). A, overall lower body injuries. B, noncontact injuries. C, thigh injuries. D, lower leg and achilles tendon injuries.



In the AL, the influence of WBGT on the overall injury occurrence tended towards significance (P = 0.05), indicating that when WBGT increased by 1 °C, there was an increase of 0.03 injuries per match (for all 22 players combined). However, the effect size and explained variance were minimal, leading to an inconclusive interpretation of this relationship. In the BL there were no associations between either temperature or WBGT and injury outcome variables. The lack of a clear relationship between hot environmental temperatures (temperature or WBGT) and increased injuries contrasts with our hypothesis of an increased injury rate due to premature fatigue and impairments in, coordinative and cognitive function in hotter temperatures (Mtibaa et al., 2018; Racinais, Ihsan, et al., 2019; Schmit et al., 2017). It further contrasts with research from occupational industries that reported an increase of acute injuries in industrialized settings when workers are exposed to hotter conditions (Spector et al., 2019). Although the potential mechanisms of this relationship are still under investigation, this was hypothesized to be the result of changes in cognitive

performance, impaired balance, more risky behaviour, increased muscle fatigue, dehydration, and poorer sleep quality (Spector et al., 2019). In the specific setting of outdoor team sports, this association is yet to be confirmed. As previous studies in rugby suggest, sport-specific factors might mitigate or mask the effects of heat exposure, that are found in other settings. These could include adjustments of playing intensity and style in the heat, influence of weather on ground conditions, and systematically differing demands in various parts of the football season (Gabbett et al., 2007; Lee & Garraway, 2000). For example, it has been shown that players decrease running distances and playing intensity when playing in hotter environments, reducing their risk of hyperthermia and thermal fatigue (Draper et al., 2022; Schwarz et al., 2024). Nevertheless, it has also been shown that high core temperatures can be reached in football players despite reductions in running distances, but also without noticeable health adversities (Mohr et al., 2012). By decreasing playing intensities in hotter conditions, the effects of higher heat stress might be mitigated, reducing the effects on cognitive and coordinative capacities shown in laboratory or occupational settings. Lower playing intensities have further been shown to lead to less injuries, for example, when comparing training to matches (aus der Fünten et al., 2023; Hägglund et al., 2013). Additionally, higher temperatures and humidity lead to softer ground conditions, which have been linked to a lower injury occurrence (Gabbett et al., 2007), possibly counteracting an increase in injuries caused by the effects of heat.

The environmental conditions in these two leagues represent a wide range of conditions that may also be observed in many other settings around the world. Nevertheless, some competitions will be held in hotter conditions due to their scheduling in the hotter summer months (e.g., national tournaments, including youth competitions, European competition qualification matches, and preseason matches). In the BL, the exposure to heat remained rare due to the off-season period over the summer and mostly cold-to-mild climates during playing months. There were no matches at extreme risk (> 27.9 °C WBGT), four at high risk (25.7 – 27.8 °C WBGT) and 40 at moderate risk (22.3 – 25.6 °C) for heat-illnesses according to American College of Sports Medicine guidelines (Roberts et al., 2023). In the AL, the overall distribution of matches indicated hotter temperatures compared to the BL, which is

understandable given that in Australia, in general warmer temperatures are recorded compared to Germany and it is a summer-based competition. However, the scheduling of many matches after 5pm may explain the reduced exposure to extreme environmental temperatures (Hosokawa et al., 2018). There were four matches kicked off at extreme risk (> 27.9 °C WBGT), five at high risk (25.7 – 27.8 °C WBGT) and 84 at moderate risk (22.3 – 25.6 °C) for heat illnesses according to American College of Sports Medicine categories (Roberts et al., 2023). In line with the relevant governing body heat policy guidelines, 16 matches contained an additional short drinking break in each half when WBGT was higher than 26 °C or temperature was above 31 °C. Previous research proposed that for practical topics related to exercising in the heat, using WBGT may not be advantageous over using temperature (Brocherie & Millet, 2015). The current data also revealed only small differences in the models using temperature or WBGT. However, it needs to be considered that WBGT was estimated based on data from weather stations and a WBGT measurement on the field of play may be more advantageous compared to obtaining only temperature. Nevertheless, given the additional difficulties in measuring WBGT (e.g., need for expensive equipment and trained staff), the consideration of appropriate environmental measures to enact heat policies or interventions remains for ongoing research and discussion. Especially in leagues lacking resources, the use of WBGT might not be applicable. Furthermore, previous publications pointed toward limitations of WBGT in describing high humidity climates, underestimating the actual heat stress posed onto players (Budd, 2008). Of note, two of the three observed heat illnesses in the current study were reported in a moderate WBGT of ~22 °C and temperature of ~25 °C, but high relative humidity of more than 65%.

Despite this novel investigation, some limitations require consideration when interpreting the findings. First, the retrospective approach to capture environmental conditions was the best available method for this study. An estimation of the WBGT based on basic meteorological data (Liljegren et al., 2008), with assumptions for solar radiation and wind speed, was used. Although this method has been shown to give reliable estimates (Lemke & Kjellstrom, 2012), on-site measurements would have been preferable and should be encouraged in the future. Especially solar radiation and

air flow may differ locally inside football stadiums and their accuracy would benefit most from a measurement at the athletes' field of play. Another limitation involves the collation of injury data from different leagues, using different data sources, which prevents the comparison between or the collation of BL and AL data. However, any over- or underreporting of injuries by one given method would be influencing all matches, regardless of the environmental conditions, therefore also not altering the investigated association. To conclude, the retrospective approach to collate weather data and inclusion of different leagues allowed for the investigation of a large amount of observed match data, accepting that this resulted in a less standardized data collection. Another limitation was the low number of matches in extreme heat conditions, as well as an inability to include variables such as acclimatization, stage of the season, prior exposure etc., which were not available. Therefore, further investigations of more extreme conditions may be warranted to account for further confounding factors.

In conclusion, there was no significant relationship between environmental temperatures and injury occurrence in male professional football matches within the observed temperature range. This relationship may be co-influenced by altered playing intensities and ground conditions in changing temperatures. Both leagues had a low exposure to challenging hot environmental conditions, likely due to scheduling matches outside the hottest periods of the year or day. With increasing global temperatures, this strategy may be applied by football governing bodies, to ensure the occupational health and safety of football players, as the effects of matches in hotter conditions, multiple consecutive heat exposures or abrupt changes from cool to hot environments on injury occurrence remain to be investigated.

Study 4: The Effects of Pre-Cooling and Cooling Breaks for Football Matches in the Heat

S4.1 Introduction and Literature Summary

Introducing pre-cooling and cooling breaks has been recommended as a measure to mitigate heat strain in football (Chalmers, 2017; Gouttebarge et al., 2023; Nassis et al., 2024). As such, it is also widely used in heat policies by different football federations (Gouttebarge et al., 2023). Nevertheless, investigations of thermoregulatory, physiological, performance and perceptual responses remain scarce.

Studies on pre-cooling, cooling during additional breaks per half and during halftime in football have mostly been conducted in laboratory settings. These include football players or trained participants performing mostly football-simulating treadmill protocols and rarely football-related performance tests (agility t-test, 20 m sprint, yoyo intermittent endurance test) in the heat. Only one study has investigated cooling during actual football training and matches (Duffield et al., 2013). The cooling protocols in these studies (see Table 15) ranged from relatively low cooling doses (e.g., water not very cold >28 °C, short exposures < 3 min), to high cooling doses, that would likely not be applicable in real world football (e.g., full body cold water immersions, wearing cooling garments during exercise, pre-cooling for 60 minutes).

All but two of these studies found that cooling reduced T_{core}, with the effect size depending on the duration, timepoint and intensity of the cooling. A lower cooling dose or cooling applied before exercise led to a T_{core} drop of 0.2 - 0.3 °C (Chalmers et al., 2019; Drust et al., 2000; Parris & Tyler, 2018; Price et al., 2009). A higher cooling dose or cooling applied in-between bouts of exercise led to a drop of 0.6 - 0.9 °C (Aldous et al., 2019; Clarke et al., 2011; Zhang et al., 2014). Cooling also lowered the thermal sensation (Clarke et al., 2011; Holm et al., 2018; Zhang et al., 2014) and improved endurance performance (Aldous et al., 2019; Clarke et al., 2011; Zhang et al., 2022; Zhang et al., 2014). A reduction in fluid loss due to potentially decreased sweating was

only detected in the field-based study (Duffield et al., 2013) and one study reported a lower reduction of blood plasma volume (Azad et al., 2016). Finally, also the mental concentration of participants was found to be increased after cooling (Clarke et al., 2011).

The effects found in the only field-based study, showed tendencies to replicate the findings from laboratory observations, but were not significant (Duffield et al., 2013). They investigated male professional Australian A-League players during a training (n=9) and a match (n=7). Using an ice slurry, cold towels to the head and an ice vest for 15 minutes before the warm-up, and repeating towels and vests during halftime, was initially successful in lowering T_{core}. However, the effect was only evident until the warm-up and then again just after half-time cooling. Accordingly, they observed an increased distance covered during training, but not the game and argue that it may be more beneficial to maintain the pre-cooling stimulus until as shortly before kick-off as possible, to not lose potential benefits during warm-up.

The implementation of 3-minute cooling breaks, although short, could enable a re-exposure to the cooling. In fact, in laboratory settings, the implementation of 3 minute in-play breaks, especially in combination with halftime cooling have been effective in lowering T_{core} by 0.2 - 0.4 °C (Brown et al., 2025; Brown et al., 2024; Chalmers et al., 2019). However, in these studies the overall heat strain remained rather low with a peak T_{core} of 38.7 - 39.4 °C, compared to field-based observations where peak T_{core} was 39.4 - 39.9 °C (Duffield et al., 2013; Edwards & Clark, 2006; Mohr et al., 2012; Özgünen et al., 2010), which is why the authors called for further investigations in field settings.

Therefore, Study 4 aimed at conducting a field-based investigation of actual football matches held in challenging environmental conditions. The aim was to test the effects of simple cooling breaks, consisting of cold towels dipped in ice and cold drinks, applied before the match, during cooling breaks and during halftime. This was compared to players performing drinking breaks consisting of passive rests and temperate drinks. As heat stress remained moderate during the initial data collection,

due to unforeseen whether events, data collection was repeated. Finally, data was collected on four occasions: In October 2023 two matches were completed with a subset of 22 players completing drinking and cooling breaks in 25 °C WBGT. In June 2024 two more matches with a different subset of 22 players were held. One match was held in 25 °C WBGT and no breaks were applied, and the other was held in 33 °C WBGT while players performed either drinking or cooling breaks. In total 40 players, participated in either two (n = 36) or all four (n = 4) matches, whilst their thermoregulatory, physiological, performance, and perceptual responses were measured.

Table 15: Literature review of studies investigating pre-cooling and cooling breaks in football simulating treadmill running (exemptions: Duffield et al. (2013) actual training and matches; Zhang et al. (2022) performance field tests).

Study	Sample	Environmental Parameters	Cooling Strategy	Effects of cooling
Drust et al., 2000	6 male University-level football players; FSTR	T1: 21 °C + 72% T2: 26 °C + 62% T3: 26 °C + 62% + Cool	Cold shower starting at 28 dropping to 24 °C for 60 min pre-exercise	•T_{core} dropped 0.3 °C during pre-cool (effect lasted until 30 min into protocol) •no effect on oxygen consumption, HR or running performance
Price et al., 2009	8 female elite players; FSTR	T1: 30 °C + 63% T2: 30 °C + 63% + Cool	Ice vests for 20 min pre-exercise and 15 min in half-time	•reduced T_{core} by 0.2 pre-exercise and 0.1 in halftime •no effect on HR or fluid loss
Clark et al., 2011	12 male University-level football players; FSTR	31°C + 42% T1: Control T2: Cooling T3: Carbs Drinks T4: Carb Drinks + Cooling	Ice vest for 60 min pre-exercise and 15 min in half-time Drinks given every 15 min	•T3 & T4 reduced T_{core} and TS by 0.2 pre-exercise and 0.1 in halftime •T4 improved running performance and attention test results
Duffield et al., 2013	9 male elite football players; Football training (n=9) and match (n=7)	Training avg.: 30°C, 75% RH, 28°C WBGT Match Match avg.: 27 °C, 80% RG 26 °C WBGT	ice slurry, cold towels (soaked in 5 °C water) to the head and an ice vest for 15 min pre-exercise and in half-time	•T_{core} was lowered but effects diminish in warm up after 10 min •Large effect for lower sweat loss •Moderate effect for increased distance covered •Moderate effect for lower RPE •Large effect on lower TS •All above effects were non-significant
Zhang et al., 2014	6 male, 1 female university students 1 half of FSTR, then halftime and performance tests	30 °C WBGT for running Then 20°C 45% RH for cooling and performance test	During halftime either: 15°C cold water immersion of forearm and hand vs. 5°C ice towels in neck vs. passive rest	•No effect on T_{core} •TS lowered in neck cooling •Yoyo endurance test performance improved with both cooling methods
Azad et al., 2016	16 young male football players; Exercise stress test	33°C + 50% G1: Control G2: CWI	Whole body CWI up to the neck at 24° C for 10mins	•No effect on T_{core} (measured orally) •Improved blood plasma volume •Time to exhaustion was 6 min longer, but this was not significant
Parris and Tyler, 2018	10 male, physically active football players FSTR	35 °C + 50% T1: Control T2: Cooling vests	Cooling vest during running (worn over the jersey) vs. Control	•reduce T_{core} by -0.2 to -0.3 °C, reduced RPE and TS •no effect on HR and performance

Abbreviations: ***Sample:*** *FSTR: Football simulating treadmill running; Yoyo int. end. lvl.1: Yoyo intermittent endurance level 1.* ***Environmental conditions:*** *T = Temperature; °C = degree Celsius; RH = Relative humidity; % = percentage (RH); WBGT = Wet-bulb globe temperature; M0= Match No.; T0 = Trial No. (same participants performing all trials); G0 = Group No (participants split across conditions); CB = cooling breaks; DB = drinking breaks; Break only = break without fluid consumption; NB = no breaks; ExtHT = extended halftime (20 min)* ***Cooling Interventions:*** *CWI = Cold water Immersion.* ***Effects:*** *T_{core} = core body temperature; T_{skin} = skin temperature; HR = heart rate; RPE = rating of perceived exertion; RoF = rating of fatigue; TS = thermal sensation.*

Table 15 (continuation):

Study	Sample	Environmental Parameters	Cooling Strategy	Effects of cooling
Aldous et al., 2019	8 male University-level football players; FSTR	31 °C + 51% T1: Control T2: Ice slurries T3: Ice packs T4: Mixed methods	Ice slurries (-1° C) and ice packs (-14°C) for 30 min pre-exercise and 15 min halftime	•T4 improved performance and reduced T_{core} in halftime 1 (-0.86 °C), no effect in halftime 2 •T2 increased T_{core} at end of halftime 1
Chalmers et al., 2019	12 male well-trained football players; FSTR	30°C WBGT (35°CT and 55% RH) T1: Control T2: DB T3: CB cold drink + ice towel T4: ExtHT	DB: cold drinks CB: ice towles + cold drinks (13 °C); Both: 3 min in-play breaks and HT: ExtHT: 20 min	•T2, T3, and T4 all reduced T_{core}, HR and RPE compared to T1. •no effect on T_{skin} or TS
Zhang et al., 2022	11 male university-level football players; Agility T-test, 20 m Sprint and Yoyo int. end. lvl. 1	40 °C WBGT T1: Control T2: full body CWI T3: legs only CWI	performance tests, then CWI at 15°C for 3 min, then performance tests	• Both CWI protocols improved agility and sprint tests •Whole body CWI improved Yoyo endurance test performance •T_{core}, RPE and HR not effected, only lower T_{skin} and TS reduced
Brown et al., 2024	12 male trained participants; FSTR	32°C WBGT; 40°CT + 41% RH T1: Control T2: Break only T3: CB T4: ExtHT T5: ExtHT + CB	CB: Ice towles + cold drinks (13 °C) for 3 min in-play breaks and HT ExtHT: 20 min	•T2, T3, T4 and T5 reduced T_{core}, at different timepoints compared to T1. •T5 was the most effective followed by T3, then T2 and finally T4 •BML was lower in T3 and T5 due to higher fluid intake, sweat rate was similar •RPE was lower in T3 and T5
Brown et al., 2025	12 female trained participants; FSTR	32°C WBGT; 40°CT + 41% RH T1: Control T2: Break only T3: CB T4: ExtHT T5: ExtHT + CB	CB: Ice towles + cold drinks (13 °C) for 3 min in-play breaks and HT ExtHT: 20 min	• T5 lowered Tcore compared to T1, T2 and T4. •T4 and T5 reduced T_{skin} and TS •BML was lower in T3 and T5 due to higher fluid intake, sweat rate was similar •T2 did not result in any benefits compared to T1
Study 4	40 male, highly trained young football players; 4 football matches	T1: CB in 25 °C WBGT T2: DB in 25 °C WBGT T3: CB in 33 °C WBGT T4: DB in 33 °C WBGT	CB: cold towels (5-7°C) and cold drinks (5°C); DB: passive rest and drink (18°C); both: 10 min pre-warmup, pre-match and halftime and 3 min in-play breaks.	•T1 reduced reduced sweat loss, reduced TS, RPE, RoF compared to T2 •T3 reducedreduced T_{core} sweat loss, reduced TS, RPE, RoF compared to T4 •no effects on running performance or HR

Abbreviations: ***Sample:*** *FSTR: Football simulating treadmill running; Yoyo int. end. lvl.1: Yoyo intermittent endurance level 1.* ***Environmental conditions:*** *T = Temperature; °C = degree Celsius; RH = Relative humidity; % = percentage (RH); WBGT = Wet-bulb globe temperature; M0= Match No.; T0 = Trial No. (same participants performing all trials); G0 = Group No (participants split across conditions); CB = cooling breaks; DB = drinking breaks; Break only = break without fluid consumption; NB = no breaks; ExtHT = extended halftime (20 min)* ***Cooling Interventions:*** *CWI = Cold water Immersion.* ***Effects:*** *T_{core} = core body temperature; T_{skin} = skin temperature; HR = heart rate; RPE = rating of perceived exertion; RoF = rating of fatigue; TS = thermal sensation.*

S4.2 Effects of Pre-Cooling and Cooling Breaks on Thermoregulatory, Physiological and Match Running Responses during Football in Moderate and Hot Temperatures.

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Sports Medicine (Under 2nd Revision)

Abstract

Purpose. This study investigated the effects of pre-cooling and cooling breaks on thermoregulatory, hydration and running responses in football (soccer) players in moderate and hot temperatures. **Methods.** Forty male youth footballers participated in at least two of four matches, during which core body temperature (T_{core}), heart rate (HR), match running, hydration and perceptual responses were measured. Cooling breaks (CB), consisting of ice-cold towels and drinks, were compared to drinking breaks (DB), consisting of passive rest and a temperate drink, applied at the same timeframes. Both were used as pre-cooling for 10 minutes before the warm-up, before the pre-match, during half-time and during additional 3-minute cooling breaks at the 25th minute of each half. Initially, 20 players performed two crossover matches in 25 °C wet bulb globe temperature (WBGT) receiving cooling (CB_{25}) and drinking (DB_{25}). A second group of 20 players played a regular match in 25 °C WBGT with no breaks (NB_{25}) and then a match in 33 °C WBGT during which they received either cooling (CB_{33}) or drinking breaks (DB_{33}). **Results.** In CB_{25}, players felt cooler ($p < 0.001$) and less fatigued ($p < 0.045$) than in DB_{25}, without differences in match running ($p > 0.20$), HR_{mean} ($p > 0.35$) or T_{core} ($p > 0.09$). Players in CB_{25} sweated less ($p = 0.005$) and drank less ($p = 0.002$), resulting in no significant difference in body mass loss compared to DB_{25}. In CB_{33}, players had lower HR_{mean} ($p = 0.007$), similar total distance ($p = 0.21$), lower peak T_{core} ($p < 0.001$) and lower body mass loss ($p = 0.007$), compared to NB_{25}. In DB_{33}, players reduced moderate (12–18 km/h; $p = 0.007$) and

high-speed running distance (18–24 km/h; p = 0.002) but had similar peak T_{core} (p = 0.71) and body mass loss (p=0.95) as in NB_{25}. **Conclusions.** In general, high T_{core} values and body mass losses were observed even when playing in moderate heat. Both drinking and cooling breaks attenuated the continuous T_{core} rise, but using cooling also improved player perceptions in moderate temperatures. In hotter temperatures, cooling breaks further lowered T_{core} and body mass loss compared to using only drinking breaks. German Clinical Trials Register: DRKS00032208.

Introduction

High temperatures are a concern for football (soccer) organizations due to their potential implications for player health and performance (Gouttebarge et al., 2023; Nassis et al., 2024; Schwarz, Duffield, Lu, et al., 2025; Schwarz et al., 2024; Schwarz, Duffield, Novak, et al., 2025). In such temperatures, footballers typically reduce total and high-speed running (Draper et al., 2022; Mohr et al., 2012; Schwarz et al., 2024); likely to mitigate heat strain based on exertion levels (Racinais, Moussay, et al., 2019). Despite this, the physical demands of football remain high under hot conditions, leading to substantial rises in core body temperature (T_{core}). Peak T_{core} values of 39.6 ± 0.3 °C and 39.7 ± 0.1 °C have been reported during matches at 36 °C and 43 °C, respectively, with some players exceeding 40 °C (Mohr et al., 2012; Özgünen et al., 2010). While athletes may tolerate hyperthermia without visible impairments, such high T_{core} values are concerning due to the increased risk of exertional heat illnesses (Maughan et al., 2010). These concerns can range from mild symptoms, such as headaches, cramps, and nausea, to severe exertional heat strokes (Roberts et al., 2023), which is one of the leading causes of exercise-related death among athletes (Racinais et al., 2023).

The best strategies to mitigate excessive heat strain in sports, such as scheduling competitions in cooler conditions (i.e., late evenings) or acclimatizing athletes to heat (Racinais et al., 2023), are often not feasible for football. In professional football, the scheduling of matches is often determined by television contractual obligations, and the congested season schedules rarely allow time to heat

acclimatize for the required durations (> 10 days), though short term heat acclimation or post-exercise heating has been proposed as a possible solution ((Casadio et al., 2017; Chalmers et al., 2014; Pethick et al., 2018)). In amateur settings, rescheduling matches is restricted by the availability of playing grounds and acclimatization may be challenging due to limited financial resources and time constraints of amateur players. Therefore, acute interventions like hydration and cooling strategies or additional breaks per half are proposed (Gouttebarge et al., 2023; Nassis et al., 2024). Football federations have introduced drinking breaks (DB) or cooling breaks (CB) when temperature or wet-bulb globe temperature (WBGT) exceeds specific thresholds. For example, the Fédération Internationale de Football Association (FIFA) mandates 3-min breaks when WBGT exceeds 32 °C (Fédération Internationale de Football Association (FIFA), 2015), while other organizations recommend breaks at 26 °C WBGT (Jones, 2024). In laboratory-based football simulations, additional 3-min breaks per half reduced T_{core} by 0.25 °C (using cold drinks) and 0.28°C (using cold drinks and ice towels) in 35 °C (30 °C WBGT), with no differences between these interventions (Chalmers et al., 2019). Whereas in 40 °C (32 °C WBGT), T_{core} reductions were greater when using cold drinks and ice towels during breaks (-0.39 °C) compared to using breaks without drinks or cooling (-0.28 °C) (Brown et al., 2024). This aligns with evidence that cooling interventions become increasingly effective as heat strain rises (Faulkner et al., 2019). Thus, cooling breaks may well be an effective heat-mitigating strategy in football.

In laboratory-based football simulations, pre-match and half-time cooling, reduced T_{core} by 0.2 - 0.3 °C (Drust et al., 2000; Parris & Tyler, 2018; Price et al., 2009) or 0.6 - 0.9 °C (Aldous et al., 2019; Clarke et al., 2011; Zhang et al., 2014), depending on the cooling dose and duration. Reduced thermal sensation (Clarke et al., 2011; Holm et al., 2018; Zhang et al., 2014) and improved endurance performance (Aldous et al., 2019; Clarke et al., 2011; Zhang et al., 2022; Zhang et al., 2014) were also reported. However, methods like 60-min pre-cooling (Clarke et al., 2011; Drust et al., 2000), full-body cold-water immersions (Azad et al., 2016), frequent fluid intake (Clarke et al., 2011), or wearing ice vests during play (Parris & Tyler, 2018) are impractical for real matches, due to the time and logistical constraints of match days

and the continuous and dynamic nature of the game. Even ice-filled towels (Brown et al., 2024; Chalmers et al., 2019), common in individual sports (Lynch et al., 2018), are logistically challenging for team sports. Although larger cooling doses yield stronger effects (Bongers et al., 2017; Minett et al., 2011), research outcomes need to meet the logistical constraints of football matches. Furthermore, studies omit warm-ups (Chalmers et al., 2019; Clarke et al., 2011; Drust et al., 2000; Price et al., 2009), which are standard match-day elements alongside travel, changing and waiting periods, which are also not incorporated in laboratory studies, thus reducing the transferability of the findings. Finally, heat strain in these laboratory studies remained lower compared to field settings (Mohr et al., 2012; Özgünen et al., 2010), where external motivation (e.g., chasing the ball, scoring) may drive players to sustain high intensities despite the heat. Therefore, field-based observations are needed, replicating match physical demands and the feasibility and applicability of cooling interventions (Bongers et al., 2015).

Only one study has investigated pre-cooling in real football matches in 26 ˚C WBGT (Duffield et al., 2013). It reported that 20 minutes of pre-cooling initially reduced T_{core} by a large effect; however, the effects disappeared after the warm-up. Although no significant effects for improved physical performance were found, moderate effects indicated more total distance was covered when cooling was applied. Nonetheless, reductions in sweat loss, perceived exertion and thermal strain were noted (Duffield et al., 2013). This highlights the challenges of transferring laboratory findings to field settings and underscores the need for repeated cooling throughout the match, though further field-based research is necessary.

This study investigated the effect of pre-cooling and cooling breaks on thermoregulatory, hydration and running responses in footballers in moderate and hot temperatures. The cooling strategy consisting of ice-cold towels and drinks applied pre-match, half-time and during additional 3-minute cooling breaks (CB) was compared to performing passive rest and a temperate drink during drinking breaks (DB) in matches held at 25 °C WBGT and 33 °C WBGT. It was hypothesized that both CB and DB would mitigate the continuous rise in T_{core}, but that CB would reduce the

heat strain more, while increasing match running, hydration status, and perceptual markers compared to DB.

Methods

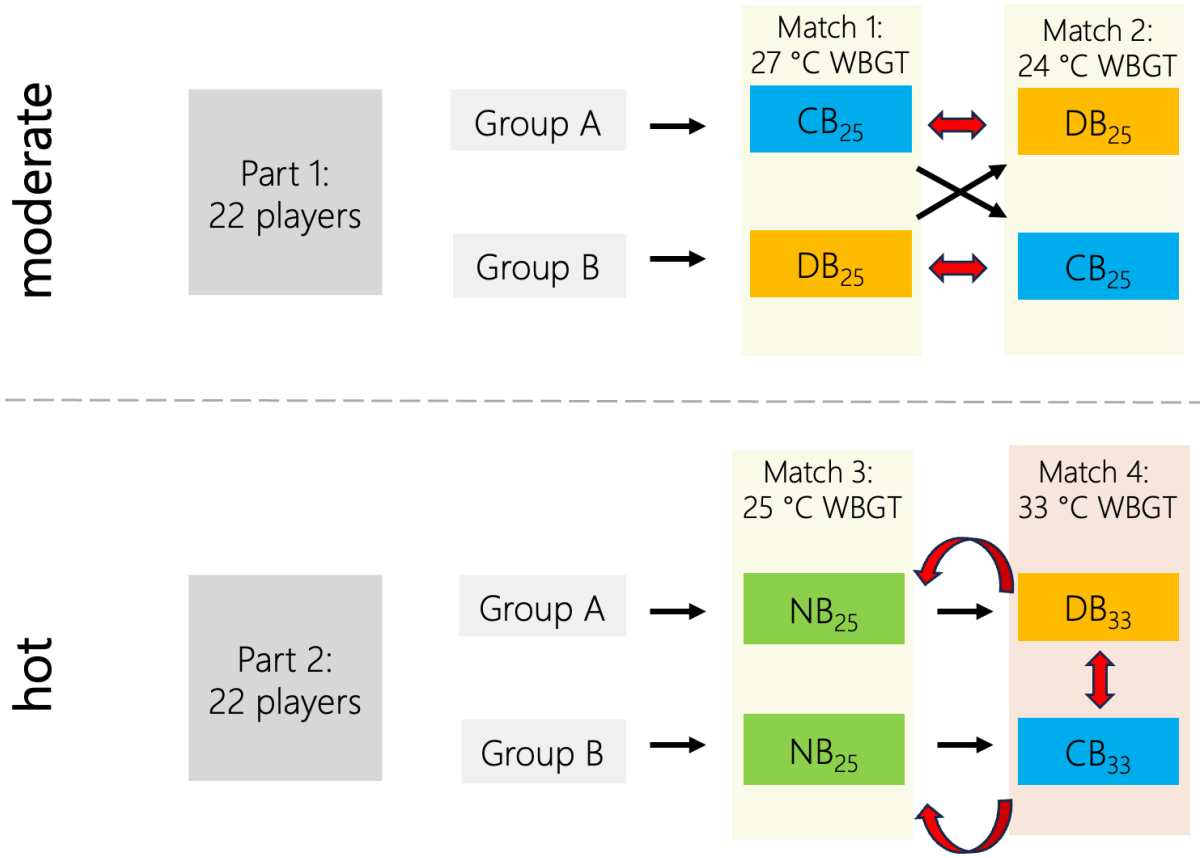
Participants and Study Overview

Forty highly trained (Tier 3; (McKay et al., 2021)) male footballers from a professional Mexican club's youth academy were recruited to participate in this study (goalkeepers excluded). The participants were between 16 and 19 years old, with a weight of 69 ± 6 kg, height of 175 ± 8 cm and BMI of 23 ± 2. Thermoregulatory responses to exercising under heat stress have been shown to be similar in children compared to adults (Smallcombe et al., 2025). Female participants were not included in this study, as only four male-based games were possible to organise for the present study. Future replications of this research, involving female athletes are warranted, as outcomes might differ (Brown et al., 2025). All participants were involved in 3-4 training sessions and 1-2 matches per week. In Monterrey (Mexico), the average daily temperature peaks are 32 °C in May, 35 °C in July, and 32 °C in September. The matches for this study were held in October 2023 (Part 1) and June 2024 (Part 2), thus all participants were seasonally acclimatized, having trained in hot conditions for over two weeks prior to testing. Each player participated in at least one of two distinct data-collections (Part 1 & 2; presented in Figure 9).

In Part 1, 22 participants (aged 17 ± 1 years), played two matches three days apart in an average of 25 °C WBGT (Match 1: 24 °C WBGT; Match 2: 27 °C WBGT) receiving cooling (CB_{25}) or drinking breaks (DB_{25}) in a crossover design. Players were split into pairs of two by the teams' coaches, based on age, body mass, playing position and skill, to then create two teams of similar strength. Participants were then randomized via an online randomiser by one of the researchers into treatment groups, with the condition to distribute treatments equally across teams and positions (i.e. each team had half of the players in CB_{25} during the first match and CB_{25} and DB_{25} had an equal number of defenders, midfielders and attackers). As the goalkeepers were excluded for the analysis and there were two cases of minor injuries, which led to study discontinuation, 18 participants remained for the analysis. Substitutions continued the match for the injured participants but were not included in the data collection. For Part 2, a second group of 22 participants (aged 18 ± 1 years; 4 overlapping with the first

group), was planned to follow the same crossover protocol in hotter conditions and were randomized to groups as described in Part 1. However, due to cooler temperatures than forecasted, Match 3 was held in 25 °C WBGT, the decision was taken to play this as a regular match with no pre-cooling and no cooling breaks (NB_{25}). Match 4 was held in 33 °C WBGT, and the initial randomization was used to distribute players into receive cooling (CB_{33}) or drinking breaks (DB_{33}). Again, goalkeepers were excluded from the analysis leading to a total of 20 participants included in the analysis. Overall, this resulted in 80 individual outfield player observations across four matches. However, for some measurements up to 19 observations had to be excluded retrospectively due to technical issues, such as the 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). The number of valid observations for each measurement is shown in Table 16, alongside the group and environmental conditions. During an initial familiarization session, all study procedures and measurements were explained via a presentation of pictures and infographics. Following this familiarization session, participants provided written informed consent to participate in the study. 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).

Figure 9: Visualization of overall design with two distinct data collections in moderate and hot conditions (the red arrows indicate which groups were compared using linear mixed models).



Abbreviations: (WBGT= wet-bulb globe temperature; CB_{25} = cooling breaks in 25 °C WBGT; DB_{25} = drinking breaks in 25 °C WBGT; NB_{25} = no breaks in 25 °C WBGT; CB_{33} = cooling breaks in 33 °C WBGT; DB_{33} = drinking breaks in 33 °C WBGT).

Table 16: Environmental conditions and the number of players with valid data per condition (missing data was due to injuries, GPS and HR device failures and/or T_{core} pills remaining in the stomach).

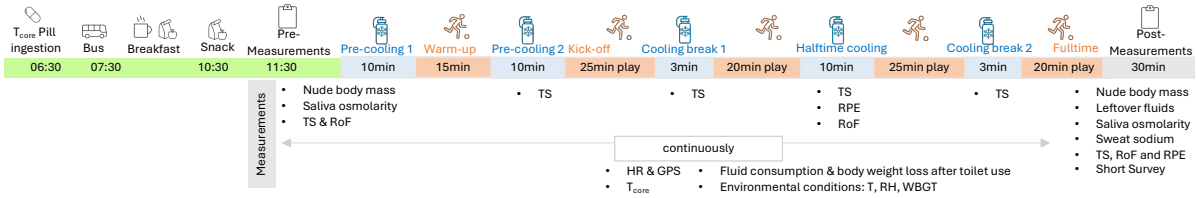
Condition	Match	WBGT	T	RH	n - Total	n - GPS	n - HR	n - T_{core}
DB_{25}	Match1&2	25.5 °C	*28.9* °C	*40.7%*	18	18	16	11
	Match 1	26.9 °C	*29.3* °C	*50.6%*				
	Match 2	24.0 °C	28.4 °C	*30.8%*				
CB_{25}	Match1&2	25.5 °C	*28.9* °C	*40.7%*	18	17	15	13
	Match 1	26.9 °C	*29.3* °C	*50.6%*				
	Match 2	24.0 °C	28.4 °C	*30.8%*				
NB_{25}	Match 3	25.5°C	*26.0* °C	*80.9%*	20	19	19	19
DB_{33}	Match 4	33.0°C	*36.5* °C	42.1%	10	10	10	10
CB_{33}	Match 4	33.0°C	*36.5* °C	42.1%	10	10	10	9

Abbreviations: WBGT = Wet-bulb globe temperature; T = Temperature; RH = Relative Humidity; n-total. = number of overall players per conditions, excluding goalkeepers and injury dropout; n – GPS = number of players with valid running data; n - HR = number of players with valid heart rate data; n - T_{core} = number of players with

Time Schedule and Logistics

For Part 1 (CB_{25} and DB_{25}), participants met at 7:30 am and started a one-hour bus ride to the match venue. Then they received a standardized breakfast (8:30 am), rested and later consumed another standardized snack (11:30 am). Pre-match measurements began at 12:30 pm and were followed by the first 10-min pre-cooling in CB or passive rest in DB (1:15 pm), a 15-min warm-up, the second 10-min pre-cooling in CB or passive rest in DB (1:45 pm), and the match onset (2:00 pm). Matches consisted of two 45 min halves, separated by a 15-min half-time (including 10 min of cooling for CB or drinking for DB), with each half containing an additional 3-min break per half at the 25th and 70th minute where players received CB or DB, except during the NB_{25} condition, where no additional breaks were performed. Post-match measurements started immediately after the match, including nude body mass measurements, downloading T_{core} data, hydration measurements and the collection of the sweat patches. All measurements were completed within 30 min post-match. For Part 2 (NB_{25}, DB_{33} and CB_{33}), the protocol (presented in Figure 10) remained the same but began two hours earlier, with the initial meeting at 5:30am and kick-off at 12:00pm, due to logistical requirements.

Figure 10: Timetable of Match 4, exemplary of an experimental match day.



Abbreviations: (HT= half-time; HR = heart rate; GPS = global positioning system; TS = thermal sensation; RoF = rating of fatigue; RPE = rating of perceived exertion).

During CB, participants received large cold towels (70 x 130 cm) covering the head, neck, shoulders and upper back. These towels, kept in 5-7 °C iced water, were re-dunked in the water after 5 min during each 10-min break and were only minimally wrung out before they were applied, to maximize the coldness of the intervention. Participants were also provided with two individual bottles: one with 500 ml of water and another with 500 ml of a commercial sports drink (Powerade, The Coca-Cola Company, Atlanta, USA), both at 5 °C. Participants were instructed to finish the sports

drink by the 2nd cooling break (70th min) to standardize carbohydrate intake, while water could be consumed and refilled *ad libitum*. During DB, participants performed a passive rest and were given the same fluids at 17 °C. To blind participants to the intervention, the sports drink was mixed with a flavouring and colouring agent (Bebida Frutal, Nature's Factory, Santa Catarina, Mexico) and described as "sports drink" to improve performance in the heat. The researchers performing the data collection were not blinded to the intervention. In the NB_{25} condition, the match started after the warm-up and no mid-half breaks were conducted. Participants received the same drinks at 17 °C and were instructed to finish the sports drink by half-time.

Measurements

Match Running and Heart Rate

All participants were fitted with a global positioning system (GPS) device (WIMU Pro Elite Tracking System, Hudl, Lincoln, USA), validated to measure running in team sports (Muñoz-López et al., 2017) and a heart rate (HR) monitor (Garmin HRM Dual™, Garmin International, Inc., Olathe, USA). Running outcomes were recorded at 100 Hz and reported over the full match and per quarter (Q1: kick-off – pre 1st cooling break; Q2: post 1st cooling break – half-time; Q3: half-time – pre 2nd cooling break; Q4: post 2nd cooling break – full-time). Metrics are presented as "per minute", to reflect time-relative match running and include total distance (TD), moderate-speed running (MSRD: 12 - 18 km/h), high-speed running (HSRD: 18 - 24 km/h) and sprinting (SD: > 24 km/h) distance. HR is presented as peak and mean values for the full match and per playing quarter.

Core Body Temperature

T_{core} was measured continuously every 30 seconds using telemetric pills (eCelcius Performance, BodyCap, Hérouville-Saint-Clair, France), validated for continuous T_{core} monitoring (Koumar et al., 2023). Participants ingested the pills at 7:30 or 8:30 am (Part 1) or 5:30 am (Part 2), allowing at least 4h to pass into the intestines. Participants with unphysiological T_{core} values (<35°C) after drinking, indicating the pill remaining in the stomach, were excluded. T_{core} is presented as overall match peak and peak values at key time points (baseline, post pre-cooling 1, post warm-up, post pre-cooling 2, post play 1 [25 min], post additional break 1, post play 2 [45 min], post half-time break, post play 3 [70 min], post additional break 2, post play 4 [90min]).

Hydration and Fluid Balance

Participant's fluid balance was assessed by measuring nude body mass pre- and post-match, as well as pre- and post-bathroom use (to monitor toilet breaks). After baseline measurements, fluid intake was monitored using individualized bottles, with participants instructed not to spit, spill or shower with water from them and measuring remaining fluid in the bottle post-match. Sweat loss (not corrected for gas exchange) was then calculated accordingly (Cheuvront & Kenefick, 2017):

$$Sweat\ Loss = Weight_{Baseline} - Weight_{Post} + Fluid\ Intake - Urine\ Loss.$$

Saliva osmolarity (SOMS) was measured pre- and post-match using a mobile device (MX3 LAB Pro, MX3 Diagnostics, Austin, USA), which has been shown to be reliable to assess changes in hydration status (Winter et al., 2024). Participants refrained from consuming food or liquid for 15 min prior to the measurement, then swallowed all their saliva, before presenting a freshly produced saliva sample on the tip of their tongue for measurement. Participants were categorized as hydrated (<65 mOsm), mildly dehydrated (65 - 100 mOsm), moderately dehydrated (100 - 150 mOsm) and severely dehydrated (>150 mOsm). These are based on SOSM values reported in literature and distributions across the MX3 costumer population. Participants started with no significant differences in pre-match saliva osmolality (DB_{25}: 61.6 ± 20.1 mOsm; CB_{25}: 62.1 ± 14.1 mOsm; $p = 0.89$; DB_{33}: 63.5 ± 18.4 mOsm; CB_{33}: 69.1 ± 16.9 mOsm; NB_{25}: 69.2 ± 28.0 mOsm; all $p \geq 0.49$).

Perceptual Measures

Rating of Fatigue (RoF) (Micklewright et al., 2017), Rating of Perceived Exertion (RPE; (Borg, 1998) and Thermal Sensation (TS) (Zhang et al., 2010) were recorded (Figure 10). All scales were translated into Spanish, introduced at the familiarization session, and shown to the participants each time they were assessed. Following the match, after players had showered and eaten a post-match meal, they completed a survey on their perceptions of the interventions. This was a shortened and adapted version of an intervention implementation survey (Weiner et al., 2017). Participants were asked to rate how much they liked each intervention on a scale from -5 (did not like it at all) to +5 (liked it very much) and whether they perceived any performance

benefits from -5 (did not perceive performance benefits at all) to +5 (perceived a lot of performance benefits).

Statistical Analyses

A sample size calculation was performed based on the study of Brown et al. (2024). The Cohen f effect size for difference in final T_{core} was 0.32 (DB vs CB) and 0.64 (CB vs NB). Based on these effect sizes, an alpha of 0.05 and power of 0.80, the optimal sample size needed for a cross-over study would be between 11 and 39 per group, to investigate the effect of cooling breaks on T_{core}. The initially planned sample size of 20 participants per group was determined by logistical factors (i.e., number of outfield players in a football match) and was further reduced due to unpredicted environmental conditions and technical issues (outlined earlier) which is a limitation of this study. Values are reported as mean and standard deviation. Due to small and dependent samples, linear mixed models were performed to test group differences, accounting for repeated measures and variability across subjects. Thus, to investigate differences between CB_{25} and DB_{25} linear mixed models with a random effect per participant were used. In total, 32 models were built, one for each outcome measure (running and HR: 5, T_{core}: 13, hydration: 4, perceptions: 10) to investigate differences between conditions in the first sample. CB_{33} and DB_{33}, were compared directly per linear mixed model with a random effect per team. Further, participants in CB_{33} and DB_{33} were also compared to their individual "reference" in NB_{25}, using linear mixed models with a random effect per player. Therefore, three models, one comparing independent samples (CB_{33} - DB_{33}) and two comparing dependent samples (CB_{33} - NB_{25}, DB_{33} - NB_{25}) were built for each of the 32 outcome measures. This design is outlined in Figure 9, with red arrows indicating the groups that were compared with linear mixed models. Model outcomes are reported as estimates and 95% confidence intervals (95%CI), standardized estimates (β) and 95%CI and explained variance (R^2). Effects were categorized as small ($\beta > 0.1$), medium ($\beta > 0.3$) or large ($\beta > 0.5$; (Nieminen, 2022)) and explained variance was categorized as small ($R^2 > 0.01$), medium ($R^2 > 0.09$) or large ($R^2 > 0.25$;(Cohen, 1988)). Significance was set at $\alpha = 0.05$. All analysis and figures were conducted using R (Version 4.4.1) using packages lme4, pwr, jtools, dplyr, ggplot2 & reshape2.

Results

Drinking (DB_{25}) and Cooling Break (CB_{25}) in 25 °C WBGT

Total distance covered was 108.0 ± 8.1 m/min in DB_{25} and 108.5 ± 8.0 m/min in CB_{25} ($p = 0.61$), with no differences observed per playing quarter (all $p \geq 0.25$; Figure 11) or at different speed zones (all $p \geq 0.73$; Table 17).

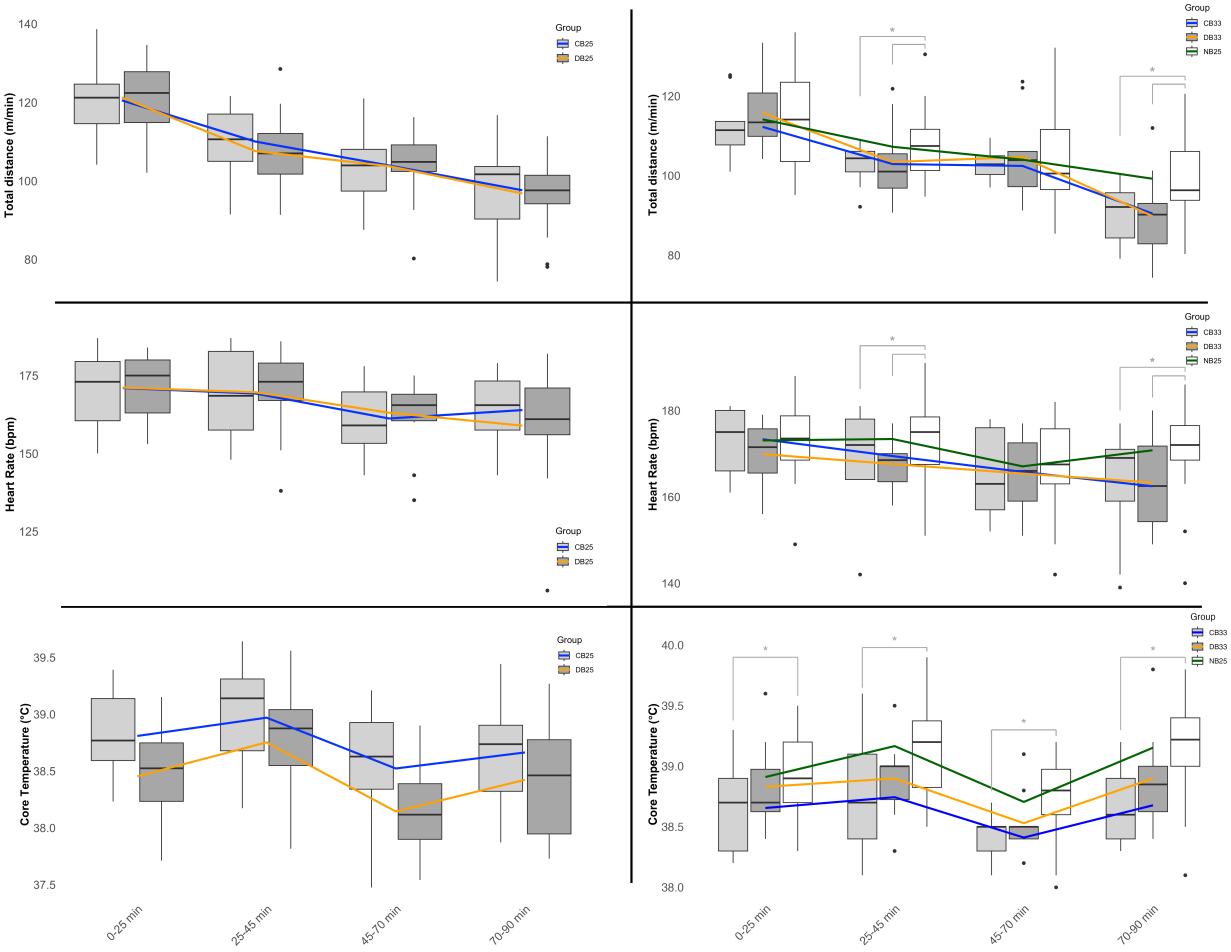
Mean HR during the match was 166 ± 11 bpm in DB_{25} and 166 ± 11 bpm in CB_{25}, with no differences overall ($p = 0.78$) or per playing quarter (all $p \geq 0.35$; Figure 11).

T_{core} did not significantly differ between conditions at any time-point (all $p \geq 0.09$; Figure 12). Resting T_{core} prior to the match was 37.5 ± 0.3 °C in DB_{25} and 37.5 ± 0.3 °C in CB_{25} ($p = 0.96$). Mean T_{core} during the match was 38.4 ± 0.5 °C in DB_{25} and 38.7 ± 0.5 °C in CB_{25} ($p = 0.28$), with no significant differences overall or per playing quarter (all $p \geq 0.15$; Figure 11). Peak T_{core} was 39.1 ± 0.6 °C in DB_{25} and 39.3 ± 0.5 °C in CB_{25} ($p = 0.42$). The mean T_{core} reduction during the additional breaks per half was -0.32 ± 0.2 °C in DB_{25} and -0.37 ± 0.2 °C in CB_{25} ($p = 0.27$).

Post-match saliva osmolarity increased to 89.7 ± 49.0 mOsm in DB_{25} and 78.7 ± 29.7 mOsm in CB_{25} but was not different between the groups ($p=0.43$). Sweat loss was 0.38 L (0.11, 0.66) higher in DB_{25} ($\beta = 0.41$; $R^2 = 0.13$; $p=0.005$) and fluid intake was 0.19 L (0.07, 0.32) higher in DB_{25} ($\beta = 0.43$; $R^2 = 0.10$; $p = 0.002$) compared to CB_{25}. This resulted in a similar body mass loss ($p = 0.69$) (Table 18).

In CB_{25}, participants reported significantly lower RoF ($p = 0.03$), RPE ($p = 0.01$), and TS ($p = 0.001$) compared to DB_{25} (Table 19). The post-match survey showed participants liked and perceived performance benefits from both but favoured (median: +3 vs. +2; $\beta = 0.35$; $R^2 = 0.12$; $p = 0.02$) and perceived greater performance benefits (median: +3 vs. +2; $\beta = 0.41$; $R^2 = 0.17$; $p = 0.01$) from CB_{25}.

*Figure 11: Mean total distance covered, heart rate and T_{core} per playing quarter in each condition (centre line= median; box = interquartile range (IQR); whiskers = smallest and largest values within 1.5 times the IQR; individual points = outliers; * = significant ($p < 0.05$) difference between those two groups).*



Abbreviations: CB25 (blue, light grey) = cooling breaks in 25 °C WBGT; DB25 (orange, dark grey) = drinking breaks in 25 °C WBGT; NB25 (green, white) = no breaks in 25 °C WBGT; CB33 (blue, light grey) = cooling breaks in 33 °C WBGT; DB33 (orange, dark grey) = drinking breaks in 33 °C WBGT.

Drinking (DB_{33}) and Cooling Breaks (CB_{33}) in 33 °C WBGT

Total distance was significantly lower in quarters 2 and 4 for both DB_{33} and CB_{33} compared to NB_{25} (all $p \leq 0.022$; Figure 11), with no significant differences between DB33 and CB33 (all $p \geq 0.40$). However, MSRD and HSRD were reduced in DB_{33}, but not in CB_{33} compared to NB_{25} (Table 17).

Mean HR was 167 ± 8 bpm in DB_{33}, 168 ± 8 bpm in CB_{33}, and 171 ± 10 bpm in NB_{25}. For participants in CB_{33} this was significantly lower compared to their values in NB_{25} ($\beta = 0.53$; $R^2 = 0.04$; $p = 0.007$), but no significant difference was observed in DB_{33} ($\beta = 0.16$; $R^2 = 0.01$; $p = 0.51$) (Figure 11).

Table 17: Running Performance in Part 1 comparing cooling (CB_{25}) compared to drinking breaks (DB_{25}) in 25 °C WBGT and Part 2 comparing cooling (CB_{33}) and drinking breaks (DB_{33}) in 33 °C WBGT to no breaks (NB_{25}) in 25 °C WBGT.

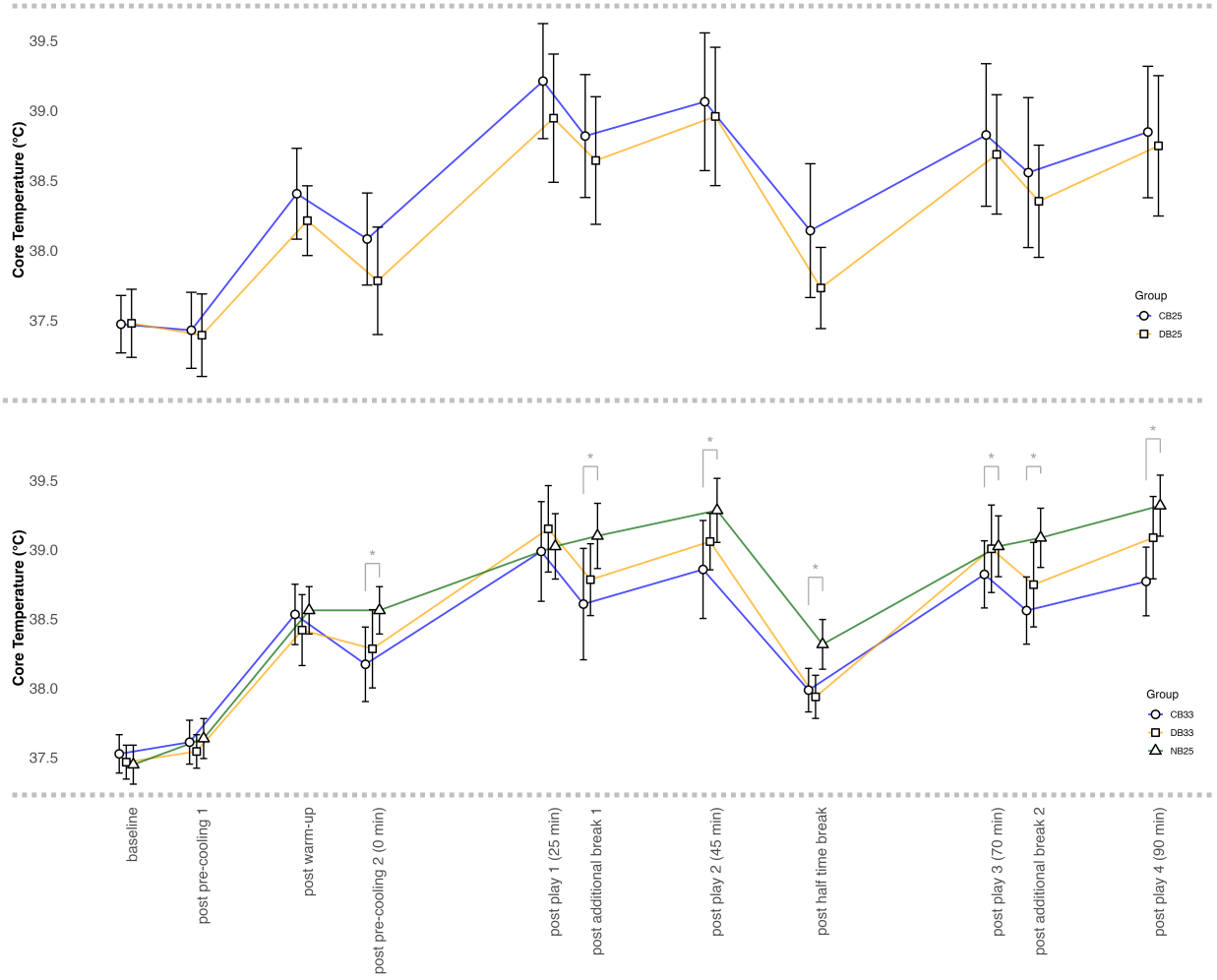
	Mean(SD)				Estimate(95%CI)	β(95%CI)	R^2 marg.	p-value
Part 1	***CB_{25}***		***DB_{25}***					
Total (m/min)	108.5(8.0)		108.0(8.1)	CB_{25}-DB_{25}	-0.5(-2.3, 1.4)	-0.1(-0.5, 0.3)	0.00	0.61
Moderate speed (m/min)	25.6(5.5)		25.5(6.4)	CB_{25}-DB_{25}	-0.1(-1.7, 1.5)	-0.0(-0.4, 0.4)	0.00	0.90
High speed (m/min)	7.9(2.8)		7.7(2.5)	CB_{25}-DB_{25}	-0.2(-1.3, 0.9)	-0.1(-0.4, 0.3)	0.00	0.73
Sprint (m/min)	1.6(1.2)		1.6(1.0)	CB_{25}-DB_{25}	-0.0(-0.5, 0.5)	0.0(-0.4, 0.4)	0.00	0.98
Part 2	***CB_{33}***	***DB_{33}***	***NB_{25}***					
Total (m/min)	102.7 (4.5)	104.3 (9.9)	106.5 (9.9)	CB_{33}-DB_{33}	1.6(-5.5, 8.7)	0.1(-0.4, 0.6)	0.01	0.66
				DB_{33}-NB_{25}	2.7(-0.6, 5.9)	0.4(-0.1, 0.8)	0.01	0.13
				CB_{33}-NB_{25}	2.7(-1.2, 6.8)	0.3(-0.3, 0.9)	0.05	0.21
Moderate speed (m/min)	20.4 (2.5)	20.3 (5.1)	23.1 (5.8)	CB_{33}-DB_{33}	-0.1(-3.7, 3.6)	-0.0(-0.5, 0.5)	0.00	0.96
				DB_{33}-NB_{25}	3.5(0.8, 6.1)	0.5(0.1, 0.9)	0.08	0.007*
				CB_{33}-NB_{25}	1.8(-0.6, 4.3)	0.4(-0.2, 0.9)	0.07	0.16
High speed (m/min)	5.5 (1.64)	6.0 (1.93)	6.8 (2.19)	CB_{33}-DB_{33}	0.5 (-1.1, 2.1)	0.1(-0.4, 0.7)	0.02	0.57
				DB_{33}-NB_{25}	1.3(0.3, 2.3)	0.5(0.1, 0.9)	0.09	0.02*
				CB_{33}-NB_{25}	0.7(-0.9, 2.3)	0.2(-0.3, 0.8)	0.04	0.38
Sprint (m/min)	1.2 (0.5)	1.2 (0.8)	1.1 (0.9)	CB_{33}-DB_{33}	0.0(-0.6, 0.6)	0.0(-0.5, 0.5)	0.00	0.94
				DB_{33}-NB_{25}	-0.1(-0.4, 0.2)	-0.2(-0.7, 0.4)	0.00	0.52
				CB_{33}-NB_{25}	-0.2(-1.0, 0.6)	-0.1(-0.7, 0.4)	0.01	0.67

Abbreviations: SD = Standard Deviation; CI = Confidence Interval; β = Standardized Estimate; R^2 marg. = Explained Variance of the fixed effects; m/min= meters per minute; Total = total distance covered; Running = distance covered 12-18 km/h; High-speed running = distance covered 18.1-24km/h; Sprint = distance covered above 24km/h.

Resting T_{core} was similar across all conditions (DB_{33}: 37.5 ± 0.2 °C; CB_{33}: 37.5 ± 0.2 °C; NB_{25}: 37.4 ± 0.3 °C; all p ≥ 0.25). Mean T_{core} in CB_{33} was 38.6 ± 0.3 °C, which was significantly lower than in NB_{25} (-0.31(0.14, 0.49) °C; β = 0.59, R^2 = 0.16; p < 0.001). The participants in DB_{33}, recorded a mean T_{core} of 38.7 ± 0.4 °C, which was not significantly lower compared to their mean T_{core} in NB_{25} (-0.14(-0.16, 0.43) °C; β = 0.22, R^2 = 0.04; p=0.36). Peak T_{core} in CB_{33} was 39.1 ± 0.5 °C, significantly lower by 0.30 °C (0.14, 0.47) compared to the 39.4 ± 0.4 °C in NB_{25} (β = 0.60, R^2 = 0.12; p < 0.001). In DB_{33}, peak T_{core} was 39.3 ± 0.3 °C, not different to NB_{25} (β = 0.09, R^2 = 0.00; p = 0.71). Direct comparison of DB_{33} and CB_{33} showed no significant difference in mean T_{core} (p = 0.33) or peak T_{core} (p = 0.23). Mean T_{core} per playing quarter is presented in Figure 11 and T_{core} development throughout the match is visualized in Figure 12. T_{core} was significantly lower in CB_{33} than NB_{25} from kick-off to full-time (all p < 0.001), except at the start of the first cooling break (p = 0.98). At full-time T_{core} was 0.62 °C (0.42, 0.83) lower in CB_{33} compared to what these participants reached in

NB_{25} (β = 0.69; R^2 = 0.48; $p < 0.001$) and 0.32 °C (-0.02, 0.65) lower compared to participants in DB_{33}, though this difference was not significant (β = 0.41; R^2 = 0.16; p = 0.08). The mean T_{core} drop during the 3-minutecooling and drinking breaks was similar between DB_{33} (0.31 ± 0.2 °C) and CB_{33} (0.32 ± 0.2 °C; $p \geq 0.76$). However, during the second pre-cooling break, T_{core} dropped by -0.4 ± 0.2 °C in CB_{33}, which was 0.23 °C (0.00, 0.45) greater than the -0.1 ± 0.3 °C drop in DB_{33} (β = -0.43; R^2 = 0.18; p = 0.049).

*Figure 12: T_{core} peaks at specific time-points throughout the match day for each condition (circle, square, triangle = group mean; whiskers = 95% confidence intervals; lines = connecting the means representing the mean change over that period; * = significant ($p < 0.05$) difference; all significant differences were players in CB_{33} remaining a lower T_{core} to what these players had achieved in NB_{25}).*



Abbreviations: CB25 (blue, circle) = cooling breaks in 25 °C WBGT; DB25 (orange, square) = drinking breaks in 25 °C WBGT; NB25 (green, triangle) = no breaks in 25 °C WBGT; CB33 (blue, circle) = cooling breaks in 33 °C WBGT; DB33 (orange, square) = drinking breaks in 33 °C WBGT.

Post-match saliva osmolarity increased to 129.3 ± 39.7 mOsm in DB_{33} and 117.7 ± 50.3 in CB_{33}, with a significantly higher increase in DB_{33} ($p = 0.047$) but not CB_{33} ($p = 0.33$) compared to NB_{25} (110.9 ± 30.5 mOsm). Sweat loss was higher in CB_{33} ($p = 0.02$) and DB_{33} ($p < 0.001$) compared to NB_{25}, but fluid intake was also greater in CB_{33} ($p < 0.001$) and DB_{33} ($p < 0.001$; Table 18). This resulted in a significantly lower body mass loss in CB_{33} ($p = 0.007$) but not DB_{33} ($p = 0.95$) and a significantly bigger change in saliva osmolarity in DB_{33} ($p = 0.01$), but not CB_{33} ($p = 0.11$; Table 3).

Significant differences in RoF, RPE and TS are presented in Table 19. Direct comparison between DB_{33} and CB_{33} showed lower TS in CB_{33} from half-time to full-time (all $p < 0.05$). Participants rated to like both CB_{33} and DB_{33} highly (median: +4) and perceived performance benefits from CB_{33} (median: +3) and DB_{33} (median: +2), with no significant differences between the conditions.

Table 18: Hydration Markers in Part 1 comparing cooling (CB_{25}) compared to drinking breaks (DB_{25}) in 25 °C WBGT and Part 2 comparing cooling (CB_{33}) and drinking breaks (DB_{33}) in 33 °C WBGT to no breaks (NB_{25}) in 25 °C WBGT.

	Mean(SD)				Estimate(95%CI)	β(95%CI)	R^2 marg.	p-value
Part 1	***CB_{25}***		***DB_{25}***					
Sweat loss (L)	2.7 (0.4)		3.0 (0.6)	CB_{25}-DB_{25}	0.4(0.1, 0.7)	0.4(0.1, 0.7)	0.13	0.005*
Fluid intake (L)	1.2 (0.3)		1.4 (0.3)	CB_{25}-DB_{25}	0.2(0.1, 0.37)	0.4(0.1, 0.7)	0.10	0.0018*
Δ Body mass (%)	-2.1 (0.5)		-2.2 (1.2)	CB_{25}-DB_{25}	0.1(-0.4, 0.6)	0.1(-0.3, 0.4)	0.00	0.69
Δ SOSM (mOsm)	20.4 (33.4)		33.2 (49.5)	CB_{25}-DB_{25}	11.6(-16.7, 39.8)	0.1(-0.2, 0.5)	0.02	0.43
Part 2	***CB_{33}***	***DB_{33}***	***NB_{25}***					
Sweat loss (L)	3.0 (0.7)	3.7 (0.6)	2.7 (0.7)	CB_{33}-DB_{33}	0.7(0.2, 1.2)	0.5(0.1, 1.0)	0.19	0.006*
				DB_{33}-NB_{25}	-0.9(-1.5, -0.4)	-0.6(-1.0, -0.2)	0.34	<0.001*
				CB_{33}-NB_{25}	-0.4(-0.8, -0.1)	-0.5(-0.9, -0.0)	0.09	0.02*
Fluid intake (L)	- 1.7 (0.3)	- 2.1 (0.7)	- 1.1 (0.3)	CB_{33}-DB_{33}	0.4(-0.0, 0.9)	0.4(-0.1, 0.9)	0.15	0.06
				DB_{33}-NB_{25}	-1.0(-1.4, -0.6)	-0.7(-1.1, -0.4)	0.51	<0.001*
				CB_{33}-NB_{25}	-0.7(-0.9, -0.5)	-0.8(-1.1, -0.5)	0.62	<0.001*
Δ Body mass (%)	- 2.0 (0.8)	- 2.4 (1.1)	- 2.5 (0.8)	CB_{33}-DB_{33}	0.4(-0.4, 1.1)	0.2(-0.3, 0.7)	0.04	0.32
				DB_{33}-NB_{25}	-0.0(-0.9, 0.9)	-0.0(-0.5, 0.5)	0.00	0.95
				CB_{33}-NB_{25}	0.5(0.1, 0.9)	0.5(0.1, 0.9)	0.12	0.007*
Δ SOSM (mOsm)	48.6 (45.3)	65.8 (29.6)	28.6 (28.8)	CB_{33}-DB_{33}	17.2(-16.2, 50.6)	0.2(-0.3, 0.7)	0.05	0.33
				DB_{33}-NB_{25}	-25.7(-47.2, -5.4)	-0.5(-0.9, -0.1)	0.17	0.01*
				CB_{33}-NB_{25}	-29.9(-63.6, 3.6)	-0.4(-0.9, 0.1)	0.14	0.11

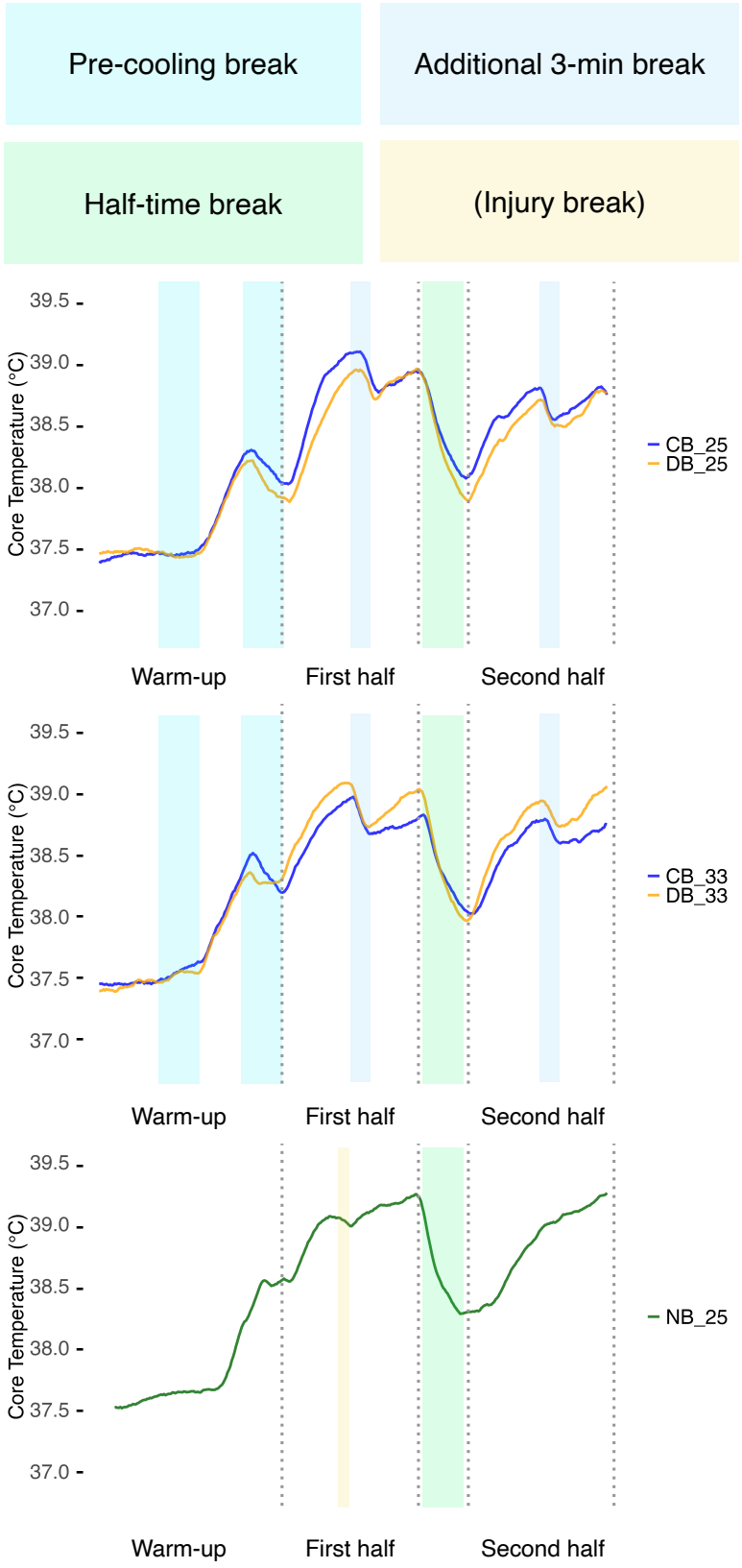
Abbreviations: SD = Standard Deviation; CI = Confidence Interval; β = Standardized Estimate; R^2 marg. = Explained Variance of the fixed effects; l = Liter; Δ = change; SOSM = Saliva Osmolarity; mOsm = milliosmole.

Table 19: Perceptual Markers in Part 1 comparing cooling (CB_{25}) compared to drinking breaks (DB_{25}) in 25 °C WBGT and Part 2 comparing cooling (CB_{33}) and drinking breaks (DB_{33}) in 33 °C WBGT to no breaks (NB_{25}) in 25 °C WBGT.

	Mean(SD)				Estimate(95%CI)	β(95%CI)	R^2 marg.	p-value
Part 1	***CB_{25}***	***DB_{25}***						
RoF half-time	3.8(1.2)	4.7(1.5)	CB_{25}-DB_{25}		0.9(0.1 - 1.8)	0.3(0.0 - 0.7)	0.11	0.029*
RoF full-time	5.8(1.3)	6.3(1.3)	CB_{25}-DB_{25}		0.5(0.1 - 0.9)	0.4(0.0 -0.7)	0.04	0.045*
RPE half-time 1	3.8(1.2)	4.7(1.4)	CB_{25}-DB_{25}		0.8(0.2 - 1.5)	0.4(0.1 - 0.7)	0.09	0.006*
RPE half-time 2	5.4(1.4)	5.9(1.3)	CB_{25}-DB_{25}		0.4(-0.2 - 1.1)	0.2(-0.1 - 0.6)	0.03	0.19
TS pre-match	0.2(1.7)	0.2(1.7)	CB_{25}-DB_{25}		0.0(0.0 - 0.0)	0.0(-0.6 - 0.6)	0.00	1.0
TS kick-off	-1.7(1.0)	0.9(1.4)	CB_{25}-DB_{25}		2.7(1.9 - 3.5)	0.8(0.5 - 1.0)	0.50	<0.001*
TS half-time	0.0(1.4)	2.3(1.3)	CB_{25}-DB_{25}		2.3(1.5 - 3.1)	0.7(0.4 - 0.9)	0.43	<0.001*
TS full-time	1.3(1.6)	1.9(1.4)	CB_{25}-DB_{25}		0.7(-0.2 - 1.5)	0.3(-0.1 - 0.6)	0.05	0.13
Part 2	***CB_{33}***	***DB_{33}***	***NB_{25}***					
RoF half-time	6.1 (0.3)	5.9 (0.9)	4.6 (1.4)	CB_{33}-DB_{33}	-0.2(-0.8 - 0.4)	-0.2(-0.7 - 0.3)	0.02	0.51
				DB_{33}-NB_{25}	-1.3(-2.2 - -0.4)	-0.5(-0.9 - -0.1)	0.18	0.002*
				CB_{33}-NB_{25}	-1.6(-2.2 - -1.0)	-0.8(-1.1 - -0.4)	0.56	<0.001*
RoF full-time	8.0 (1.3)	8.7 (0.7)	7.9 (1.1)	CB_{33}-DB_{33}	0.7(-0.2 - 1.6)	0.4(-0.1 - 0.8)	0.11	0.14
				DB_{33}-NB_{25}	-1.1(-1.8 - -0.5)	-0.6(-0.9 - -0.2)	0.24	<0.001*
				CB_{33}-NB_{25}	0.2(-0.2 - 0.6)	0.2(-0.3 - 0.8)	0.01	0.34
RPE half-time 1	5.4 (1.1)	5.3 (1.6)	4.2 (1.6)	CB_{33}-DB_{33}	-0.1(-1.3 - 1.1)	-0.0(-0.5 - 0.5)	0.00	0.87
				DB_{33}-NB_{25}	-1.1(-2.7 - 0.5)	-0.3(-0.8 - 0.2)	0.08	0.21
				CB_{33}-NB_{25}	-1.2(-1.9 - -0.5)	-0.5(-0.9 - -0.2)	0.25	<0.001*
RPE half-time 2	8.1 (1.7)	7.8 (1.1)	7.5 (1.7)	CB_{33}-DB_{33}	-0.3(-1.6 - 1.0)	-0.1(-0.6 - 0.4)	0.01	0.65
				DB_{33}-NB_{25}	-0.5(-1.9 - 0.9)	-0.2(-0.7 - 0.4)	0.03	0.49
				CB_{33}-NB_{25}	-0.4(-1.2 - 0.4)	-0.2(-0.8 - 0.3)	0.02	0.34
TS pre-match	2.7 (1.2)	2.6 (0.7)	1.5 (1.2)	CB_{33}-DB_{33}	-0.1(-0.9 - 0.7)	-0.1(-0.6 - 0.4)	0.00	0.82
				DB_{33}-NB_{25}	-0.8(-1.5 - -1.1)	-0.5(-0.9 - 0.0)	0.20	0.014*
				CB_{33}-NB_{25}	-1.6(-2.2 - -1.1)	-0.7(-0.9 - -0.4)	0.31	<0.001*
TS kick-off	2.6 (1.1)	3.2 (0.4)	1.8 (0.9)	CB_{33}-DB_{33}	0.6(-0.1 - 1.3)	0.4(-0.1 - 0.8)	0.12	0.12
				DB_{33}-NB_{25}	-1.8(-2.3 - -1.3)	-0.9(-1.1 - -0.6)	0.72	<0.001*
				CB_{33}-NB_{25}	-0.5(-1.4 - 0.4)	-0.3(-0.7 - 0.2)	0.06	0.27
TS half-time	3.3 (0.7)	3.8 (0.4)	1.2 (1.7)	CB_{33}-DB_{33}	0.5(0.0 - 1.0)	0.4(-0.0 - 0.9)	0.17	0.04*
				DB_{33}-NB_{25}	-2.4(-3.1 - -1.7)	-0.8(-1.0 - - 0.5)	0.60	<0.001*
				CB_{33}-NB_{25}	-2.4(-3.7 - -1.1)	-0.6(-1.0 - -0.3)	0.40	<0.001*
TS full-time	3.0 (0.8)	3.9 (0.3)	2.0 (1.8)	CB_{33}-DB_{33}	0.9(0.4 - 1.4)	0.6(0.2 - 1.0)	0.36	0.0012*
				DB_{33}-NB_{25}	-1.8(-2.8 - -0.8)	-0.6(-1.0 - 0.2)	0.39	<0.001*
				CB_{33}-NB_{25}	-1.2(-2.3 - -0.2)	-0.5(-0.9 - -0.0)	0.14	0.02*

Abbreviations: SD = Standard Deviation; CI = Confidence Interval; β = Standardized Estimate; R^2 marg. = Explained Variance of the fixed effects; RoF = Rating of Fatigue; RPE = Rating of Perceived Exertion; TS = thermal sensation.

Figure 13: Continuous mean T_{core} for each condition, with coloured highlights indicating when breaks took place (supplementary figure for Study 4).



Abbreviations: CB_25 (blue) = cooling breaks in 25 °C WBGT; DB_25 (orange) = drinking breaks in 25 °C WBGT; NB_25 (green) = no breaks in 25 °C WBGT; CB_33 (blue) = cooling breaks in 33 °C WBGT; DB_33 (orange) = drinking breaks in 33 °C WBGT).

Discussion

This study investigated the effects of cooling (CB) and drinking breaks (DB) on thermoregulatory, physiological and perceptual responses in 40 highly trained male youth footballers during four matches played at 25 °C and 33 °C WBGT. This field-based evidence shows how pre-cooling and additional breaks per half mitigate the continuous rise in T_{core}, suggesting their utility for managing heat strain in footballers. Adding ice-cold drinks and towels during breaks reduced perceptual strain and sweat loss in milder conditions and further limited the T_{core} rise in hotter environments.

Match running did not differ between DB and CB in 25 °C WBGT. In 33 °C WBGT, total distance and mean HR were reduced in the second and fourth quarters for both DB_{33} and CB_{33} compared to NB_{25}. This indicates participants adjusted workloads to manage heat strain, consistent with previous research (Draper et al., 2022; Schwarz et al., 2024). However, participants in DB_{33} reduced MSRD (12 - 18 km/h) and HSRD (18 - 24 km/h) compared to NB_{25}, whereas players in CB_{33} maintained these, suggesting benefits from the cooling intervention in 33 °C WBGT. This may be linked to the lower T_{core}, but also the lower thermal sensations observed in CB_{33}, as previous research has shown that skin temperature and thermal perception can influence exercise intensity in the heat (Schlader et al., 2011).

Despite a ~10.5 °C difference in ambient temperature and ~8 °C WBGT across matches, participants reached similar peak T_{core} values, with most (n = 43) exceeding 39.0 °C and some (n = 17) exceeding 39.5 °C. The highest mean T_{core} peak, was observed in NB_{25}, including one participant exceeding 40 °C, potentially due to the more continuous running in the match without breaks. This indicates tolerable, but substantial heat strain even at 25 °C WBGT in a match without breaks for seasonally acclimatized participants. Similar peak T_{core} values in 25 °C and 33 °C WBGT may reflect the reduced running distances in 33 °C WBGT, underscoring the interplay between workload and thermal strain in football (Duffield et al., 2009; Duffield et al., 2012). This further enforces that heat strain, i.e. T_{core}, and the risk of heat illnesses, are related to the exertion levels (i.e., running demands) and not environmental

conditions alone (Duffield et al., 2009; Epstein et al., 1999; Racinais, Moussay, et al., 2019).

The initial pre-cooling had no immediate effect on T_{core}, but the second pre-cooling lowered T_{core} at kick-off by ~0.3 °C, suggesting that reducing warm-up time and allowing for a break before starting the match, may be beneficial to increase heat storage capacity, as proposed in previous research (Nassis et al., 2024; Racinais et al., 2023). During the additional 3-min breaks, regardless of the environment and whether DB or CB was applied, mean T_{core} reduced by ~0.1 °C per minute, consistent with laboratory findings (Brown et al., 2024; Chalmers et al., 2019). However, overall heat strain in our study was higher and more comparable to field-based research (Mohr et al., 2012; Özgünen et al., 2010) than in laboratory conditions with pre-break T_{core} of ~38 °C (Chalmers et al., 2019) or ~38.5 °C (Brown et al., 2024). The continuous T_{core} rise observed in NB_{25} and previous field studies (Mohr et al., 2012; Özgünen et al., 2010), was attenuated, when breaks were implemented, suggesting benefits even in milder heat (25 °C WBGT). FIFA's cooling break is scheduled at the 30th minute of each half, which is based on research showing peak T_{core} occurs around this time (Chalmers et al., 2019; Özgünen et al., 2010). Though, if peaks occur around the 30th minute, a break should precede this to prevent high T_{core} peaks. Therefore, in this study, breaks were held at the 25th minute. Since T_{core} did not exceed pre-break levels by the end of each half, this timing appears effective. The continuous mean T_{core} per group can be seen in Figure 13.

Adding ice-cold drinks (5 °C) and towels (5-7 °C) during breaks reduced perceptual strain and thermal sensation in milder heat and effectively lowered T_{core} in severe heat compared to drinking cool beverages (17 °C) alone. This aligns with research showing that cooling interventions are more effective in higher heat strain (Wegmann et al., 2012). However, individual factors, such as fitness level, acclimatization, and health status, co-determine heat strain; thus, cooling effectiveness might vary between players and across days (Bernard et al., 2024). Cooling strategies should therefore be tailored to individual player needs (and team resources) (Racinais et al., 2023).

Sweat loss and body mass changes were high across all conditions, with 29 players losing over 3 L, 5 exceeding 4 L, 40 losing more than 2%, and 10 more than 3% of body mass in one match. Existing literature shows that a dehydration > 2% impairs athletic performance, with endurance tasks being most affected (Cheuvront & Kenefick, 2014). Breaks provided hydration opportunities, facilitating greater fluid intake compared to the match without breaks. Cooling during breaks reduced sweat loss, potentially linked to a decreased thermoregulatory drive (Heydenreich et al., 2023). However, reduced sweating may have limited evaporative cooling, possibly explaining the lack of T_{core} differences between CB_{25} and DB_{25}. In DB_{25}, players matched higher sweat loss with increased fluid intake, maintaining body mass losses similar to CB_{25}. This could suggest participants regulated fluid intake in response to the higher sweat loss. Although a similar outcome existed in 33 °C participants in DB_{33} were not able to offset the higher sweat loss completely, leading to a higher body mass loss in DB_{33} compared to participants in CB_{33}, potentially due to the sweat loss difference being too high to compensate with sufficient fluid intake. Notably, 64% of players began matches hypoydrated (saliva osmolarity >65 mOsm). Although these categorizations are based on unpublished data and company thresholds (MX3) this is consistent with previous findings (Williams & Blackwell, 2012). This is of particular concern, as hypohydration impairs the sweat response, reducing heat dissipation, thus increasing the heat strain (Périard et al., 2021). This was confirmed in a study using football simulating treadmill running in hot conditions, were higher HR and T_{core} were observed in hypohydrated compared to euhydrated participants (Benjamin et al., 2021). Given the importance of hydration for performance, thermoregulation and preventing heat-related issues, educating players and stakeholders on proper hydration strategies seems essential (Maughan et al., 2010; Racinais et al., 2023; Roberts et al., 2023).

Perceptual markers, including RoF and TS, were higher in 33 °C WBGT, confirming environmental stress as a key driver of perceived fatigue (Stevens et al., 2018). Cooling reduced the RoF and TS in CB_{25} vs. DB_{25} and in CB_{33} vs. DB_{33}, demonstrating perceptual benefits even when T_{core} remained unchanged under lower heat stress. This is noteworthy, as interventions reducing thermal sensation, even if

not affecting T_{core} or T_{skin}, have been linked to improved performance (Stevens et al., 2018). In line with this, participants reported liking the cooling interventions highly and perceiving performance benefits in both 25 °C and 33 °C WBGT.

While this study provides novel outcomes in ecologically valid environments, several limitations should be noted. Missing T_{core} data, especially in the first sample (due to pills remaining in the stomach) reduced the initially planned sample size. The use of a different group in the second sample limited direct comparisons of DB_{25} and CB_{25} to NB_{25}, DB_{33} and CB_{33}. Unpredicted weather events led to a decision to adjust the study protocol in the third match. As a result, the two initially planned crossovers were not feasible, and it decreased the sample size per group in the second part of the data collection. Additionally, the high relative humidity in NB25 should be considered, as WBGT is known to underestimate heat stress in humid conditions (Budd, 2008). The participants were seasonally acclimatized by having exercised in high temperatures for two weeks prior to the study, as well as throughout their football careers in a country with high average temperatures. As acclimatization reduces heat strain, cooling interventions are expected to be more beneficial for non-acclimatized players (Bernard et al., 2024). Due to team availability, this study only included male youth players, however, it was shown that no relevant differences exist in the response to exercising under heat stress between children and adults and heat policies may therefore be transferable (Smallcombe et al., 2025). Certainly, sex alone is not necessarily affecting the response to heat stress but differences between aerobic capacity and surface area-to-mass ratio between men and women might result in different physiological responses to heat stress (Convit et al., 2024; Kenney, 1985). In football simulating treadmill running, cooling breaks were less effective in females compared to men (Brown et al., 2025; Brown et al., 2024). Therefore, a replication with female players is needed. To summarize, small sample sizes, particularly in subgroup analyses, limit the generalizability of these findings. Future research should replicate this novel field-based approach with other cohorts and focus on (alternative) practical cooling strategies.

Practical Implications

The findings suggest that pre-cooling strategies, such as an extended rest post-warm-up, are simple and effective for reducing initial heat strain. Additional 3-min cooling or drinking breaks can mitigate the continuous rise in T_{core}, and may prevent potentially dangerous T_{core} peaks even in moderate heat. The presented outcomes suggest an implementation of the breaks at the 25th minute, opposing recommendations of introducing breaks around the 30th minute. Incorporating cooling strategies during breaks may enhances player comfort in moderate ambient conditions and further reduces heat strain and sweat loss in severe heat. Drinking breaks facilitated greater fluid intake while cooling breaks reduced sweat loss. Hydration monitoring and education are essential, as players' pre-match hydration status was often suboptimal, and sweat loss and dehydration during matches were high.

Future Research

The findings of the study highlight the need for further applied investigations of match day cooling strategies in football. This study should be replicated with other cohorts such as females, adults and unacclimatized players in both elite and amateur settings. Additionally, to identify optimal break structures, different cooling break and half-time durations should be examined. Furthermore, higher cooling doses could be tested, such as the use of ice vest during warm-ups or more aggressive cooling during half-time, as these methods might be feasible in elite settings. However, it remains at least equally important to consider practical approaches for lower-competition settings, which may be more affected by high temperatures and have less medical support.

Conclusions

In conclusion, pre-cooling and additional 3-min breaks per half, with or without cooling, mitigate the otherwise continuous T_{core} rise during football matches in moderate and high heat. Cooling reduced perceptual fatigue and thermal sensation in moderate temperatures and may further minimize the T_{core} rise and dehydration in hotter conditions. These findings support the implementation of additional 3-min breaks in football and highlight the potential benefits of cooling strategies.

Study 5: Core Temperatures responses during Football Matches in the Heat

S5.1 Introduction and Literature Summary

When exercising in elevated temperatures, athletes may develop a high T_{core} and increased risk of developing an exertional heat illness. Recently it has been shown that this does not necessarily lead to negative health implications, and that athletes can even perform at a high level with a T_{core} above 40 °C (Singh et al., 2023). Nevertheless, as the exact pathways, when and why exertional heat illnesses develop, remain elusive, such high heat strains remain a risk for athletes' health and safety (Epstein & Yanovich, 2019; Périard et al., 2022). Therefore, it is of importance to explore which factors are associated with the development of a high T_{core}.

Only four studies (see Table 20) have investigated T_{core} developments during actual football matches. Edwards and Clark (2006) presented an initial observation of eight recreational, compared to seven professional male soccer players. The recreational match was held in 16 °C T and 47% RH, compared to the professional match in 19 °C T and 53% RH. The peak T_{core} recorded in the recreational players was 38.5 ± 0.6 °C and in the professionals 39.3 ± 0.5 °C, both times in the first half of play. Özgünen et al. (2010) investigated eleven semi-professional male players in two experimental matches. One was held 34 °C T and 38% RH and the other 36 °C T and 61% RH. During the first, they found a mean peak T_{core} of 39.1 ± 0.4 °C and in the second 39.6 ± 0.3 °C, with the highest observation recorded at 40.2 °C. Mohr et al. (2012) investigated seventeen elite male players during one experimental match at 21°C T and 55% RH and the other at 43 °C T and 12% RH. They found mean T_{core} peaks of 38.7 ± 2 °C in the first and 39.6 ± 1 °C in the second match. Finally, Duffield et al. (2013) investigated seven elite male players in actual Australian A-league competition. With an average environmental temperature of 27 ± 2 °C T, 80 ± 10% RH and 26 ± 2 °C WBGT, they found mean T_{core} peaks of 39.9 ± 0.4 °C.

These investigations show that a high T_{core} can develop throughout the match, but none of these studies explored associations between other factors such as the running

behaviour, hydration or perceptual markers of individual players. Only one study in Australian Football explored factors associated with high T_{core} (Duffield et al., 2009). They found that reaching high T_{core} values were associated with high running intensities, especially in the beginning of the match and later reductions in low to moderate speed running may helped in reaching a T_{core} plateau (Duffield et al., 2009).

Therefore Study 5 aimed at exploring factors that are associated with recording a high T_{core} during football match play. Overall, 61 individual player observations were investigated across four matches, with some participants recording between one and three valid T_{core} observations. Linear mixed models were performed to investigate which physiological, performance and perceptual markers were associated with developing a high T_{core}. The aim was to observe which factors may be relevant across all four matches, independently of environmental conditions and whether a heat mitigation strategy (cooling or drinking breaks) was applied or not. Therefore, these factors were included in the models as fixed effects.

Table 20: Literature review of studies investigating core temperatures in actual football matches.

Study	Sample	Environmental Parameters	Core temperature response
Edwards et al., 2006	2 matches; 8 male University-level football players; 7 male professional football players	2x T, RH: G1: 16 °C + 47% (amateurs) G2: 19 °C + 53% (professionals)	•G1: mean peak T_{core} ~ 39.4 °C •G2: mean peak T_{core} ~38.8 °C •exact values not reported, but mean peaks are estimated from figure
Özgünen et al., 2010	2 matches; experimental; 11 male semi-professional players	2x T, RH and HI: M1: 34 °C + 38% = 35 HI M2: 36 °C + 61% = 49 HI	•M1: peak T_{core} = not reported; mean peak T_{core} = 39.1 ± 0.4 °C •M2: peak T_{core} = 40.2 °C; mean peak T_{core} = 39.6 ± 0.3 °C •M1 and M2 only significantly different at end of halftime 1 •T_{core} not associated with running distance •T_{core} peaks at end of halftime 1 not 2
Mohr et al., 2012	2 matches; experimental; 2 teams; 17 male players	2 T + RH combinations M1: 21 °C + 55% M2: 43 °C + 12%	•M1: mean peak T_{core} = ; 38.8 ± 0.2 °C •M2: mean peak T_{core} was 39.7 ± 0.1 °C •M1 and M2 significantly different at end of halftime 1 and 2
Duffield et al., 2013	7 male elite football players; 2 competitive matches	Mean: 26 ± 2 °C WBGT (with and without pre-cooling)	•no-cooling: 39.9 °C •pre-cooling: 39.7 °C (estimated from figure) •exact T_{core} peaks not reported, but mean peaks are estimated from figure
Study 5	40 male, highly trained young football players; 4 football matches	4x WBGYT M1: 26.9 °C WBGT M2: 24.5 °C WBGT M3: 33.3 °C WBGT M4: 25.5 °C WBGT M1-3: with CB or DB M4: regular match	•M1: mean peak T_{core} = 39.5 ± 0.5 °C •M2: mean peak T_{core} = 38.9 ± 0.5 °C •M3: mean peak T_{core} = 39.4 ± 0.4 °C •M4: mean peak T_{core} = 39.3 ± 0.4 °C •T_{core} associated with total running and covering more in low-moderate speeds but less walking • T_{core} also associated with higher heart rate and sweat loss •T_{core} not related to thermal sensation

Abbreviations: ***Environmental conditions:*** *T = Temperature; °C = degree Celsius; RH = Relative humidity; % = percentage (RH); WBGT = Wet-bulb globe temperature; M= Match; G = Group (participants split across conditions); CB = cooling breaks; DB = drinking breaks;* ***Effects:*** *T_{core} = core body temperature.*

S5.2 Core Temperature Responses during Football Matches in the Heat – Associations with Physiological and Running Demands

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Abstract

Purpose. This study describes core temperature (T_{core}) responses during football matches in warm to hot conditions. Additionally, it aims to identify which physiological, running, and perceptual factors are associated with reaching high T_{core} values whilst controlling for different environmental conditions and cooling strategies. **Methods.** Forty male highly-trained youth football players participated in at least two out of four matches held at temperatures between 26.0 and 42.1 °C (corresponding to 24 – 33 °C Wet Bulb Globe Temperature (WBGT)). T_{core}, heart rate (HR), hydration markers, match running, and perceptual responses were measured. In three out of four matches, heat mitigation strategies in the form of either drinks breaks (DB: passive rest and 17 °C drinks) or cooling breaks (CB: cold towels and 5° C drinks) were applied pre-match, at half-time, and in additional breaks per half. Linear mixed models associated T_{core} with physiological, running, and perceptual responses while accounting for environmental conditions and heat mitigation strategies used per match. **Results.** Peak T_{core} was 39.2 °C ± 0.5 (range: 37.9 to 40.1 °C) in outfield players and 39.2 ± 0.4 °C in goalkeepers. Increased total distances (β = 0.39, CI95[0.13, 0.64], p = 0.004) and distances at low-to-moderate speeds (β = 0.44, CI95[0.18, 0.69], p = 0.001) were associated with higher peak T_{core}, while walking distance was inversely associated (β = -0.42, CI95[-0.69, -0.15], p = 0.003). High-speed and sprinting distances were not associated with peak T_{core}. Higher HR (β = 0.37, CI95[0.10, 0.64], p = 0.008), sweat loss (β = 0.38, CI95[0.14, 0.62], p = .002) and percentage of body mass loss (β = 0.20, CI95[0.00, 0.40], p = 0.047) were also associated with higher peak T_{core}. Perceptual markers 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 regardless of environmental

condition and heat mitigation used and seemed to be mainly driven by running behaviour. Covering more distance at low to moderate running speed likely results in a higher risk of excessive heat strain, whereas walking more (instead of running) can help mitigate a high T_{core}.

Introduction

Due to global warming, outdoor sports athletes across all performance levels are increasingly exposed to hot environmental conditions (Christidis et al., 2015; Klingelhöfer et al., 2023; Perkins et al., 2012; World Meteorological Organization, 2023). Consequently, playing football (soccer) in the heat has emerged as a growing concern for players' health and performance (Gouttebarge et al., 2023; Nassis et al., 2024; Schwarz, Duffield, Lu, et al., 2025). During exercise, three primary determinants contribute to heat stress: exercise intensity drives metabolic heat production, and environmental conditions and clothing determine heat dissipation capacities (Cramer & Jay, 2016). Any heat stress results in an individual heat strain, which is moderated by personal and situational factors, such as acclimatization or hydration status (Bernard et al., 2024). In warmer conditions, heat dissipation mechanisms, such as sweating and subcutaneous vasodilation, become less efficient. Therefore, it needs to be increased, resulting in greater cardiovascular strain and decreased performance (Périard et al., 2021).

If heat dissipation cannot offset metabolic heat production, elevated core temperatures (T_{core}) can be observed in various sports, such as football (Singh 2023). While a high T_{core} is not necessarily linked to health adversities, excessive heat strain may lead to the development of exertional heat illnesses (EHI) ranging from cramps, nausea and headaches to life-threatening exertional heat strokes (EHS) (Roberts et al., 2023). Furthermore, playing football in higher heat stress may be associated with an increased risk of injury (Schwarz, Duffield, Lu, et al., 2025).

Despite this, only a few field-based studies have assessed T_{core} responses during football match play under different environmental conditions (Duffield et al., 2013; Edwards & Clark, 2006; Mohr et al., 2012; Özgünen et al., 2010). 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) (Edwards & Clark, 2006) to 39.7 ± 0.1 °C recorded in 43 °C T and 12% RH (Mohr et al., 2012). Individual values exceeding 40 °C were also reported (Duffield et al., 2013; Mohr et al., 2012; Özgünen et al., 2010). 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 (Périard et al., 2021). 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 (Draper et al., 2022; Illmer & Daumann, 2022; Schwarz et al., 2024; Schwarz, Duffield, Novak, et al., 2025). 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 (Périard et al., 2021), implementing additional breaks per half (Chalmers et al., 2019), and applying cooling techniques (Bongers et al., 2017). Currently, most heat policies in football involve the introduction of additional breaks per half (Gouttebarge et al., 2023). 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 (Brown et al., 2024). Laboratory-based studies suggest that such strategies can attenuate T_{core} rise, but high heat strain can develop nonetheless (Brown et al., 2024; Chalmers et al., 2019). The matches presented in this study were also part of another investigation on 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 (Study 4). 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, whilst controlling for environmental conditions and heat mitigation strategies used. We hypothesise that elevated T_{core} peaks would be associated with greater distances covered, higher heart rates, and greater sweat losses.

Methods

Participants

Forty highly trained (McKay et al., 2021) male footballers (18 ± 1 years) from a professional Mexican club's youth academy participated in this study. Participants had 3 to 4 training sessions and 1 to 2 matches per week and were seasonally acclimatized having trained in hot conditions for more than 2 weeks prior to the testing. Each player participated in at least two out of four experimental matches, with four players participating in all matches. In every match, the starting twenty 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).

Overview

The four matches analysed 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 minutes before and after the warm-up as a pre-cooling before the match, for 10 minutes 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 (study 4). 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; (7) 33.0 °C WBGT - DB. Accordingly, combined match data was analysed to assess associations between T_{core} and match running and physiological responses while controlling for the influence of WBGT and heat mitigation strategies.

Measurements

In the morning, four to five hours 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} (Koumar et al., 2023). 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 (Muñoz-López et al., 2017), 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 (Winter et al., 2024). 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 applied to the participant's forearm. The patches were applied before the match and analysed post-match with the same mobile system (MX3 Lab Pro, MX3 Diagnostics, Austin, USA).

Perceptual responses were recorded using the Rating-of-Fatigue (RoF) ranging from "not fatigued at all" (0) to "total fatigue/exhaustion" (10) (Micklewright et al., 2017), the Rating of Perceived Exertion (RPE) on a scale from "no effort" (0) to "maximum effort" (10) (Borg, 1998) and Thermal Sensation (TS) ranging from "very cold" (-5) to "very hot" (5) (Zhang et al., 2010). These were recorded pre-match (except RPE), at halftime and post-match and are presented as peak values reported per match.

Statistical Analyses

This is an observational study and data are reported as mean and standard deviation to describe characteristics of each match (Table 21). 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 the heat mitigation strategies used are reported in a separate work (Study 4). 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:

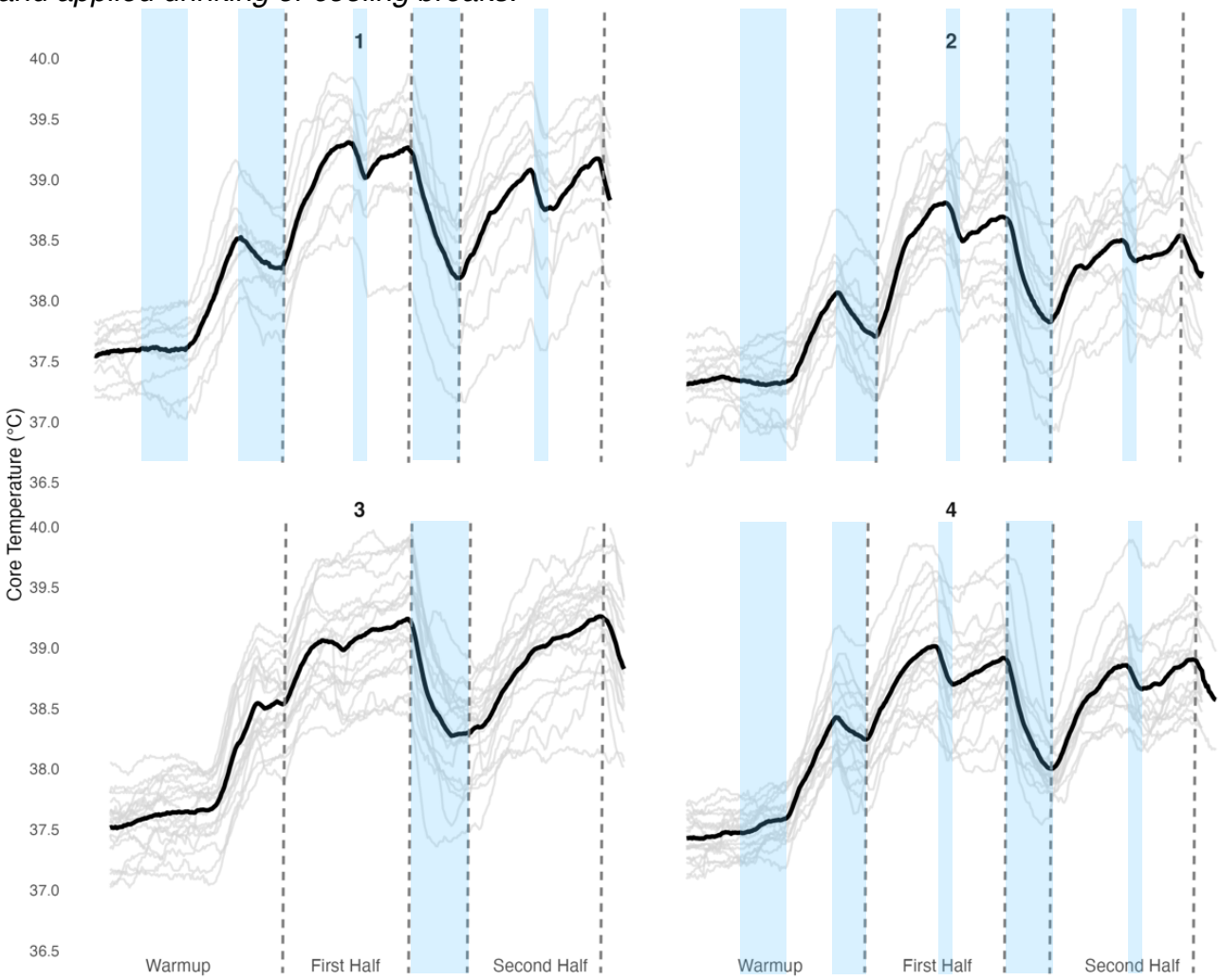
$$peak\ T_{core} \sim Parameter + (WBGT \times HMS) + (1|Player\ ID)$$

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 (β > 0.1), medium (β > 0.3) or large (β > 0.5; (Nieminen, 2022) and explained variance was categorized as small (R^2 > 0.01), medium (R^2 > 0.09) or large (R^2 > 0.25) (Cohen, 1988). Significance was set at α = 0.05, but as each predictor was analysed 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.

Results

A descriptive summary of environmental, physiological, running, and perceptual markers per match is presented in Table 21. 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). Figure 14 shows the continuous variation of the mean T_{core} throughout each match and per individual player. T_{core} follows similar patterns in Match 1, 2 and 4, 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. Figure 15 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).

Figure 14: T_{core} development per match for all participants (black) and each individual observation (grey) with a blue band indicating the times participants rested and applied drinking or cooling breaks.



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.

Figure 15: T_{core} development of goalkeepers.

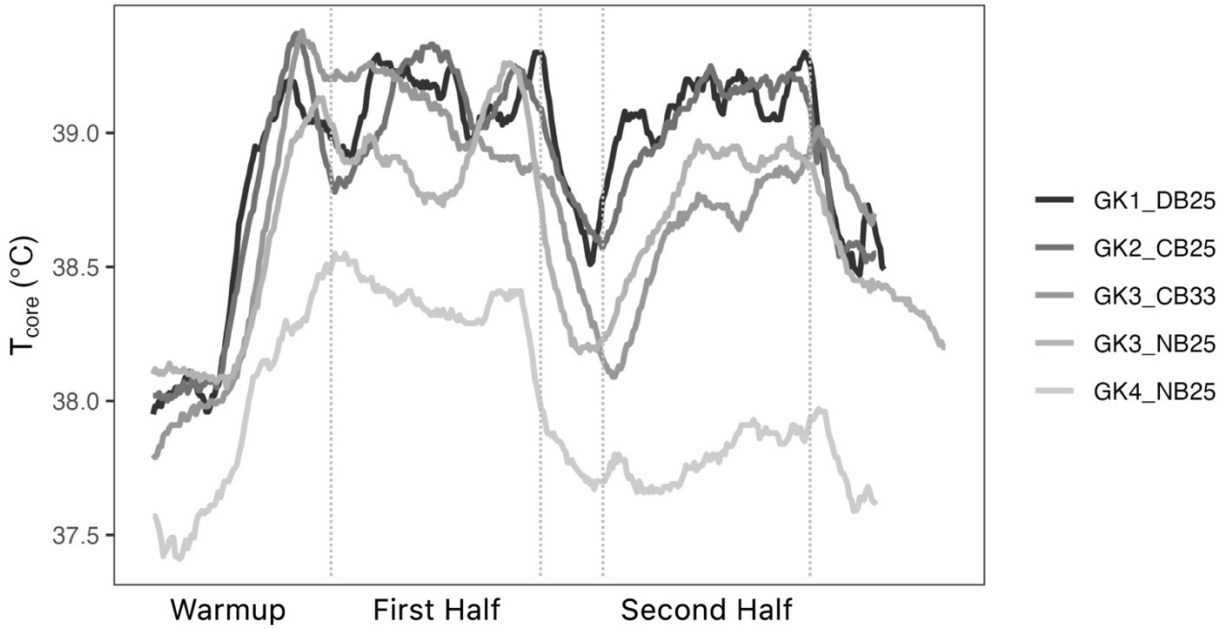


Table 21: Mean ± SD per Match ordered left to right from low to high WBGT.

	Match 2	Match 3	Match 1	Match 4
Situational				
WBGT	**24.0**	**25.5**	**26.9**	**33.0**
T (°C)	28.4	26.0	29.3	42.1
RH (%)	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	39.4 ± 0.40	39.5 ± 0.46	39.3 ± 0.41
Mean T_{core} (°C)	38.4 ± 0.43	38.9 ± 0.40	38.9 ± 0.44	38.6 ± 0.30
HR (b/min)	163.8 ± 9.4	170.7 ± 9.80	171.0 ± 10.1	167.5 ± 8.10
Sweat loss (L)	2.9 ± 0.30	2.7 ± 0.70	2.7 ± 0.62	3.4 ± 0.76
Fluid intake (L)	1.4 ± 0.34	1.1 ± 0.27	1.3 ± 0.33	1.9 ± 0.56
Body mass loss (%)	2.1 ± 0.54	2.5 ± 0.83	2.2 ± 0.7	2.2 ± 0.95
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	106.5 ± 9.92	110.4 ± 4.32	103.6 ± 7.79
Walking (<6km/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 TS	7.1 ± 1.3	7.4 ± 0.9	7.1 ± 1.3	8.8 ± 0.4
Peak RoF	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: SD = standard deviation; WBGT = wet-bulb globe temperature; T = temperature; °C = degree celsius; RH (%) = relative humidity; T_{core} = core body temperature; HR (b/min) = heart rate in beats per minute; L = liter; mOsmol = milliosmole; m/min = meters per minute; km/h = kilometers per hour; RoF = rating of fatigue; RPE = rating of Perceived exertion; TS = thermal sensation.

Across all participant's observations, covering greater total distances was associated with higher peak T_{core} (β = 0.39[0.13, 0.64], *p* = .004). Additionally, greater distance covered at low-to-moderate speed was associated with higher peak T_{core} (β = 0.44[0.18, 0.69], *p* = .001). The distance covered walking was negatively associated with a high peak T_{core} (β = –0.42[–0.69, –0.15], *p* = .003). High-speed running (β = 0.08[–0.20, 0.35], *p* = .58) and sprinting (β = 0.02[–0.23, 0.27], *p* = .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* = .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* = .07), pre-match SOSM (β = -0.07[–0.29, 0.15], *p* = .54) or post-match SOSM (β = 0.20[–0.03, 0.43], *p* = .09). Peak TS (β = 0.01[–0.30, 0.30], *p* = .98), RoF (β = 0.06[–0.32, 0.44], *p* = .74) and RPE (β = 0.04[–0.26, 0.34], *p* = .78) were not associated with peak T_{core}. Figure 16 presents the relationships between peak T_{core} and selected running performance, physiological and perceptual markers. Table 22 summarizes the outcomes of the linear mixed models and Figure 17 illustrates the effect size (ß) for each of the tested associations, ranking them from the largest positive association to the largest negative association.

Table 22: Linear mixed model outcomes.

	Estimate (95CI)	ß: standardized estimate (95CI)	R^2 (marginal)	p-value	p-value (fdr-adjusted)
TD (m/min)	0.02 (0.01, 0.03)	0.39 (0.14, 0.64)	0.341	0.004**	0.013*
WD (m/min)	-0.05 (-0.09, -0.02)	-0.42 (-0.69, -0.15)	0.349	0.003** #	0.013*
LMSD (m/min)	0.02 (0.01, 0.03)	0.44 (0.18, 0.69)	0.375	0.001*** #	0.013*
HSD (m/min)	0.01 (-0.04, 0.07)	0.08 (-0.20, 0.35)	0.206	0.577	0.807
SD (m/min)	0.01 (-0.11, 0.13)	0.02 (-0.23, 0.27)	0.202	0.894	0.963
HR (b/min)	0.02 (0.01, 0.03)	0.37 (0.10, 0.64)	0.305	0.008	0.024
Fluid intake (L)	0.27 (-0.01, 0.55)	0.3 (-0.02, 0.62)	0.256	0.068	0.136
Sweat Loss (L)	0.26 (0.10, 0.41)	0.38 (0.14, 0.62)	0.302	0.002** #	0.013*
BML (%)	0.12 (0.01, 0.23)	0.20 (0.01, 0.40)	0.228	0.047	0.109
Pre-SOSM (mOsm)	-0.00 (-0.01, 0.00)	-0.07 (-0.29, 0.15)	0.204	0.537	0.807
Post-SOSM (mOsm)	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 alpha)*

Abbreviations: 95CI = 95% confidence interval; fdr-adjusted = adjusted with false-discovery rate method; TD = total distance; m/min = meters per minute; WD = walking distance; LMSD = low-to-moderate-speed distance; HSD = high-speed distance; SD = sprint distance; HR (b/min) = heart rate in beats per minute; L = liter; mOsm = milliosmole; TS = thermal sensation; RoF = rating of fatigue; RPE = rating of perceived exertion.

During this study one case of EHI was recorded during the match at 33 °C WBGT. The affected participant 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 (body mass loss = 2.2%) and severe dehydration post-match (SOSM = 150 mOsmol). He also covered 106.3 m/min TD including 2.9 m/min at sprinting speed, the highest sprinting distance of all participants in that match.

Figure 16: Associations between different markers and peak T_{core}.

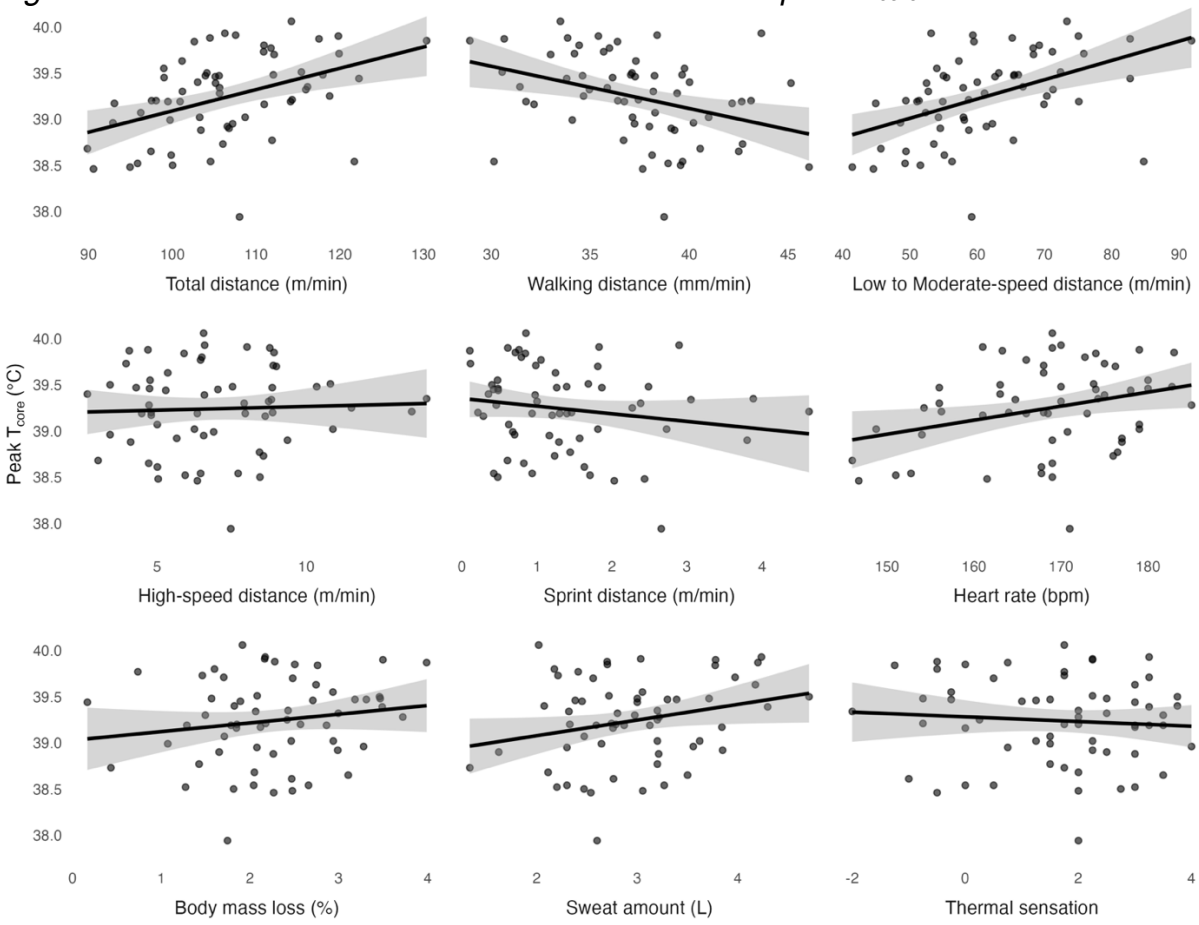
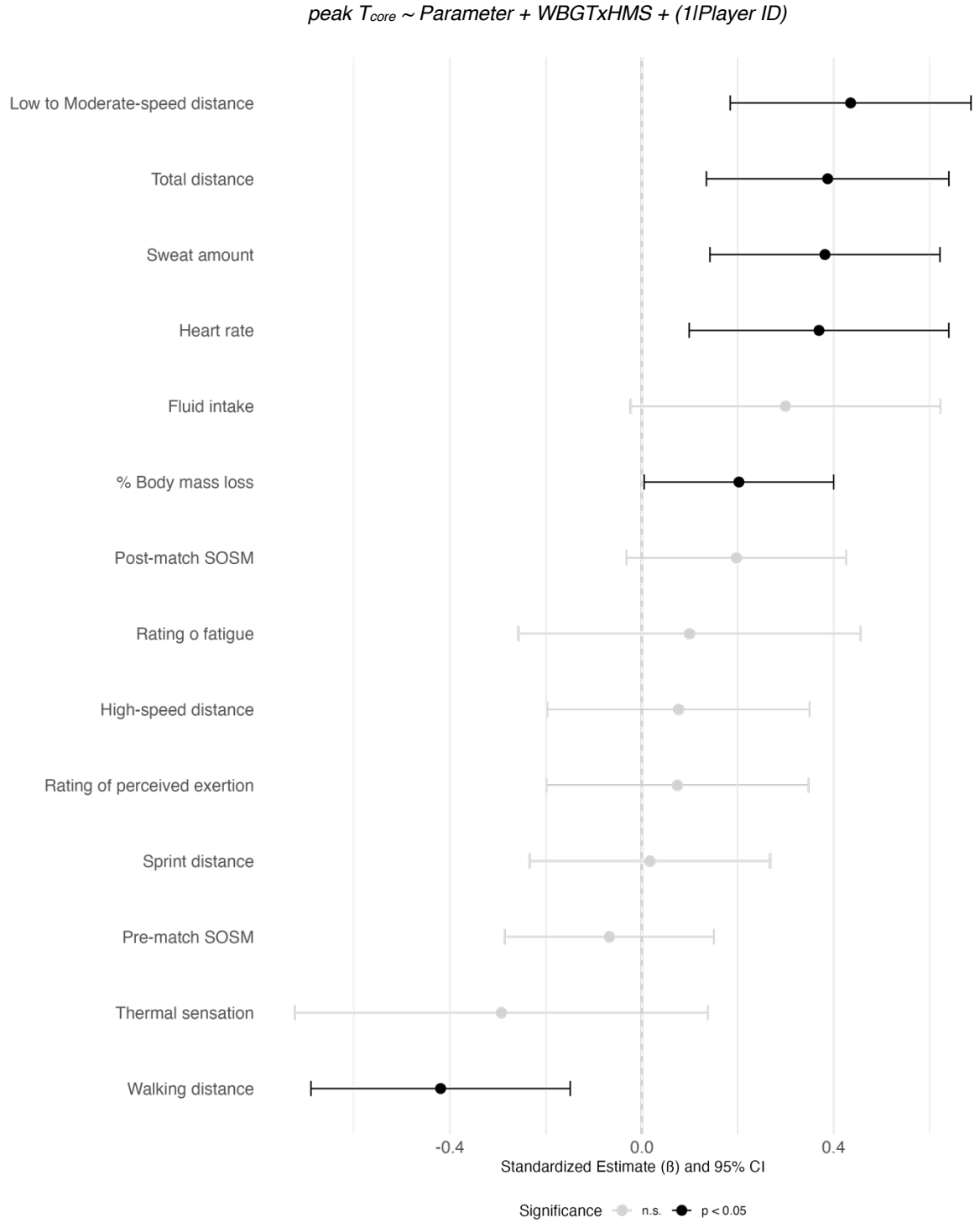


Figure 17: Factors associated with a higher peak T_{core} whilst controlling for different heat stress (WBGT) and heat mitigation strategies (HMS) used.



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 – 42 °C (24 – 33 °C WBGT). Regardless of

environmental heat stress, similarly elevated T_{core} (39.2 ± 0.5) was observed consistently, with at least some participants reaching 39.5 °C or higher in each match. Increased T_{core} was primarily 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.

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 (Edwards & Clark, 2006), 39.6 ± 0.3 °C (Özgünen et al., 2010), 39.7 ± 0.1 °C (Mohr et al., 2012), and 39.9 ± 0.4 °C (Duffield et al., 2013). 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 (Özgünen et al., 2010) and 43 °C (Mohr et al., 2012) and the participating players were not acclimatized to such conditions (Mohr et al., 2012; Özgünen et al., 2010). Additionally, in Mohr et al. (2012) players covered higher running volumes compared to this study. In Duffield et al. (2013) actual league competition was investigated, where intensities might be higher compared to experimental matches in youth competitions. Interestingly, Edwards and Clark (2006) 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, whilst previous studies investigated regular matches without cooling breaks.

Match running performance in this study was comparable to that reported previously in similar age groups (Palucci Viera et al., 2019), 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 (Edwards & Clark, 2006; Mohr et al., 2012; Özgünen et al., 2010). Concerningly, SOSM measurements indicated that 52% of participants were not optimally hydrated pre-match. This value increased post-match to 80%, including 16

players categorised 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% (Aragón-Vargas et al., 2009) and 66% (Williams & Blackwell, 2012) of football players were training in a dehydrated state.

The main factors associated with reaching high T_{core} values were running performance metrics. This is consistent with the thermoregulatory theory, as the metabolic rate based on individual match demands was a key driver of heat strain (Cramer & Jay, 2016; Périard et al., 2021; Racinais, Moussay, et al., 2019). Previous studies have observed that players reduce their total distance covered in hotter environmental conditions (Draper et al., 2022; Schwarz et al., 2024); 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 are directly linked to metabolic heat production and, thus, heat strain (Cramer & Jay, 2016; Périard et al., 2021). 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 (Duffield et al., 2009). Additionally, teams or players aiming to maintain high running loads even when playing in the heat may need to consider intensified heat mitigation strategies, such as cooling and hydration. Goalkeepers also reached high peak T_{core} values exceeding 39 °C. Interestingly, in contrast to outfield players, goalkeepers reached peaks towards 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 leads to an increased thermoregulatory response, including subcutaneous vasodilation and sweating to dissipate heat (Périard et al., 2021). 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 needs a higher HR to maintain the cardiac output (Nybo et al.,

2014). 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} (Chalmers et al., 2019; Duffield et al., 2013; Zhang et al., 2022; Zhang et al., 2014).

In football, investigations on the incidence of EHI are scarce. In American collegiate soccer competition, 0.7 and 1.1 EHI were reported per 10.000 athletes exposures during the season and pre-season (Yeargin et al., 2019). However, actual incidences are likely higher, due to many suspected non-reported cases (Roberts et al., 2023). 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 (Gamage et al., 2020). 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 a 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 hours 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 (Palucci Viera et al., 2019), 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 (Brown et al., 2025; Brown et al., 2024). 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 (Périard et al., 2021). Therefore, further studies with different cohorts are needed to determine T_{core} responses in other settings.

In conclusion, football players experienced high heat strain, 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, and lower walking distance. These findings suggest that football players and coaches may consider adjusting their playing style and tactics to better manage heat strain. Nevertheless, players with higher running loads might benefit from individualized cooling and hydration strategies.

DISCUSSION

Discussion

D1. General Discussion

D1.1 Discussion of Studies 1, 2 and 3

The first three aims of this thesis were to characterize changes that can be expected when elite football matches are played under hot environmental conditions. This was investigated through three observational studies, examining associations between environmental temperatures and (i) match running performance, (ii) match play characteristics, and (iii) match injury occurrence.

D1.1.1 Study 1: Match running performance in the heat

Match running performance in the heat was found to be reduced, confirming previous research (see Table 1). When T or WBGT increase by 10 °C, total distance covered per player was lower by 168 m or 200 m per match. This was also observed for high-speed running (-23 m or -27 m per 10 °C T or WBGT) and sprinting (-14 m or -18 m per 10 °C T or WBGT). These findings indicate a slower and less intense match, confirming the findings previously proposed by other studies (Mohr et al., 2012; Nassis et al., 2015).

However, while most comparable studies reported reductions in running performances, a few did not observe reductions in total (Coker et al., 2020; Konefał et al., 2014; Loxston et al., 2019; Nassis et al., 2015), or high-speed running (Coker et al., 2020; Özgünen et al., 2010; Trewin et al., 2018). This might be linked to methodological limitations in previous studies investigating only small samples and analysing heat stress in distinct categories. For instance, Özgünen et al. (2010) compared only two matches with small difference in environmental conditions (34 °C T, 38% RH vs. 36 °C T, 61% RH) and Trewin et al. (2018) compared performance above and below 21 °C T. Other studies included 3 or 4 temperature categories but only investigated between 12 and 64 matches, resulting in limited observations per category (Coker et al., 2020; Konefał et al., 2014; Loxston et al., 2019; Nassis et al., 2015). Given the methodological limitations of these studies, and that the findings of

this thesis are consistent with most of the existing literature, it is concluded that total, high-speed and sprint distances are indeed reduced in the heat.

D1.1.2 Study 2: Match play characteristics in the heat

Match play characteristics (i.e., tactical and technical parameters) were also altered in hotter conditions. Reductions were observed for the number of passes, short passes, passes into the final third, touches, touches in the final third, take-ons and turnovers. In contrast, shots, goals, key passes, tackles, duels and fouls were unaffected, while the rate of successful passes was higher in hotter conditions. These findings suggest that matches played in the heat involve fewer overall actions, consistent with the reductions in running distances described prior. However, primarily high-volume actions, such as passes and touches were affected, while key performance indicators, which are more directly linked to football success (i.e., shots, goals and tackles), remained unchanged.

Contrary to these findings, most previous studies reported no significant change in the number of passes under hotter temperatures (Chmura et al., 2021; Loxston et al., 2019; Mohr et al., 2012; Nassis et al., 2015; Zhou et al., 2019). However, these studies often included a limited number of matches and heat stress categories (see Table 5). Notably, Chmura et al. (2021) analysed 1530 matches Bundesliga matches (also included in the presented Study 2) but found no associations between any performance indicator and temperatures. Compared to the presented Study 2, they analysed data per playing position, limiting the number of observations per group and used a slightly different statistical approach. This methodological difference, along with possible differences in T and WBGT data, which the authors did not specify how it was obtained, may explain the differential findings.

Across the existing literature, the most consistent result is an increased rate of successful passes (Mohr et al., 2012; Nassis et al., 2015; Zhou et al., 2019) and decrease in turnovers (Loxston et al., 2019; Mohr et al., 2012) in hotter conditions. Both were confirmed by our study and previously attributed to the reduced running activity in the heat. The lower amount of overall and high speed running could lower defensive pressure and reduce transition sequences including high-risk passes (Mohr

et al., 2012; Nassis et al., 2015). Thus, a more structured, possession-based style of play in the heat is suggested. The increase in pass rates and lower number of turnovers may also be linked to the reduction in overall passes and touches. Although speculative, players might adopt more risk-averse decisions, choosing safer passes or controlling the ball for longer, to conserve energy and avoid losing possession, which would result in greater running efforts.

D1.1.3 Study 3: Match injury occurrence in the heat

Match injury occurrence was not clearly associated with changes in heat stress, but observed trends suggest important implications for future research. Although this topic has not been investigated in football previously, it was hypothesised that higher temperatures could increase the injury risk, by affecting cognitive function and fatigue (Distefano et al., 2013; Schmit et al., 2017). However, no relationship between injury occurrence and heat stress was observed in the German Bundesliga. This may be explained by several reasons. First, the lower total and high-speed running distances observed in hot conditions may mitigate fatigue and reduce the exposure to high-intensity actions. Second, prior research has suggested that softer playing surfaces, which are more likely to occur in warmer and more humid conditions, are associated with fewer injuries (Gabbett et al., 2007). Lastly, the number of matches played under severe heat stress was low and previous research indicated that only a substantial heat strain leads to cognitive impairments (Schmit et al., 2017). In the Australian A-League, slightly more, but still relatively few, hot matches took place. Interestingly, a minimal but significant relationship was found, showing 0.3 more injuries occurring during matches per 10 °C WBGT was higher. In comparable existing studies the overall exposure to hot conditions also remained low, with the hottest matches below 22.2 °C (Lee & Garraway, 2000) and 29.6 °C T(Gabbett et al., 2007). Given that injuries are relatively rare events, large datasets with a higher number of matches played in hot conditions are necessary to understand this relationship.

D1.2 Discussion of Studies 4 and 5

The fourth aim of this thesis was to investigate a simple and applicable heat mitigation strategy for football played in hot conditions. This was addressed through a series of four football matches, during which participants' T_{core}, HR, running performance, hydration and perceptions regarding exertion, fatigue and thermal sensation were measured. In the first two matches, conducted in 25 °C WBGT, 22 participants were observed, applying either drinking (DB: passive rest and 17 °C drink) or cooling (CB: cold towels and 5 °C drink) during pre-cooling and cooling breaks. The third and fourth match included a second cohort of 22 participants (four overlapping from the first sample). One of these matches was conducted in 25 °C WBGT with no breaks (NB) while the other was held at 33 °C WBGT and included again the two conditions DB and CB. In total, 40 players were assessed across five experimental conditions: drinking breaks at 25 °C WBGT (DB_{25}), cooling breaks at 25 °C WBGT (CB_{25}), no breaks at 25 °C WBGT (NB_{25}), drinking breaks at 33 °C WBGT (DB_{33}), and cooling breaks at 33 °C WBGT. The fifth aim of this thesis was to explore factors associated with the development of a high peak T_{core} across all four observed matches.

D1.2.1 Study 4: Effects of pre-cooling and cooling breaks in 25 °C WBGT

In 25 °C WBGT cooling was effective in improving perceptual parameters, though no substantial physiological or performance differences were observed between CB_{25} and DB_{25}. T_{core}, HR and running metrics did not differ between the groups. These findings align with Duffield et al. (2013), who investigated pre-match and halftime cooling in actual matches and reported no sustained T_{core} reductions after the warm-up phase. In both CB_{25} and DB_{25}, T_{core} reduced by 0.4 ± 0.2 °C during the first and 0.3 ± 0.2 °C during the second additional break. These values are consistent with Chalmers et al. (2019), who reported that additional breaks reduced T_{core} in football simulating treadmill running at 30 °C WBGT, compared to a protocol without breaks. They also found no significant difference in breaks where players used iced towels (T_{core}: -0.28 °C) or not (T_{core}: -0.25 °C). In contrast, Brown et al. (2024) observed more pronounced T_{core} reductions when cooling breaks were applied (T_{core}: -0.4 °C) compared to drinking breaks (T_{core}: -0.2 °C) at 32 °C WBGT. Yet again, no statistically

significant difference was reported. The lack of physiological differences in the presented study could be related to the reduced sweat loss observed in CB_{25}, which may have limited evaporative cooling. Previous research indicates that cooling can suppress the sweat response and, especially under dry heat conditions, the cooling achieved through sweat evaporation may offset the benefits of cooling applications (Jay & Morris, 2018). Nevertheless, lower sweat rates may help mitigate dehydration, which is similarly important for health and performance (Cheuvront & Kenefick, 2014). In Study 4 however, no difference in body mass loss was observed, as participants in DB_{25} compensated for their greater sweat loss with an increased fluid intake. Despite similar physiological responses, players subjectively reported greater perceived performance benefits from CB_{25} than DB_{25}. Additionally, participants in CB_{25} reported reduced ratings of fatigue and lower thermal sensations compared to DB_{25}.

D1.2.2 Study 4: Effects of pre-cooling and cooling breaks in 33 °C WBGT

In 33°C WBGT, cooling resulted in more pronounced effects compared to 25 °C WBGT. Players in CB_{33} exhibited a lower HR, maintained similar running performance, and had lower T_{core} values, compared to what they had recorded in NB_{25}. In contrast, players in DB_{33} showed reduced running distances in speed zone 2 and 3 and reached similar T_{core} values compared to NB_{25}. Considering that CB_{33} and DB_{33} were played in 8 °C WBGT higher than NB_{25}, the results imply that the additional breaks in both conditions were effective in attenuating elevated thermal strains expected under such heat stress. Further, this supports the notion that T_{core} is influenced more by the exercise work rate and less linked to environmental conditions alone (Duffield et al., 2009; Epstein et al., 1999; Racinais, Moussay, et al., 2019).

During the second pre-cooling break (post-warm-up), T_{core} reduced more in CB_{33} compared to DB_{33}, resulting in a 0.4 °C lower T_{core} at kick-off in participants in CB_{33} compared to what they had reached during NB_{25}. However, this reduction was no longer present at the 25th minute of play, confirming findings by Duffield et al. (2013) that pre-cooling can lower T_{core} initially, but effects diminish quickly.

During the additional breaks per half, T_{core} reduced similarly in both CB_{33} and DB_{33} by 0.4 ± 0.2 °C during the first and 0.3 ± 0.2 °C during the second in-play break,

comparable to the observations in 25 °C WBGT. This contributed to participants in CB_{33} maintaining lower T_{core} levels compared to what they recorded during NB_{25} and was more effective compared to DB_{33}. In DB_{33}, participants' T_{core} values were similar to their values in NB_{25}. By the end of the match, players in CB_{33} had T_{core} values 0.32 °C lower than in DB_{33} and 0.63 °C lower than in NB_{25}. These differences were more pronounced than those reported by Chalmers et al. (2019) and Brown et al. (2024), which might be related to the overall higher levels of heat strain observed in the field.

Playing in 33 °C WBGT resulted in greater sweat losses in both CB_{33} (+0.4 L) and DB_{33} (+0.9 L) compared to NB_{25} (2.7 ± 0.7 L). However, players increased their fluid intake accordingly, consuming an additional 0.7 L in CB_{33} and 0.9 L in DB_{33} compared to NB_{25}. This resulted in similar body mass loss between DB_{33} (2.4 ± 1.1%) and NB_{25} (2.5 ± 0.8%), while CB_{33} demonstrated a lower body mass loss (2.0 ± 0.8%). This beneficial effect of cooling on dehydration confirms findings from both laboratory (Brown et al., 2024) and field studies (Duffield et al., 2013). These improvements were also reflected in lower saliva osmolality (SOSM) changes from pre- to post, indicating that players receiving CB_{33} were able to maintain a better hydration status. Finally, while players reported higher values of RoF, RPE and TS when playing in 33 °C WBGT compared to NB_{25}, those in CB_{33} reported lower TS compared to DB_{33}. They further reported to like and perceive performance benefits from both CB_{33} and DB_{33}.

D1.2.3 Study 4: Effects of pre-cooling and cooling breaks overall

Pre-cooling and cooling breaks were effective in mitigating the continuous rise in T_{core}. Pre-cooling has been shown to lower initial heat storage, as demonstrated previously in a field study (Duffield et al., 2013). In contrast to Duffield et al. (2013), where pre-cooling occurred prior to the warm-up, the second pre-cooling in the present study was applied between warm-up and match. This potentially increases the relevance for actual match play. Additionally, the cooling stimulus was renewed during 3 min additional breaks per half, during which T_{core} dropped by 0.3 - 0.4 °C, confirming promising findings from controlled laboratory experiments (Brown et al., 2024; Chalmers et al., 2019).

Adding a simple cooling intervention, consisting of ice-cold drinks and large cold towels during pre-cooling, additional breaks and halftime, had minimal effects under moderate heat stress (25° WBGT), but demonstrated greater benefits under severe heat stress (33 °C WBGT). This aligns with the established understanding that cooling interventions become more effective when heat strain is high (Wegmann et al., 2012). Finally, it is noteworthy that considerable inter- and intra-individual differences in T_{core} responses were observed. For example, one player exhibited a T_{core} reduction of -0.15 °C during the first cooling break, but -0.81 °C during the second additional break of the same match, despite entering both breaks with an identical T_{core}. Individual cooling rates during halftime ranged from -0.43 to -2.07 °C, while peak T_{core} values spanned from 38.51 – 40.06 °C.

D1.2.4 Study 5: T_{core} responses and associated factors in football

The fifth aim of this thesis was to characterize T_{core} responses in football and identify associated factors with the development of a high peak T_{core}. This was examined across all four experimental matches using linear mixed models. These models accounted for the repeated measures by including each player as a random effect and controlled for different environmental conditions and heat mitigation strategies as fixed effects. Developing higher peak T_{core} values was associated with a higher HR, greater body mass loss and increased total distance covered, particularly at low-moderate speeds (6-18 km/h), alongside a reduced distance covered walking (< 6 km/h). This suggests that players who maintained a lower peak T_{core} redistributed their workload by performing less low-moderate speed running and more walking. Similar findings were reported in a previous study conducted in Australian Football, where reductions in moderate intensity running were associated with mitigating the rise in T_{core} (Duffield et al., 2009). These findings reflect the link between T_{core} and metabolic rate described during the introduction of this thesis (Cramer & Jay, 2016; Duffield et al., 2012; Périard et al., 2021). Notably, high-speed running and sprinting distances were not associated with peak T_{core}. This is again in line with existing literature (Duffield et al., 2009) and might reflect either the short overall duration spend at such intensities or the success of individual pacing strategies.

D2. General Limitations

D2.1 Limitations of Studies 1, 2 and 3

Limitations of the three observational studies primarily arise from the retrospective nature of the data collection. Match performance and injury data were originally collected for league internal load or injury monitoring, media coverage or previous research projects. Therefore, data sources varied in the presented studies: some were shared by the participating leagues (match running and match play data from Germany, match play and injury data from Australia, match running data from Turkey), while others were web-scraped from open-access websites (match play data from Spain, match running data from Japan), or available from prior research projects (match injury data from Germany). The media-based injury data from Germany has been used and validated previously (aus der Fünten et al., 2023) and was collected by two researchers who identified and categorised injuries based on media reports. In contrast to the injury data from Australia, where injuries were only recorded if they lead to missing a match, the media-based approach captured injuries even if they only led to missing a training. Although some degree of under- or overreporting cannot be excluded, any such bias is likely to be consistent across the full temperature range, and therefore should not affect the association between injury and heat stress. Nevertheless, due to the heterogeneity in the data sources, no direct comparisons between leagues were conducted. Instead, the aim was to identify consistent associations across multiple contexts.

Similarly, environmental data were retrospectively aligned to each match. Data were sourced from an open-access platform (Meteostat.net) for all but the Australian data. The Australian league had already integrated environmental data using a commercial provider (UBIMET GmbH) in the data they shared. In both cases, T, RH and wind speed were interpolated using data from up to four nearby weather stations, weighted by distance and elevation difference and solar radiation was estimated based on the solar angle. These variables were then used to estimate WBGT via a validated method (Lemke & Kjellstrom, 2012). Whilst this approach is considered reliable, direct measurements at the field-of-play would of course provide more

accurate assessments of the heat stress (Chalmers et al., 2020; Racinais et al., 2023). Especially, solar radiation and air flow display higher local variations and could differ inside football stadiums. Nevertheless, the WBGT estimations primarily relied on T and RH, which exhibit less spatial fluctuations.

Finally, the models used did not control for additional contextual factors, which could influence performance metrics and injury occurrence, such as the match venue (home or away), match importance, match congestion, opponent strength, or team tactics. Nonetheless, accepting these limitations enabled the inclusion of a larger data sets. Prior to this thesis, research regarding the influence of heat on match running had observed 4635 matches (mean = 340, range = 2-2426; see Table 1), 1942 matches on match play (mean = 324; range = 2-1530; see Table 5), and 742 matches on match injury occurrence (mean = 371, range = 137-605; see Table 11). By investigating larger samples across diverse professional football leagues, geographical settings and climates, the current work was able to identify robust and generalizable effects. Thus, it is argued that the benefits of this approach outweigh the presented limitations.

D2.2 Limitations of Studies 4 and 5

Limitations of the experimental data collection primarily arise from their field-based nature. While previous research has emphasised the need for more field studies to investigate the applicability of pre-cooling and cooling breaks in football (Bongers et al., 2017; Brown et al., 2025; Brown et al., 2024; Chalmers et al., 2019; Duffield et al., 2013), only one prior study has investigating pre- and halftime-cooling in actual football matches (Duffield et al., 2013). This reflects the considerable logistical challenges and inherent risks associated with conducting such a field-based experiment in hot conditions. The less controlled nature of the field environments inevitably introduces limitations but simultaneously enhances the external validity and practical applicability. A major obstacle in organizing field-based studies on heat mitigations strategies is the requirement for hot (and ideally consistent) environmental conditions during testing. Unless creating an environmental chamber the size of a football field, researchers thereby rely on the weather. Yet, football matches involving

22 players, three referees, multiple coaching and performance staff, a medical team and multiple researchers, must be scheduled weeks in advance, long before specific weather conditions can be confirmed. Thereby, scheduling can only be guided by historical weather data and must ideally leave some room for spontaneous adjustments. However, the use of ingestible telemetric pills to measure T_{core}, necessitates that a decision regarding testing is taken early, to allow the pills to travel through the stomach. Therefore, specific weather conditions for the day can only be estimated through weather forecasts at the time of the final decision. As such, successful implementation requires a setting that meets several criteria: (a) reliable access to players and staff, (b) sufficient professionalism of organization to accommodate the research needs (e.g., high-quality facilities, players and coaches buy-in, flexibility to adapt schedules, support staff), and (c) a geographic location with consistently high ambient temperatures. Ultimately, such a setting was found in Monterrey Mexico, and still, the presented challenges led to the two-part data collection presented in Study 4:

A first round of data collection was designed to investigate two experimental matches using a randomised crossover design in October 2023. This approach can balance the effects of varying environmental conditions per match. The professional football organization in Monterrey, Mexico (*Club Tigres UANL)* agreed to participate in such a data collection, as playing in hot conditions is a big concern for their teams. Indeed, Monterrey is predicted to be one of the hottest venue for the 2026 FIFA World Cup (Gouttebarge et al., 2023; Linder-Cendrowska et al., 2024). Historical weather data for October in Monterrey between 2012 and 2022 was analysed. Temperature (measured in the shade) exceeded 30 °C on 26% and above 25 °C on 51% of the days with an average relative humidity of 50%. Based on this, observing warm to hot conditions was considered likely. However, due to an unexpected temperature drop, caused by Hurricane Norma making landfall at the pacific coast of Mexico, the observed WBGT remained lower than anticipated. While data collection was completed successfully, the matches did not take place under extremely challenging conditions, especially for the acclimatized participants. As previously highlighted, the benefits associated with cooling strategies increase with greater heat stress (Wegmann et al., 2012).

A second round of data collection was therefore planned for the following year in June, a month not typically affected by Hurricanes, but already displaying very high temperatures. The aim was to replicate the previous data collection under conditions of more severe heat stress. Historical weather data from the past 10 years (2013-23) showed that temperature exceeded 30 °C on 78% of days, with an average humidity of 45%. This was considered highly favourable for observing hot conditions. Unfortunately, unforeseen cyclone activities, led to a significant temperature drop again. Tropical Storm Alberto, directly aimed at Monterrey, brought heavy rainfall and strong winds, highly atypical for the region during summer. After postponing the match dates, the environmental conditions initially appeared promising on the morning of the third scheduled match. Additionally, due to the team's schedule, it was not feasible to delay the testing further, so match procedures were initiated. Unfortunately, shortly before starting the pre-match measurements, rain began, and temperatures dropped. To avoid repeating data collection under moderate heat (as in the year prior), the study protocol was adjusted. Instead of applying pre-cooling, cooling or drinking breaks, the match was conducted without any cooling or breaks. In the subsequent (fourth overall) match, conditions finally aligned with the expectations (33.3 °C WBGT) and the planned comparison of cooling and drinking interventions was implemented.

To summarize, data was collected on four occasions: In October 2023, two matches were conducted in 25 °C WBGT, during which drinking (DB_{25}) and cooling (CB_{25}) breaks were applied. In June 2024, two additional matches were held with a different subset of players. One match in 25 °C WBGT without any breaks (NB_{25}) and the other 33 °C WBGT with players assigned to either drinking (DB_{33}) or cooling (CB_{33}) breaks. Within the given time frame the researchers and *Club Tigres UANL* made considerable efforts to conduct testing under the hottest possible conditions. Despite this, the lack of a full crossover design in high heat, remains a limitation. Another limitation stemming from the unexpected weather disruptions is resulting heterogeneity of the samples. There are five different conditions with different players participating in two or four matches. To address this issue, linear mixed models were performed instead of ANOVA's, as they are more robust in handling smaller samples with repeated measures. Data from 2023 (CB_{25} and DB_{25}) was analysed separately

from the data from 2024 (CB_{33}, DB_{33} and NB_{25}) and comparisons between the two years were limited to the discussion. Data from 2024 was analysed in two ways: first, data from CB_{33} and DB_{33} were compared to the same players data in NB_{25}; second, data from CB_{33} and DB_{33} were compared directly. While this approach does not match the strength of the initially planned crossover design, it offered advantages over a simple comparison of two independent samples in 33.3 °C WBGT. This enabled a more detailed interpretation of the differences between CB_{33} and DB_{33}. Moreover, repeating the study enabled the inclusion of twice as many observations and facilitated the investigation of a match without any breaks. As a result, the second data collection addressed two key questions remaining after the initial study: (1) how responses differ to matches without any breaks, and (2) how outcomes change under more severe heat stress.

For Study 5 the aim was to characterize T_{core} responses to football in the heat and identify which factors are associated with T_{core}. However, it needs to be considered that in three of the four matches heat mitigation strategies were applied. Although the heat mitigation strategies and environmental conditions were included in the model to attempt to control for their influence on associated factors, the peak T_{core} that was recorded, might be lower compared to what could be observed when matches are played without heat mitigation strategies. Furthermore, the intensity reached in actual competition might be higher than that observed in the experimental matches. Nevertheless, the study confirmed associations between match running and heat strain known from thermoregulatory theory (Cramer & Jay, 2016).

Another challenging aspect of the data collection for Study 4 and 5 was organizing a match day and nutritional program that incorporated multiple meals, measurements and specific procedures for 22 players. Key considerations included: (a) ensuring early access to players for telemetric pill ingestion, (b) providing players with appropriate nutrition throughout the entire match day, (c) maintaining players engagement and compliance, (d) scheduling measurements and instructions to disrupt regular match day procedures as least as possible, and (e) allocating responsibilities to staff members. Despite thorough planning, this resulted in T_{core}

measurement errors. On match day 1, telemetric pills were ingested around 8:30 am, allowing 4 - 5 hours for them to pass into the lower intestines. However, this timing was sufficient in only about half of the participants. In response, the ingestion time was moved earlier for the consecutive matches, which resolved the issue. In contrast, in 2024, one player in the first match and two in the second excreted the pill prematurely.

D3. Practical Implications

Studies 1 and 2 demonstrated that football performance is affected by elevated temperatures. Teams should be aware of these effects and may consider adapting their tactical strategies accordingly. However, such tactical considerations need to account for multiple factors. For teams, whose playing styles rely on high running volumes and intensities, implementing heat mitigation strategies might be considered. In Study 4 the use of cooling did not affect performance in moderate conditions but was effective in preserving running metrics during more severe heat. The threshold for “severe” heat stress may vary depending on team specific factors. For instance, in non-acclimatized players, this might be lower than the 33 °C WBGT observed in this study.

The findings from Study 3 indicated a potential association between WBGT and injury occurrence, in a league where the hottest match was held at 37.1 °C T and 29.6 °C WBGT. Although further research is needed to confirm this relationship, it may be hypothesized that in more severe heat stress, this association becomes more pronounced. Therefore, implementing heat mitigation strategies earlier might be a reasonable preventative approach.

Study 4 and 5 demonstrated that the continuous rise in T_{core}, observed during regular match (NB_{25}), can be mitigated through additional pre-cooling and cooling breaks. The pre-cooling break between warm-up and match lowered T_{core} by 0.2 °C. In moderate heat, there were no differences whether CB_{25} or DB_{25} was applied in these breaks. However, under severe heat stress, CB_{33} resulted in a more pronounced T_{core} reduction of 0.4 °C. Additional drinking or cooling breaks per half further attenuated

the rise in T_{core}, with average reductions of 0.3 - 0.4 °C during each 3-minute break. Again, no notable physiological differences were found between CB_{25} and DB_{25}, besides a reduced sweat loss. In severe heat, CB_{33} resulted in maintaining lower T_{core} and reduced dehydration compared to DB_{33}. Importantly, perceptual improvements were consistently reported for both, CB_{25} and CB_{33}, showing their benefits for player wellbeing and performance. Across all four matches, players covering greater total distances and distances at low to moderate speeds was associated with higher peak T_{core} values. This indicates that players with higher running volumes are at higher risk of developing high heat strain, and cooling interventions might be especially beneficial for those players. Furthermore, goalkeepers also reached high T_{core} peaks, suggesting they should not be excluded from cooling protocols.

These findings challenge the widely adopted threshold of 32 °C WBGT for introducing cooling breaks. Study 3 indicated an association of WBGT with injury occurrence below 30 °C WBGT. Additionally, studies 4 and 5 demonstrated that even under moderate heat stress conditions (25 °C WBGT) some players approached a T_{core} of 40 °C. Nevertheless, as presented in chapter B10, it remains challenging to determine a fixed threshold for the implementation of heat mitigation strategies, especially when a federation is attempting to cover a broad range of climate regions and playing levels (such as FIFA). The different acclimatization of players from different regions leads to different heat strains at fixed heat stress thresholds. Whilst a 32 °C WBGT threshold might be too high in many settings, a much lower threshold might lead to the policy being disregarded in regions where it is passed too regularly. In lower playing levels, the lower availability of medical support calls for more conservative thresholds in such settings. The alternative approach would be to implement flexible guidelines, where certain stakeholders can decide for each match-day whether cooling breaks should be implemented or not, given the acute heat stress, player characteristics and other present risk factors (e.g., stage of the season, beginning of summer). Whilst such an approach could work in elite level football, where match-day medical officers are present. In contrast, for lower-level competitions, where referees need to implement cooling breaks, it could be challenging to educate referees on how to take this decision. As limitations exist for

both, fixed and flexible strategies, a hybrid approach may be the best solution. Fixed thresholds can call for mandatory interventions when heat stress passes severe levels, but stakeholders are encouraged to implement them earlier based on their individual heat stress assessments. To support such decisions, heat guidelines and information on risk factors (see summary box 2) needs to be provided.

In addition to implementing a lower threshold, it should be reconsidered whether an alternative, or at least supplementary heat stress index can be adopted alongside WBGT. Although WBGT remains the most-used index in research and heat guidelines, it presents several critical limitations (Brocherie & Millet, 2015; Budd, 2008; d'Ambrosio Alfano et al., 2014). Accurate WBGT measurements require expensive, well-calibrated equipment operated by trained personnel. However, this is often not the case, resulting in misinterpretations, to the extent that WBGT is frequently regarded as a regular ambient air temperature (d'Ambrosio Alfano et al., 2014). When the appropriate tools are unavailable, WBGT is often estimated using conventional weather data from meteorological stations or online sources (Brocherie & Millet, 2015). This approach introduces further variation, as heat stress is no longer measured at the athlete's field of play. Microclimates, influenced by the urban layout, nearby surrounding structures and playing surfaces, can diverge from the data reported by weather stations (Racinais et al., 2023). Moreover, WBGT does not incorporate valid corrections for the metabolic heat production or the type of clothing worn by the athletes (Brocherie & Millet, 2015). Most critically, WBGT has been shown to underestimate heat stress, particularly under conditions of high humidity and low airflow (Budd, 2008). Therefore, it has been proposed that the use of newer heat stress indices, such as the Universal Thermal Climate Index (UTCI) is further developed (Brocherie & Millet, 2015). Alternatively, even the use of simple ambient temperature might be used for a more consistent and practical application (Brocherie & Millet, 2015). In football competitions, this is a very important consideration in youth and amateur settings, where both the equipment and the knowledge required to interpret more complex heat stress indices may be limited. Unpublished survey data from 1365 German football referees (officiating from amateur to first league level) supports this: only 92 participants indicated that they were familiar with WBGT. This is concerning,

as referees are critical stakeholders in the implementation of drinking and cooling breaks.

FIFA guidelines currently require organizers to provide cooling equipment such as ice boxes, cold towels and drinks. The current findings suggest that this may not be needed in moderate heat stress, as cooling only provided perceptual benefits in such conditions and could therefore be a team responsibility. In contrast, under more severe heat stress conditions, additional cooling strategies were effective in mitigating heat strain. Finally, the option to reschedule or cancel matches should be presented if heat stress becomes too severe. Therefore, a multi-level threshold system may be implemented. The first, and lowest threshold, recommends the implementation of additional breaks per half, with optional cooling managed at team levels. The second, higher threshold, requires event organizers to supply cooling resources to each team. The final, third threshold, would indicate to delay the match start or postpone the match. A summary of the key implications for developing and refining heat policies in football is presented in Summary Box 6.

Summary Box 6: Implications for football federations heat policies.

- **Players run less and perform less match actions** in higher heat stress.
- **Injury occurrence might increase** in higher heat stress.
- **Players can experience substantial heat strain** even in moderate heat.
- **Heat mitigation strategies should be introduced at a lower level** than 32 °C WBGT and will depend on player acclimatization and level.
- **In moderate heat**, implementing additional 3-min breaks is a feasible strategy to reduce heat strain in players. Cooling interventions during these breaks or prior to the match may reduce sweat loss and improve player comfort but should remain a team responsibility at this stage.
- **In severe heat**, competition organizers should provide and promote the use of additional cooling strategies as they further reduce heat strain and dehydration and improve player comfort.

To further support the implementation of heat mitigation strategies, players participating in the studies 4 and 5 were asked about their perceptions of the cooling interventions. Some quotes from the participants (translated from Spanish) were: “It seems to work, I really felt a change in my performance”; “The towels help me a lot to recover”; “I don’t like that the jersey gets too wet”; “I liked how the cold towel refreshed me, and that helped me to put up with the hot temperatures”; “It was good, but tedious nonetheless to play in such temperatures”; and “I liked it, I wouldn’t change anything about the intervention”. These quotes highlight how the cooling strategy was appreciated by the players and explains why the cooling protocol keeps being used in regular league competition by the club participating in the study. Based on these insights, and the findings of this thesis, Summary Box 7 offers practical guidance for practitioners to implement cooling strategies effectively.

Summary Box 7: Implications for football teams implementing heat mitigation strategies.

- **Expect performance impairments** in the heat and plan match strategies accordingly.
- **Introducing a pre-cooling break** between warm-up and match can lower initial heat strain.
- **Iced towels and drinks** can be prepared in cooling boxes filled with water and ice and kept next to the field. At least 2 persons should be responsible to facilitate a quick distribution of drink and towel.
- **In moderate heat,** applying cooling can lower dehydration and improve players’ comfort and thermal sensation, which is perceived as a performance benefit.
- **In severe heat** applying cooling can additionally lower core temperature and help maintain running performance.
- **Cooling procedures should be tested in practice**. Although most players reported to like the cooling intervention, some didn’t like to get severely wet.
- **Goalkeepers should be included in cooling procedures**, as they reach high heat strains similar to outfield players. They might want to remove gloves before cooling, to avoid getting them wet and improve heat dissipation.

D4. Future Research

This thesis presents several novel findings and contributes health and performance implications for playing football in the heat. However, it also highlights the need for future investigations, based on limitations presented in this work, to explore other cohorts, or to address how findings can be effectively translated into practice.

For instance, building on the findings of this thesis, future research could set up prospective observations on football performance and injury occurrence under varying environmental conditions. A key improvement of this research would be to implement a systematic monitoring of environmental conditions at football venues. If researchers can collaborate with leagues and federations to implement routine match-day measurements, these could be aligned with performance and injury data. Such integration would facilitate more comprehensive analyses. This is particularly important in the light of the expected global rise in temperatures (Klingelhöfer et al., 2023; World Meteorological Organization, 2023). Continued research should monitor the development of heat exposure in football competitions and especially the associations between injury risk and severe heat.

The warming climate also calls for improved monitoring of exertional heat illnesses and exertional heat stroke in football. To date, the number of cases remains largely unknown, due to the difficulties in detecting and likely underreporting of cases (Périard et al., 2022; Roberts et al., 2023). Establishing a dedicated registry to document these cases could provide valuable insights, while simultaneously raising awareness and inform about the prevention and treatment of severe cases.

Further field-based studies are also needed to assess T_{core} responses in football, under diverse conditions. Research needs to address different cohorts, such as different age groups or competition levels. Further the application of various cooling strategies, the effect of multiple congested matches as for example present in youth tournaments (Bergeron, 2009) or playing without acclimatization, potentially in combination with recent travel, is of interest. Additionally, future studies may

investigate whether cooling breaks remain effective under even more extreme heat, or whether competition rescheduling becomes inevitable at some point.

Field-based observations are also necessary in football training, given that football training may result in equal, if not higher exercise intensities than matches, especially during pre-season, often held during summer months. Only one observation has investigated this to date (Duffield et al., 2013). Future investigations should therefore explore T_{core} responses during training and determine optimal break structures and heat mitigation strategies.

For all studies presented in this thesis, a replication with female populations is strongly encouraged. Football performance, physiological and body composition differences, as well as the influence of the menstrual cycle might change study outcomes as shown recently by Brown et al. (2025). They could not replicate the effects of cooling breaks found in male participants (Brown et al., 2024). Although menstrual cycle tracking presents logistical challenges, future research must address this gap to ensure sex-specific recommendations.

To improve the practical translation of findings, qualitative studies could guide the implementation of heat policies into the field, especially at the amateur level. Surveys could target players and coaches perceptions of heat stress, its impact on health, wellbeing and performance, as well as their attitudes towards heat mitigation strategies and perceived barriers for their implementation. A similar investigation should assess referees knowledge and perceptions of heat policies. Given their key role for the implementation of such policies in amateur settings, understanding their abilities and attitudes regarding heat stress assessments and decision-making on heat mitigation strategies is essential.

D5. Conclusions

1. Football running performance is impaired in the heat. Higher temperatures lead to reductions in total distance, high-speed running and sprinting.

2. Football match play characteristics are altered in the heat. Fewer passes, touches, take-ons and turnovers are performed. The success rate of passes increases. Goal scoring, shooting, key passes and defensive parameters remain unaffected.

3. Injury occurrence may increase in higher heat strain, though more observations in hotter temperatures are needed to confirm this association.

4. When playing football matches, players' T_{core} can reach critical values approaching 40 °C even in moderate heat (~25 °C WBGT).

5. Simple heat mitigation strategies, such as pre-cooling and additional 3-minute breaks are effective in reducing the continuous rise in T_{core}. Pre-cooling was especially effective when placed between the warmup and the kick-off.

6. In moderate heat (~25 °C WBGT), applying cooling breaks (iced towels and cold drinks), compared to just drinking breaks, resulted in perceptual benefits and a reduced sweat amount.

7. In severe heat (~ 33 °C WBGT), applying cooling breaks compared to drinking breaks further reduces T_{core} and dehydration and benefits match running.

8. Players like the cooling application and perceive performance benefits from it.

9. Higher running volumes, especially in moderate to low speeds are associated with higher T_{core} peaks alongside a higher heart rate and higher sweat loss.

10. Goalkeepers are also exposed to high heat strains, similar to those of outfield players, but reach T_{core} peaks during the warm-up.

REFERENCES

References

Aldous, J. F. E., Chrismas, B. C. R., Akubat, I., Stringer, C. A., Abt, G., & Taylor, L. (2019). Mixed-methods pre-match cooling improves simulated soccer performance in the heat. *Eur J Sport Sci*, *19*(2), 156-165. https://doi.org/10.1080/17461391.2018.1498542

Alentorn-Geli, E., Myer G D, Silvers H J, Samitier G, Romero D, Lazaro-Haro C, & Cugat R. (2009). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*, *17*(7), 705-729.

Anderson, B. G., & Bell, M. L. (2009). Weather-Related Mortality. How Heat, Cold, and Heat Waves Affect Mortality in the United States. *Epidemiology*, *20*(2), 205-213. https://doi.org/10.1097/EDE.0b013e318190ee08

Andrzejewski, M., Olivia-Lozano, J. M., Chmura, P., Chmura, J., Slawomir, C., Kowalczuk, E., Rokita, A., Muyor, J. M., & Konefal, M. (2022). Analysis of team success based on match technical and running performance in a professional soccer league. *BMC Sports Sci Med Rehabil*, *14*(82). https://doi.org/10.1186/s13102-022-00473-7

Aquino, R., Gocalves, L. G., Galgaro, M., Maria, T. S., Rostaiser, E., Pastor, A., Nobari, H., Garcia, G. R., Moares-Neto, M. V., & Nakamura, F. Y. (2021). Match running performance in Brazilian professional soccer players: comparisons between successful and unsuccessful teams. . *BMC Sports Sci Med Rehabil*, *13*(93). https://doi.org/10.1186/s13102-021-00324-x

Aragón-Vargas, L. F., Moncada-Jiménez, J., Hernandez-Elizondo, J., Barrenechea, A., & Monge-Alvarado, M. (2009). Evaluation of pre-game hydration status, heat stress, and fluid balance during professional soccer competition in the heat. *Eur J Sport Sci*, *9*, 269-276. https://doi.org/10.1080/17461390902829242

Competition Operations Manual, (2023). https://assets.the-afc.com/downloads/miscellaneous-regulations/AFC-Competition-Operations-Manual-(Edition-2023).pdf

Asociación del Fútbol Argentino (AFA). (2025). *Reglamento Torneos Proyección. Temporada 2025. Liga Profesional de Fútbol de AFA.* Retrieved August 8, 2025 from https://www.ligaprofesional.ar/wp-content/uploads/2025/01/Reglamento-Torneos-LPF-Proyeccion-2025.pdf

aus der Fünten, K., Tröß, T., Hadji, A., Beaudouin, F., Steendahl, I. B., & Meyer, T. (2023). Epidemiology of Football Injuries of the German Bundesliga: A Media-Based, Prospective Analysis over 7 Consecutive Seasons. *Sports Med - Open*, *9*(1). https://doi.org/10.1186/s40798-023-00563-x

Azad, A., Mousavi, M., Gorzi, A., & Ghasemnian, A. (2016). The Effect of Precooling on Exhaustive Performance in the Hot Environment. *Asian J Sports Med*, *7*(3), e33125. https://doi.org/10.5812/asjsm.33125

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *J Stat Softw*, *67*(1), 1-48. https://doi.org/10.18637/jss.v067.i01

Benjamin, C. L., Sekiguchi, Y., Morrissey, M. C., Butler, C. R., Filep, E. M., Stearns, R. L., & Casa, D. J. (2021). The effects of hydration status and ice-water

dousing on physiological and performance indices during a simulated soccer match in the heat. *J Sci Med Sport*, *24*(8), 723-728. https://doi.org/10.1016/j.jsams.2021.05.013

Bergeron, M., Bahr R, Brätsch P, Bourdon L, Calbet JAL, Carlsen KH, Castagna O, González-Alonso J, Lundby C, Maughan RJ, Millet G, Mountjoy M, Racinais S, Rasmussen P, Singh DG, Subudhi AW, Young AJ, Soligard T, & Engebretsen L. (2012). International Olympic Committee consensus statement on thermoregulatory and altitude challenges for high-level athletes. *Br J Sports Med*, *46*, 779-779. https://doi.org/10.1136/bjsports-2012-091296

Bergeron, M. F. (2009). Youth Sports in the Heat. *Sports Med*, *39*, 513-522. https://doi.org/10.2165/00007256-200939070-00001

Bernard, T. E., Wolf, S. T., & Kenney, W. L. (2024). A Novel Conceptual Model for Human Heat Tolerance. *Exerc Sport Sci Rev*, *52*(2), 39-46. https://doi.org/10.1249/JES.0000000000000332

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2012). Comparison of UTCI to selected thermal indicies. *Int J Biometeorol*, *56*, 515-535. https://doi.org/https://doi.org/10.1007/s00484-011-0453-2

Błażejczyk, K., Jendritzky, G., Bröde, P., Fiala, D., Havenith, G., Epstein, Y., Psikuta, A., & Kampmann, B. (2013). An introduction to the Universal Thermal Climate Index (UTCI). *Geogr Pol*, *86*(1), 5-10. https://doi.org/10.7163/GPol.2013.1

Bongers, C., Hopman, M., & Eijsvogel, T. (2017). Cooling interventions for athletes: an overview of effectiveness, physiological mechanisms, and practical considerations. *Temperature*, *4*(1), 60-78. https://doi.org/10.1080/23328940.2016.1277003

Bongers, C., Thijssen, D., Veltmeijer MTW, Hopman, M., & Eijsvogels, T. (2015). Precooling and percooling (cooling during exercise) both improve performance in the heat: a meta-analytical review. *Br J Sports Med*, *49*, 377-384. https://doi.org/10.1136/bjsports-2013-092928

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Human Kinetics.

Bostanci, Ö., Mayda, H., Ceylan, L., Kaplan, A., Satici, A., & Yazici, Ö. (2018). 2016 UEFA European Championship: Pass and shot association. *J Human Sport Exerc*, *13*, 319-327. https://doi.org/10.14198/jhse.2018.132.07

Bradley, P., & Noakes, T. (2013). Match running performance fluctuations in elite soccer: Indicative of fatigue, pacing or situational influences? *J Sports Sci*, *31*(15). https://doi.org/10.1080/02640414.2013.796062

Bradley, P. S., Mascio, M., Peart, D., Olsen, P., & Sheldon, B. (2010). High-intensity activity profiles of elite soccer players at different performance levels. *J Strength Cond Res*, *24*, 2343-2351. https://doi.org/10.1519/JSC.0b013e3181aeb1b3

Brazen, D. M., Todd, M. K., Ambegaoknar, J. P., Wunderlich, R., & Peterson, C. (2010). The effect of fatigue on landing biomechanics in single-leg drop landings. *Clin J Sport Med*, *20*(4), 286-292. https://doi.org/10.1097/JSM.0b013e3181e8f7dc

Brearly, M., Berry, R., Hunt, A. P., & Pope, R. (2023). A Systematic Review of Post-Work Core Temperature Cooling Rates Conferred by Passive Rest. *Biology*, *12*(5). https://doi.org/10.3390/biology12050695

Brocherie, F., & Millet, G. P. (2015). Is the Wet-Bulb Globe Temperature (WBGT) Index Relevant for Exercise in the Heat? . *Sports Med*, *45*, 1619-1621. https://doi.org/10.1007/s40279-015-0386-8

Broich, H., Mester, J., Seifriz, F., & Yue, Z. (2014). Statistical Analysis for the First Bundesliga in the Current Soccer Season. *Progr Appl Math*, *7*(2), 1-8. https://doi.org/10.3968/4886

Brown, H., Chalmers, S., Topham, T., Clark, B., Meyer, T., Jowett, A., Jay, O., & Périard, J. (2025). Efficacy of the FIFA cooling break heat policy during an intermittent treadmill football simulation in hot conditions in trained females. *J Sci Med Sport*, *28*(6), 491-497. https://doi.org/10.1016/j.jsams.2025.02.003

Brown, H. A., Chalmers, S., Topham, T. H., Clark, B., Jowett, A., Meyer, T., Jay, O., & Périard, J. D. (2024). Efficacy of the FIFA cooling break heat policy during an intermittent treadmill football simulation in hot conditions in trained males. *Br J Sports Med*, *58*(18), 1044-1051. https://doi.org/10.1136/bjsports-2024-108131

Buchheit, M., Cholley, Y., & Lambert, P. (2016). Psychometric and Physiological Responses to a Preseason Competitive Camp in the Heat With a 6-Hour Time Difference in Elite Soccer Players. *Int J Sports Physiol Perform*, *11*(2), 176-181. https://doi.org/10.1123/ijspp.2015-0135

Buchheit, M., Voss, S. C., Nybo, L., Mohr, M., & Racinais, S. (2011). Physiological and performance adaptations to an in-season soccer camp in the heat: Associations with heart rate and heart rate variability. *Scand J Med Sci Sports*, *21*(6), e477-e485. https://doi.org/10.1111/j.1600-0838.2011.01378.x

Budd, G. M. (2008). Wet Bulb Globe Temperature (WBGT) – its history and its limitations. *J Sci Med Sport*, *11*, 20-32. https://doi.org/10.1016/j.jsams.2007.07.003

Byrne, C., Lee, J. K. W., Chew, S. A. N., Lim, C. L., & Tan, E. Y. M. (2006). Continuous thermoregulatory responses to mass-participation distance running in heat. *Med Sci Sports Ecerc*, *38*(5), 803-810. https://doi.org/10.1249/01.mss.0000218134.74238.6a

Carling, C., Dupont, G., & Le Gall, F. (2011). The effect of a cold environment on physical activity profiles in elite soccer match-play. *Int J Sports Med*, *32*(7), 542-545. https://doi.org/10.1055/s-0031-1273711

Casadio, J. R., Kilding, A. E., Cotter, J. D., & Laursen, P. B. (2017). From Lab to Real World: Heat Acclimation Considerations for Elite Athletes. *Sports Med*, *47*, 1467-1476. https://doi.org/10.1007/s40279-016-0668-9

Casanueva, A. (2019). *HeatStress*. In Casanueva, A. https://zenodo.org/records/3264930

Chalmers, S., Anderson, G., & Jay, O. (2020). Considerations for the development of extreme heat policies in sport and exercise. *BMJ Open Sport Exerc Med*, *6*(1), e000774. https://doi.org/10.1136/bmjsem-2020-000774

Chalmers, S., Esterman, A., Eston, R., Bowering, K., & Norton, K. (2014). Short-Term Heat Acclimation Training Improves Physical Performance: A Systematic Review, and Exploration of Physiological Adaptations and Application for Team Sports. *Sports Med*, *44*, 971-988. https://doi.org/10.1007/s40279-014-0178-6

Chalmers, S., Siegler J, Lovell R, Lynch G, Gregson W, Marshall P, & Jay O. (2019). Brief in-play cooling breaks reduce thermal strain during football in hot

conditions. *J Sci Med Sport*, *22*(8), 912-917. https://doi.org/10.1016/j.jsams.2019.04.009
Chalmers, S. M. (2017). In-play cooling strategies for sport in hot and humid conditions. *Temperature*, *4*(4), 353-355. https://doi.org/10.1080/23328940.2017.1361502
Chang, C., Bernard, T. E., & Logan, J. (2017). Effects of heat stress on risk perceptions and risk taking. *Appl Ergon*, *62*, 150-157. https://doi.org/10.1016/j.apergo.2017.02.018
Cheuvront, S., & Kenefick, R. (2017). CORP: Improving the status quo for measuring whole body sweat losses. *J Appl Physiol*, *123*(3), 632-636. https://doi.org/10.1152/japplphysiol.00433.2017
Cheuvront, S. N., & Kenefick, R. W. (2014). Dehydration: physiology, assessment, and performance effects. *Compr Physiol*, *4*(1), 257-285. https://doi.org/10.1002/cphy.c130017
Chmura, P., Konefał, M., Andrzejewski, M., Kosowski, J., Rokita, A., & Chmura, J. (2017). Physical activity profile of 2014 FIFA World Cup players, with regard to different ranges of air temperature and relative humidity. . *Int J Biometeorol*, *61*(4), 677-684. https://doi.org/10.1007/s00484-016-1245-5
Chmura, P., Konefał, M., Chmura, J., Kowalczuk, E., Zajac, T., Rokita, A., & Andrzejewski, M. (2018). Match outcome and running performance in different intensity ranges among elite soccer players. *Biol Sport*, *35*(2), 197-203. https://doi.org/https://doi.org/10.5114/biolsport.2018.74196
Chmura, P., Liu, H., Andrzejewski, M., Chmura, J., Kowalczuk, E., Rokita, A., & Konefał, M. (2021). Is there meaningful influence from situational and environmental factors on the physical and technical activity of elite football players? Evidence from the data of 5 consecutive seasons of the German Bundesliga. *PLoS ONE*, *16*(3), e0247771. https://doi.org/10.1371/journal.pone.0247771
Christidis, N., Jones, G. S., & Stott, P. A. (2015). Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nature Clim Change*, *5*, 46-50. https://doi.org/https://doi.org/10.1038/nclimate2468
Clarke, N. D., Maclaren, D. P. M., Reilly, T., & Drust, B. (2011). Carbohydrate ingestion and pre-cooling improves exercise capacity following soccer-specific intermittent exercise performed in the heat. *Eur J Appl Physiol*, *111*, 1447-1455. https://doi.org/10.1007/s00421-010-1771-5
Coehoorn, C. J., Stuart-Hill, L. A., Abibola, W., Neary, J. P., & Krigolson, O. (2020). Firefighter neural function and decision-making following rapid heat stress. *Fire Saf J*, *118*. https://doi.org/https://doi.org/10.1016/j.firesaf.2020.103240
Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd Ed ed.). Laurence Erlbaum Associates.
Coker, N. A., Wells, A. J., & Gepner, Y. (2020). Effect of Heat Stress on Measures of Running Performance and Heart Rate Responses During a Competitive Season in Male Soccer Players. *J Strength Cond Res*, *34*(4), 1141-1149. https://doi.org/10.1519/JSC.0000000000002441
Confederación Sudamericana de Fútbol (CONMEBOL). (2024, August 8, 2025). *Protocolos Comisión Médica*. https://cdn.conmebol.com/wp-content/uploads/2024/05/Protocolos-de-recomendaciones-medicas-CONMEBOL-Copa-America-USA-2024-ESP.pdf

Convit, L., Kelly, M. K., Jardine, W. T., Pèriard, J. D., Carr, A. J., Warmington, S., Bowe, S. J., & Snipe, R. M. J. (2024). Influence of acute heat mitigation strategies on core temperature, heart rate andaerobic performance in females: A systematic literature review. *J Sport Sci*, *42*(16), 1491-1511. https://doi.org/10.1080/02640414.2024.2396225

Cooper, E., Grundstein, A., Rosen, A., Miles, J., Ko, J., & Curry, P. (2017). An Evaluation of Portable Wet Bulb Globe Temperature Monitor Accuracy. *J Athl Train*, *52*(12), 1161-1167. https://doi.org/10.4085/1062-6050-52.12.18

Cramer, M. N., & Jay, O. (2016). Biophysical aspects of human thermoregulation during heat stress. *Auton Neurosci*, *196*, 3-13. https://doi.org/doi:10.1016/j.autneu.2016.03.001

d'Ambrosio Alfano, F. R., Malchaire, J., Palella, B. I., & Riccio, G. (2014). WBGT Index Revisited After 60 Years of Use. *Ann Occup Hyg*, *58*(8), 955-970. https://doi.org/doi:10.1093/annhyg/meu050

Deutscher Fußball-Bund (DFB). (2024). *Empfehlungen der Medizinischen Kommission des Deutschen-Fußball-Bundes bei Hitze*. Retrieved August 8, 2025 from https://www.fk-sbb.de/db.php/download/759/Empfehlung+Medizinische+Kommission+bei+Hitze.pdf

Distefano, L. J., Casa, D. J., Vansumeren, M. M., Karslo, R. M., Huggins, R. A., Demartini, J. K., Stearns, R. L., Armstrong, E. L., & Maresh, C. M. (2013). Hypohydration and hyperthermia impair neuromuscular control after exercise. *Med Sci Sports Exerc*, *45*(6), 1166-1173. https://doi.org/10.1249/MSS.0b013e3182805b83

Dolci, F., Hart, N. H., Kilding, A. E., Chivers, P., Piggott, B., & Spiteri, T. (2020). Physical and energetic demands of soccer: A brief review. *Strenght Cond J*, *42*(3), 70-77. https://doi.org/10.1519/SSC.0000000000000533

Draper, G., Atkinson, G., Chesterton, P., Portas, M., & Wright, M. (2023). Elite North American soccer performance in thermally challenging environments: An explorative approach to tracking outcomes. *J Sport Sci*, *41*(11), 1107-1114. https://doi.org/10.1080/02640414.2023.2259262

Draper, G., Wright, M. D., Ishida, A., Chesterton, P., Portas, M., & Atkinson, G. (2022). Do environmental temperatures and altitudes affect physical outputs of elite football athletes in match conditions? A systematic review of the 'real world' studies. *Sci Med Footb*, *7*(1), 81-92. https://doi.org/10.1080/24733938.2022.2033823

Drawer, S., & Fuller, C. W. (2002). Evaluating the level of injury in English professional football using a risk based assessment process. *Br J Sports Med*, *36*(6), 446-451. https://doi.org/10.1136/bjsm.36.6.446

Drust, B., Cable, N. T., & Reilly, T. (2000). Investigation of the effects of the pre-cooling on the physiological responses to soccer-specific intermittent exercise. *Eur J Appl Physiol*, *81*, 11-17. https://doi.org/10.1007/PL00013782

Duffie, J. A., & Beckman, W. A. (2013). *Solar Engineering of Thermal Processes* (4th ed.). John Wiley & Sons, Inc. https://doi.org/10.1002/9781118671603

Duffield, R., Coutts, A., McCall, A., & Burgess, D. (2013). Pre-cooling for football training and competition in hot and humid conditions. *Eur J Sport Sci*, *13*(1), 58-67. https://doi.org/10.1080/17461391.2011.589474

Duffield, R., Coutts, A. J., & Quinn, J. (2009). Core temperature responses and match running performance during intermittent-sprint exercise competition in warm conditions. *J Strength Cond Res*, *23*(4), 1238-1244. https://doi.org/10.1519/JSC.0b013e318194e0b1

Duffield, R., McCall, A., Coutts, A. J., & Pfeiffer, J. J. (2012). Hydration, sweat and thermoregulatory responses to professional football training in the heat. *J Sport Sci*, *30*(10), 957-965. https://doi.org/10.1080/02640414.2012.689432

Dvorak, J., Junge, A., Chomiak, J., Graf-Baumann, T., Peterson, L., Rösch, D., & Hodgson, R. (2000). Risk Factor Analysis for Injuries in Football Players. Possibilities For a Prevention Program. *A J Sports Medicine*, *28*(5), 69-74. https://doi.org/10.1177/28.suppl_5.s-69

Edouard, P., Dandrieux, P., Klöwer, M., Junge A, Racinais S, Branco, P., Hollander, K., & Navarro, L. (2025). Association between feels-like temperatures and injury risk during international outdoor athletic championships: a prospective cohort study on 29 579 athlete starts during 10 championships. *Br J Sports Med*, *59*(1), 36-47. https://doi.org/10.1136/bjsports-2023-108050

Edwards, A. M., & Clark, N. A. (2006). Thermoregulatory observations in soccer match play: Professional and recreational level applications using an intestinal pill system to measure core temperature. *Br J Sports Med*, *40*, 133-138. https://doi.org/10.1136/bjsm.2005.021980

Eichner, E. R. (2019). Fatal Exertional Heat Stroke in Football: The Coaches Are the Culprits. *Curr Sports Med Rep*, *18*(7), 251-252. https://doi.org/10.1249/JSR.0000000000000612

Ekstrand, J., Hägglund, M., & Walden, M. (2011). Injury incidence and injury patterns in professional football: the UEFA injury study. *Br J Sports Med*, *45*(7), 553-558. https://doi.org/10.1136/bjsm.2009.060582

Epstein, Y., Moran, D. S., Shapiro, Y., Sohar, E., & Shemer, J. (1999). Exertional heat stroke: a case series. *Med Sci Sports Exerc*, *31*(2), 224-228. https://doi.org/10.1097/00005768-199902000-00004

Epstein, Y., & Yanovich, R. (2019). Heatstroke. *N Engl J Med*, *380*, 2449-2459. https://doi.org/10.1056/NEJMra1810762

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *J Sport Sci*, *30*(7), 625-631. https://doi.org/10.1080/02640414.2012.665940

Faulkner, S. H., Broekhuijzen, I., Raccuglia, M., Hupperets, M., Hodder, S. G., & Havenith, G. (2019). The Threshold Ambient Temperature for the Use of Precooling to Improve Cycling Time-Trial Performance. *Int J Sports Physiol Perform*, *14*(3), 323-330. https://doi.org/10.1123/ijspp.2018-0310

FBREF. *Football Stats and History*. Retrieved April 8, 2023 from https://fbref.com/en/

Fédération Internationale de Football Association (FIFA). (2015). *Football Emergency Medicine Manual 2nd Edition*. Retrieved August 8, 2025 from https://schoolsfootball.org/wp-content/uploads/2021/07/football-emergency-medicine-manual-2nd-edition-2015-2674609.pdf

FIFPRO - Football Players Worldwide. (n.d., August 8, 2025). *GUIDELINES AND MITIGATION STRATEGIES FOR HOT CONDITIONS IN PROFESSIONAL FOOTBALL*. https://fifpro.org/media/pl1ppgbb/heat-guidelines_en-1.pdf

Fogleman, M., Fakhrzadeh, L., & Bernard, T. E. (2005). The relationship between outdoor thermal conditions and acute injury in an aluminum smelter. *Int J Ind Ergon*, *35*(1), 47-55. https://doi.org/10.1016/j.ergon.2004.08.003

Football Australia. (n.d.). *Football Australia Heat Policy*. Retrieved August 8, 2025 from https://www.footballaustralia.com.au/ffa-heat-policy#:~:text=The%20FIFA%20Heat%20Policy%20recommends,WBGT%20reaches%2028%20degrees%20Celsius

Fuller, C. W., Ekstrand, J., Junge, A., Andersen, T. E., Bahr, R., Dvorak, J., Hägglund, M., McCrory, P., & Meeuwisse, W. H. (2006). Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Br J Sports Med*, *40*, 193-201. https://doi.org/10.1136/bjsm.2005.025270

Gabbett, T., Minbashian, A., & Finch, C. (2007). Influence of environmental and ground conditions on injury risk in rugby league. *J Sci Med Sport*, *10*(4), 211-218. https://doi.org/10.1016/j.jsams.2006.11.003

Gamage, P. J., Fortington, L. V., & Finch, C. F. (2020). Epidemiology of exertional heat illnesses in organised sports: A systematic review. *J Sci Med Sport*, *23*, 701-709. https://doi.org/10.1016/j.jsams.2020.02.008

Gaoua, N., Grantham, J., El Massioui, F., Girard O, & Racinais, S. (2011). Cognititive decrements do not follow neuromuscular alterations during passive heat exposure. *Int J Hyperth*, *27*(1), 10-19. https://doi.org/10.3109/02656736.2010.519371

Gaoua, N., Racinais, S., Grantham, J., & Massioui, F. E. (2011). Alterations in cognitive performance during passive hyperthermia are task dependent. *Int J Hyperthermia*, *27*(1), 1-9. https://doi.org/10.3109/02656736.2010.516305

Geneva, I. I., Cuzzo, B., Fazili, T., & Javaid, W. (2019). Normal Body Temperature: A Systematic Review. *Open Forum Infect Dis*, *6*(4). https://doi.org/10.1093/ofid/ofz032

Gilbert, M., Busund, R., Skagseth, A., Nilsen, P. Å., & Solbø, J. P. (2000). Resuscitation from accidental hypothermia of 13.7 degrees C with circulatory arrest. *Lancet*, *355*(9201), 375-376. https://doi.org/10.1016/S0140-6736(00)01021-7

Girard, O., Brocherie, F., & Bishop, D. J. (2015). Sprint performance under heat stress: A review. *Scand J Med Sci Sports*, *25*(S1), 79-89. https://doi.org/10.1111/sms.12437

Gonzalez, R. R. (1995). Biophysics of Heat Exchange and Clothing: Applications to Sports Physiology. *Med Exerc Nutr Health*, *4*, 290-305.

Gouttebarge, V., Duffield, R., den Hollander, S., & Maughan, R. (2023). Protective guidelines and mitigation strategies for hot conditions in professional football: starting 11 Hot Tips for consideration. *BMJ Open Sport Exerc*, *9*(30). https://doi.org/10.1136/bmjsem-2023-001608

Griffin, J., Larsen, B., Horan, S., Keogh, J., Dodd, K., Andreatta, M., & Minahan, C. (2020). Women's Football: An Examination of Factors That Influence Movement Patterns. *J Strength Cond Res*, *34*(8), 2384-2393. https://doi.org/10.1519/JSC.0000000000003638

Hägglund, M., Waldén, M., Magnusson, H., Kristenson, K., Bengtsson, H., & Ekstrand, J. (2013). Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League

injury study. *Br J Sports Med*, *47*(12), 807-808. https://doi.org/10.1136/bjsports-2013-092215

Hemmatjo, R., Motamedzade, M., Aliabadi, M., Kalatpour, O., & Farhadian, M. (2017). The effect of practical cooling strategies on physiological response and cognitive function during simulated firefighting tasks. *Health Promotion Perspectives*, *7*(2), 66-73. https://doi.org/10.15171/hpp.2017.13

Heydenreich, J., Koehler, K., Braun, H., Grosshauser, M., Heseker, H., Koenig, D., Lampen, A., Mosler, S., Niess, A., Schek, A., & Carlsohn, A. (2023). Effects of internal cooling on physical performance, physiological and perceptional parameters when exercising in the heat: A systematic review with meta-analyses. *Front Physiol*, *14*. https://doi.org/10.3389/fphys.2023.1125969

Holm, R. L., Pribyslavska, V., Scudamore, E. M., Johnson, S., Langford, T. W., Stevenson-Wilcoxson, M. C., Lowe, J. B., Green, J. M., Katica, C. P., & O'Neal, E. K. (2018). Performance and Perceptual Responses of Collegiate Female Soccer Players to a Practical External and Internal Cooling Protocol. *Int J Exerc Sci*, *8*(4), 331-340. https://doi.org/10.70252/RQCQ8069

Hoppe, M. W., Slomka, M., Baumgart, C., Weber, H., & Freiwald, J. (2015). Match Running Performance and Success Across a Season in German Bundesliga Soccer Teams. *Int J Sports Med*, *36*(7), 563-566. https://doi.org/10.1055/s-0034-1398578.

Hosokawa, Y., Grundstein, A. J., & Casa, D. J. (2018). Extreme Heat Considerations in International Football Venues: The Utility of Climatologic Data in Decision Making. *J Athl Train*, *53*(9), 860-865. https://doi.org/10.4085/1062-6050-361-17

Illmer, S., & Daumann, F. (2022). The effects of weather factors and altitude on physical and technical performance in professional soccer: A systematic review. *JSAMS Plus*, *1*. https://doi.org/10.1016/j.jsampl.2022.100002

Ingersoll, C. D., Knight, K. L., & Merrick, M. A. (1992). Sensory perception of the foot and ankle following therapeutic applications of heat and cold. *J Athl Train*, *27*(3), 231-234.

Jacobson, I., & Tegner, Y. (2006). Injuries among female football players – With special emphasis on regional differences. *Adv Physiother*, *8*(2), 66-74. https://doi.org/10.1080/14038190600621706

Jay, O., & Morris, N. B. (2018). Does Cold Water or Ice Slurry Ingestion During Exercise Elicit a Net Body Cooling Effect in the Heat? *Sports Med*, *48*, 17-29. https://doi.org/10.1007/s40279-017-0842-8

Jendritzky, G., de Dear, R., & Havenith, G. (2012). UTCI - Why another thermal index? *Int J Biometeorol*, *56*, 421-428. https://doi.org/10.1007/s00484-011-0513-7

Jones, M. (2024). *Football Australia Heat Policy*. Retrieved December 19, 2024 from https://www.footballaustralia.com.au/ffa-heat-policy

Kenney, W. L. (1985). A review of comparative responses of men and women to heat stress. *Environ Res*, *37*(1), 1-11. https://doi.org/10.1016/0013-9351(85)90044-1

Klingelhöfer, D., Braun, M., Brüggmann, D., & Groneberg, D. A. (2023). Heatwaves: does global research reflect the growing threat in the light of climate change? *Global Health*, *19*(56). https://doi.org/10.1186/s12992-023-00955-4

Konefał, M., Chmura, P., Andrzejewski, M., & Chmura, J. (2014). Analysis of motor performance of professional soccer players in different environmental conditions. *Trends Sport Sci*, *4*(21), 221-227.

Konefał, M., Chmura, P., Zacharko, M., Baranowski, J., & Andrzejewski, M. (2021). The influence of thermal stress on the physical and technical activities of soccer players: lessons from the 2018 FIFA World Cup in Russia. *Int J Biometeorol*, *65*, 1291-1298. https://doi.org/https://doi.org/10.1007/s00484-020-01964-3

Kong, Q., & Huber, M. (2022). Explicit calculations of wet-bulb globe temperature compared with approximations and why it matters for labor productivity. *Earth's Future*, *10*, e2021EF002334. https://doi.org/10.1029/2021EF002334

Koumar, O. C., Beaufils, R., Chesneau, C., Normand, H., & Bessot, N. (2023). Validation of e-Celsius gastrointestinal telemetry system as measure of core temperature. *J Therm Biol*, *112*. https://doi.org/10.1016/j.jtherbio.2023.103471

Krutsch, W., Memmel, C., Alt, V., Krutsch, V., Tröß, T., aus der Fünten, K., & Meyer, T. (2022). Timing return-to-competition: a prospective registration of 45 different types of severe injuries in Germany's highest football league. *Arch Orthop Trauma Surg*, *142*(3), 455-463. https://doi.org/10.1007/s00402-021-03854-8

Laitano, O., King, M. A., & Leon, L. R. (2019). Common Misconceptions in Classic and Exertional Heat Stroke. In J. Périard & S. Racinais (Eds.), *Heat Stress in Sport and Exercise* (pp. 91-112). Springer. https://doi.org/https://doi.org/10.1007/978-3-319-93515-7_5

Lee, A. J., & Garraway, W. M. (2000). The influence of environmental factors on rugby football injuries. *J Sports Sci*, *18*, 91-95. https://doi.org/10.1080/026404100365153

Lemke, B., & Kjellstrom, T. (2012). Calculating Workplace WBGT from Meteorological Data: A Tool for Climate Change Assessment. *Ind Health*, *50*(4), 267-278. https://doi.org/10.2486/indhealth.ms1352

Lepschy, H., Wäsche, H., & Woll, A. (2020). Success factors in football: an analysis of the German Bundesliga. *Int J Perform Anal Sport*, *20*(2), 150-164. https://doi.org/10.1080/24748668.2020.1726157

Liljegren, J. C., Carhart, R. A., Lawday, P., Tschopp, S., & Sharp, R. (2008). Modelling the Wet Bulb Globe Temperature Using Standard Meteorological Measurements. *J Occup Environ Hyg*, *5*(10), 645-655. https://doi.org/10.1080/15459620802310770

Linder-Cendrowska, K., Leziak, K., Bröde, P., Fiala, D., & Konefał, M. (2024). Prospective heat stress risk assessment for professional soccer players in the context of the 2026 FIFA World Cup. *Sci Rep*, *14*. https://doi.org/10.1038/s41598-024-77540-1

Link, D., & Weber, H. (2015). Effect of ambient temperature on pacing in soccer depends on skill level. *J Strength Condition Res*, *31*(7), 1766-1770. https://doi.org/10.1519/JSC.0000000000001013

Liu, H., Gomez, M. A., Goncalves, B., & Sampaio, J. (2015). Technical performance and match-to-match variation in elite football teams. *J Sports Sci*, *34*(6), 509-518. https://doi.org/10.1080/02640414.2015.1117121

Long, J. A. (2022). *_jtools: Analysis and Presentation of Social Scientific Data_*. In *R package version 2.2.0* https://cran.r-project.org/package=jtools

Lossius, K., Eriksen, M., & Walløe, L. (1993). Fluctuations in blood flow to acral skin in humans: connection with heart rate and blood pressure variability. *J Phyisol*, *460*, 641-655. https://doi.org/10.1113/jphysiol.1993.sp019491

Loxston, C., Lawson, M., & Unnithan, V. (2019). Does environmental heat stress impact physical and technical match-play characteristics in football? *Sci Med Football*, *3*(3), 191-197. https://doi.org/10.1080/24733938.2019.1566763

Lu, D., McCall, A., Jones, M., & Duffield, R. (2022). The relationship between team-level and league-level injury rate, type and location in a professional football league. *J Sci Med Sport*, *25*(7), 564-568. https://doi.org/10.1016/j.jsams.2022.03.017

Lu, D., McCall, A., Jones, M., Steinweg, J., Gelis, L., Fransen, J., & Duffield, R. (2021). The financial and performance cost of injuries to teams in Australian professional soccer. *J Sci Med Sport*, *24*(5), 463-467. https://doi.org/10.1016/j.jsams.2020.11.004

Lynch, G., Périard, J. D., Pluim, B. M., Brotherhood, J. R., & Jay, O. (2018). Optimal cooling strategies for players in Australian Tennis Open conditions. *J Sci Med Sport*, *21*(3), 232-237. https://doi.org/10.1016/j.jsams.2017.05.017

Mack, G. W., & Nadel, E. R. (1996). Body Fluid Balance During Heat Stress in Humans. In M. Fregly & C. Blatteis (Eds.), *Handbook of Physiology: Environmnetal Physiology* (pp. 187-214). Oxford University Press.

Martínez-Solanas, È., López-Ruiz, M., Wellenius, G. A., Gasparrini, A., Sunyer, J., Benavides, F. G., & Basagaña, X. (2018). Evaluation of the Impact of Ambient Temperatures on Occupational Injuries in Spain. *Environ Health Perspect*, *126*(6). https://doi.org/10.1289/EHP2590

Maughan, R., & Shirreffs, S. (2008). Development of Individual Hydration Strategies for Athletes. *Int J Sport Nutr Exerc Metab*, *18*(5), 457-472. https://doi.org/10.1123/ijsnem.18.5.457

Maughan, R., Shirreffs, S., Ozgünen, K., Kurdak, S., Ersöz, G., Binnet, M., & Dvorak, J. (2010). Living, training and playing in the heat: challenges to the football player and strategies for coping with environmental extremes. *Scand J Med Sci Sports*, *20*(3), 117-124. https://doi.org/10.1111/j.1600-0838.2010.01221.x

McKay, A. K. A., Stellingwerff, T., Sheppard, J., & Burke, L. M. (2021). Defining Training and Performance Caliber: A Participant Classification Framework. *Int J Sports Physiol Perform*, *17*(2), 317-331. https://doi.org/10.1123/ijspp.2021-0451

Meteostat.net. *The Weather's Record Keeper*. Retrieved November 12, 2023 from https://meteostat.net/en/

Micklewright, D., Gibson, A. S. C., Gladwell, V., & Al Salman, A. (2017). Development and Validity of the Rating-of-Fatigue Scale. *Sports Med*, *47*(11), 2375-2393. https://doi.org/10.1007/s40279-017-0711-5

Minett, G. M., Duffield, R., Marino, F. E., & Portus, M. (2011). Volume-Dependent Response of Precooling for Intermittent-Sprint Exercise in the Heat. *Med Sci Sports Exerc*, *43*(9), 1760-1769. https://doi.org/10.1249/MSS.0b013e318211be3e

Mohr, M., Nybo, L., Grantham, J., & Racinais, S. (2012). Physiological Responses and Physical Performance during Football in the Heat. *PLoS ONE*, *7*(6), e39202. https://doi.org/10.1371/journal.pone.0039202

Montain, S. J., Ely, M. R., & Cheuvront, S. N. (2007). Marathon Performance in Thermally Stressing Conditions. *Sports Med*, *37*, 320-323. https://doi.org/10.2165/00007256-200737040-00012

Mora-Rodriguez, R. (2012). Influence of Aerobic Fitness on Thermoregulation During Exercise in the Heat. *Exerc Sport Sci Rev*, *40*(2), 79-87. https://doi.org/10.1097/JES.0b013e318246ee56

Mtibaa, K., Thomson, A., Nichols, D., Hautier, C., & Racinais, S. (2018). Hyperthermia-induced Neural Alterations Impair Proprioception and Balance. *Med Sci Sports Exerc*, *50*(1), 46-53. https://doi.org/10.1249/MSS.0000000000001418

Muñoz-López, A., Granero-Gil, P., Ortega, J. P., & de Hoyo, M. (2017). The validity and reliability of a 5-hz GPS device for quantifying athletes' sprints and movement demands specific to team sports. *J Human Sport Exerc*, *12*(1), 156-166. https://doi.org/10.14198/jhse.2017.121.13

Nassis, G., Girard, O., Chiampas, G., Krustup, P., & Racinais, S. (2024). In-match strategies to mitigate the effect of heat on football (soccer) players' health and performance. *Br J Sports Med*, bjsports-2023-107907. https://doi.org/10.1136/bjsports-2023-107907

Nassis, G. P., Brito, J., Dvorak, J., Chalabi, H., & Racinais, S. (2015). The association of environmental heat stress with performance: analysis of the 2014 FIFA World Cup Brazil. *Br J Sports Med*, *49*, 609-613. https://doi.org/10.1136/bjsports-2014-094449

Nieminen, P. (2022). Application of Standardized Regression Coefficient in Meta-Analysis. *Bio Med Informatics*, *2*(3), 434-458. https://doi.org/10.3390/biomedinformatics2030028

Nybo, L., Girard, O., Mohr, M., Knez, W., Voss, S., & Racinais, S. (2013). Markers of Muscle Damage and Performance Recovery after Exercise in the Heat. *Med Sci Sports Exerc*, *45*(5), 1-9. https://doi.org/10.1249/MSS.0b013e31827ded04

Nybo, L., Rasmussen, P., & Sawka, M. N. (2014). Performance in the Heat – Physiological Factors of Importance for Hyperthermia-Induced Fatigue. *Compr Physiol*, *4*(2), 657-689. https://doi.org/10.1002/cphy.c130012

Orchard, J., & Seward, H. (2002). Epidemiology of injuries in the Australian Football League, seasons 1997-2000. *Br J Sports Med*, *36*, 39-45. https://doi.org/10.1136/bjsm.36.1.39

Otte im Kampe, E., Kovats, S., & Hajat, S. (2016). Impact of high ambient temperature on unintentional injuries in high-income countries: a narrative systematic literature review. *BMJ Open*, *6*, e010399. https://doi.org/10.1136/bmjopen-2015-010399

Özgünen, K. T., Kurdak, S. S., Maughan, R. J., Zeren, C., Korkmaz, S., Yazici, Z., Ersöz, G., Shirreffs, S. M., Binnet, M. S., & Dvorak, J. (2010). Effect of hot environmental conditions on physical activity patterns and temperature response of football players. *Scand J Med Sci Sports*, *20*, 140-147. https://doi.org/10.1111/j.1600-0838.2010.01219.x

Palucci Viera, L. H., Carling, C., Barbieri, F. A., Aquino, R., & Pereira Santiago, P. R. (2019). Match Running Performance in Young Soccer Players: A Systematic Review. *Sports Med*, *49*, 289-318. https://doi.org/10.1007/s40279-018-01048-8

Parris, K., & Tyler, C. J. (2018). Practical Torso Cooling During Soccer-Specific Exercise in the Heat. *J Athl Train*, *53*(11), 1098-1097. https://doi.org/10.4085/1062-6050-417-17

Patel, T., Mullen, S. P., & Santee, W. R. (2013). Comparison of Methods for Estimating Wet-Bulb Globe Temperature Index From Standard Meteorological Measurements. *Mil Med*, *178*(8), 926-933. https://doi.org/10.7205/MILMED-D-13-00117

Périard, J., DeGroot, D., & Jay, O. (2022). Exertional heat stroke in sport and the military: epidemiology and mitigation. *Exp Physiol*, *107*, 1111-1121. https://doi.org/10.1113/EP090686

Périard, J., Eijsvogels, T., & Daanen, H. (2021). Exercise under heat stress: thermoregulation, hydration, performance implications and mitigation strategies. *Physiol Rev*, *101*, 1873-1979. https://doi.org/10.1152/physrev.00038.2020

Périard, J., & Racinais, S. (2019). *Heat Stress in Sport and Exercise. Thermophysiology of Health and Performance*. Springer.

Perkins, S. E., Alexander, L. V., & Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophys Res Lett*, *39*. https://doi.org/10.1029/2012GL053361

Pethick, W. A., Stellingwerff, T., Lacroix, M. A., Bergstrom, C., & Meylan, C. M. (2018). The effect of a team sport-specific heat acclimation protocol on plasma volume in elite female soccer players. *Sci Med Footb*, *2*(1), 16-22. https://doi.org/10.1080/24733938.2017.1384559

Plakias, S., Tasoulis, S., Kyranoudis, A. E., Kokkotis, C., & Moustakidis, S. (2025). The Limited Impact of Running Performance on Football Success in the Turkish Super League. *Appl Sci*, *15*(637). https://doi.org/10.3390/app15020637

Plakias, S., Tsatalas, T., Mina, M. A., Kokkotis, C., Flouris, A. D., & Giakas, G. (2024). The Impact of Heat Exposure on the Health and Performance of Soccer Players: A Narrative Review and Bibliometric Analysis. *Sports*, *12*(9). https://doi.org/10.3390/sports12090249

Price, M. J., Boyd, C., & Goosey-Tolfrey, V. L. (2009). The physiological effects of pre-event and midevent cooling during intermittend running in the heat in elite female soccer players. *Appl Physiol Nutr Metab*, *34*, 942-949. https://doi.org/10.1139/H09-078

Puga, T., Schafer, J., Scigliano, N., Thiel, G., & Treffer, K. (2022). Exertional Heat Illness: A Yearly Preventable Cause of Illness and Death in Athletes. *Int J Sport Exerc Health Res*, *6*(2), 99-102. https://doi.org/10.31254/sportmed.6201

R Core Team. (2023). *_R: A Language and Environment for Statistical Computing_*. In *R Foundation for Statistical Computing* https://www.R-project.org/

Racinais, S., Hosokawa, Y., Akama, T., Bermon, S., Bigard, X., Casa, D. J., Grundstein, A., Jay, O., Massey, A., Migliorini, S., Mountjoy, M., Nikolic, N., Pitsiladis, Y. P., Schobersberger, W., Steinacker, J. M., Yamasawa, F., Zideman, D. A., Engebretsen, L., & Budgett, R. (2023). IOC consensus statement on recommendations and regulations for sport events in the heat. *Br J Sports Med*, *57*(1), 8-25. https://doi.org/10.1136/bjsports-2022-105942

Racinais, S., Ihsan, M., & Périard, J. D. (2019). Neural and Muscular Funtion in the Heat. In J. D. Périard & S. Racinais (Eds.), *Heat Stress in Sport and Exercise. Thermophysiology of Health and Performance* (pp. 67-88). Springer.

Racinais, S., Mohr, M., Buchheit, M., Voss, S. C., Gaoua, N., Grantham, J., & Nybo, L. (2012). Individual responses to short-term heat acclimatisation as predictors of football performance in a hot, dry environment. *Br J Sports Med*, *46*(11), 810-815. https://doi.org/10.1136/bjsports-2012-091227

Racinais, S., Moussay, S., Nichols, D., Travers, G., Belfekih, T., Schumacher, Y. O., & Periard, J. D. (2019). Core temperature up to 41.5°C during the UCI Road Cycling World Championships in the heat. *Br J Sports Med*, *53*, 426-429. https://doi.org/10.1136/bjsports-2018-099881

Racinais, S., Periard, J. D., Karlsen, A., & Nybo, L. (2015). Effect of Heat and Heat Acclimatization on Cycling Time Trial Performance and Pacing. *Med Sci Sports Exerc*, *47*(3), 601-606. https://doi.org/10.1249/MSS.0000000000000428

Rampinini, E., Impellizzeri, F. M., Castagna, C., Coutts, A. J., & Wisloff, U. (2009). Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. *J Sci Med Sport*, *12*(1), 227-233. https://doi.org/10.1016/j.jsams.2007.10.002

Ravanelli, N., Bongers, C. C. W. G., & Jay, O. (2019). The Biophysics of Human Heat Exchange. In J. Périard & S. Racinais (Eds.), *Heat Stress in Sport and Exercise.* (pp. 29-43). Springer. https://doi.org/https://doi.org/10.1007/978-3-319-93515-7_2

Rein, R., Raabe, D., & Memmert, D. (2017). „Which pass is better?“ Novel approaches to assess passing effectiveness in elite soccer. *Hum Mov Sci 55*, 172-181. https://doi.org/10.1016/j.humov.2017.07.010

Roberts, W. O., Armstrong, E. L., Sawka, M. N., Yeargin, S. W., Heled, Y., & O'Connor, F. G. (2023). ACSM Expert Consensus Statement on Exertional Heat Illness: Recognition, Management, and Return to Activity. *Curr Sports Med Rep*, *20*(9), 470-484. https://doi.org/10.1249/JSR.0000000000000878

Saldaris, J. M., Landers, G. J., & Brendan, S. L. (2019). Physical and perceptual cooling: Improving cognitive function, mood disturbance and time to fatigue in the heat. *Scand J Med Sci Sports*, *30*, 801-811. https://doi.org/10.1111/sms.13623

Schlader, Z., Stannard, S., & Mundel, T. (2010). Human thermoregulatory behavior during rest and exercise - a prospective review. *Physiol Behav*, *99*(3), 269-275. https://doi.org/10.1016/j.physbeh.2009.12.003

Schlader, Z. J., Simmons, S. E., Stannard, S. R., & Mundel, T. (2011). The independent roles of temperature and thermal perception in the control of human thermoregulatory behavior. *Physiol Behav*, *103*(2), 217-224. https://doi.org/10.1016/j.physbeh.2011.02.002

Schmit, C., Duffield, R., Hausswirth, C., Coutts, A. J., & Le Meur, Y. (2015). Pacing Adjustments Associated With Familiarization: Heat Versus Temperate Environments. *Int J Sports Physiol Perform*, *11*(7), 855-860. https://doi.org/10.1123/ijspp.2015-0572

Schmit, C., Hausswirth, C., LeMeur, Y., & Duffield, R. (2017). Cognitive Functioning and Heat Strain: Performance Responses and Protective Strategies. *Sports Med*, *47*(7), 1289-1302. https://doi.org/10.1007/s40279-016-0657-z

Schulze, E., Julian, R., & Meyer, T. (2021). Exploring Factors Related to Goal Scoring Opportunities in Professional Football. *Sci Med Footb*, *6*(2), 181-188. https://doi.org/10.1080/24733938.2021.1931421

Schwarz, E., Duffield, R., Lu, D., Fullagar, H., aus der Fünten, K., Skorski, S., Tröß, T., Hadji, A., & Meyer, T. (2025). Associations between injury occurrence and environmental temperatures in the Australian and German professional football leagues. *Environ Epidemiol*, *9*(1), e364. https://doi.org/10.1097/EE9.0000000000000364

Schwarz, E., Duffield, R., Novak, A., Görres, T., & Meyer, T. (2024). Associations Between Match Running Performance and Environmental Temperatures in 4 Professional Football Leagues. *Int J Sports Physiol Perform*, *20*(1), 109-119. https://doi.org/10.1123/ijspp.2024-0248

Schwarz, E., Duffield, R., Novak, A. R., Compton, D. A., & Meyer, T. (2025). Associations Between Match-Play Characteristics and Environmental Temperatures in 4 Professional Football Leagues. *Eur J Sport Sci*, *25*(3), e12256. https://doi.org/10.1002/ejsc.12256

Singh, G., Bennett, K. J. M., Taylor, L., & Stevens, C. J. (2023). Core body temperature responses during competitive sporting events: A narrative review. *Biol Sport*, *40*(4), 1003-1017. https://doi.org/10.5114/biolsport.2023.124842

Skein, M., Duffield, R., Cannon, J., & Marino, F. (2012). Self-paced intermittent-sprint performance and pacing strategies following respective pre-cooling and heating. *Eur J Appl Physiol*, *112*, 253-266. https://doi.org/10.1007/s00421-011-1972-6

Slattery, K., & Coutts, A. J. (2019). The Application of Heat Stress to Team Sports: Football/Soccer, Australian Football and Rugby: Thermophysiology of Health and Performance. In J. Périard & S. Racinais (Eds.), *Heat Stress in Sport and Exercise* (pp. 181-202). Springer. https://doi.org/10.1007/978-3-319-93515-7_9

Slovis, C. M., Anderson, G. F., & Casolaro, A. (1982). Survival in a heat stroke victim with a core temperature in excess of 46.5 C. *Ann Emerg Med*, *11*(5), 269-271. https://doi.org/10.1016/s0196-0644(82)80099-1

Smallcombe, J. W., Topham, T. H., Brown, H. A., Tiong, M., Clark, B., Broderick, C., Chalmers, S., Orchard, J., Mavros, Y., Périard, J. D., & Jay, O. (2025). Thermoregulation and dehydration in children and youth exercising in extreme heat compared with adults *Br J Sports Med*, *59*(16), 1151-1159. https://doi.org/10.1136/bjsports-2025-109832

Spector, J. T., Masuda, Y. J., Wolff, N. H., Calkins, M., & Seixas, N. (2019). Heat Exposure and Occupational Injuries: Review of the Literature and Implications. *Curr Environ Health Rep*, *6*(4), 286-296. https://doi.org/10.1007/s40572-019-00250-8

Stachenfeld, N. S. (2014). The Interrelationship of Research in the Laboratory and the Field to Assess Hydration Status and Determine Mechanisms Involved in Water Regulation During Physical Activity. *Sports Med*, *44*, 97-104. https://doi.org/10.1007/s40279-014-0155-0

STATS PERFORM. *Opta Data*. Retrieved November 12, 2023 from https://www.statsperform.com/opta/

Stevens, C. J., Mauger, A. R., Hasmmèn, P., & Taylor, L. (2018). Endurance Performance is Influenced by Perceptions of Pain and Temperature: Theory,

Applications and Safety Considerations. *Sports Med*, *48*, 525-537. https://doi.org/10.1007/s40279-017-0852-6
Stoviz, S. D., & Shrier, I. (2012). Injury rates in team sport events: tackling challenges in assessing exposure time. *Br J Sports Med*, *46*(14), 960-963. https://doi.org/10.1136/bjsports-2011-090693
Sugawara, M., Manabe, Y., Yamasawa, F., & Hosokawa, Y. (2022). Athlete Medical Services at the Marathon and Race Walking Events During Tokyo 2020 Olympics. *Front Sports Act Living*, *4*. https://doi.org/10.3389/fspor.2022.872475
Sunderland, C., Morris, J. G., & Nevill, M. E. (2010). A heat acclimation protocol for team sports. *Br J Sports Med*, *42*(5), 327-333. https://doi.org/10.1136/bjsm.2007.034207
Syndicus, M., Wiese, B. S., & van Treeck, C. (2018). In the Heat and Noise of the Moment: Effects on Risky Decision Making. *Environ Behav*, *50*(1). https://doi.org/10.1177/0013916516680700
Teixeira, J. E., Branquinho, L., Leal, M., Marinho, D. A., Ferraz, R., Barbosa, T. M., Monteiro, A. M., & Forte, P. (2022). Modeling the Major Influencing Factor on Match Running Performance during the In-Season Phase in a Portuguese Professional Football Team. *Sports*, *10*(8). https://doi.org/10.3390/sports10080121
The International Football Association Board (IFAB). (2025). *Laws of the Game 25/26*. The International Football Association Board (IFAB),. Retrieved August 8, 2025 from https://downloads.theifab.com/downloads/laws-of-the-game-2025-26?l=en
Trewin, J., Meylan, C., Varley, M. C., Cronin, J., & Ling, D. (2018). Effect of match factors on the running performance of elite female soccer players. *J Strength Cond Res*, *32*(7), 2002-2009. https://doi.org/10.1519/JSC.0000000000002584
Tsai, L., Sigward, S. M., Pollard, C. D., Fletcher, M. J., & Powers, C. M. (2009). Effects of Fatigue on Recovery on Knee Mechanics during Side-Step Cutting. *Med Sci Sports Ecerc*, *41*(10), 1952-1957. https://doi.org/10.1249/MSS.0b013e3181a4b266
Turk, E. E. (2010). Hypothermia. *Forensic Sci Med Pathol*, *6*, 106-115. https://doi.org/10.1007/s12024-010-9142-4
Tyler, C. J., Reeve, T., Hodges, G. J., & Cheung, S. S. (2016). The Effects of Heat Adaptation on Physiology, Perception and Exercise Performance in the Heat: A Meta-Analysis. *Sports Med*, *46*, 1699-1724. https://doi.org/10.1007/s40279-016-0538-5
UBIMET GmbH. *UBIMET WEATHER MATTERS*. Retrieved November 12, 2023 from https://www.ubimet.com/en/
Union des associations européennes de football (UEFA). (2025). *UEFA Medical Regulations*. Retrieved August 8, 2025 from https://documents.uefa.com/r/Technical-Regulations/UEFA-Medical-Regulations-Online
US Soccer. (n.d.). *Heat Guidelines*. Retrieved August 8, 2025 from https://static1.squarespace.com/static/57125d942eeb814000fb1ca5/t/5a1c4fdc8165f542d6d78d16/1511804893401/1609024+Heat+Guidelines.pdf
Villavañas, V., Sánchez-Sánchez, J., García-Unanue, J., López, J., & Gallardo, L. (2016). The influence of various types of artificial turfs on football fields and

their effects on the thermal profile of surfaces. *Proceedings of the Institution of Mechanical Engineers Part P Journal of Sports Engineering and Technology*, *231*(1), 21-32. https://doi.org/10.1177/1754337115624819

Waldén, M., Hägglund, M., Orchard, J., Kristenson, K., & Ekstrand, J. (2013). Regional differences in injury incidence in European professional football. . *Scand J Med Sci Sports*, *23*, 424-430. https://doi.org/10.1111/j.1600-0838.2011.01409.x

Walker, A. J., Arent, M. A., McFadden, B. A., & Arent, S. M. (2019). Physical Performance Testing in Soccer. In R. Curtis, C. Benjamin, R. Huggins, & D. Casa (Eds.), *Elite Soccer Players. Maximizing Performance and Safety.* (pp. 137-156). Routledge. https://doi.org/10.4324/9780429465536

Wardenaar, F. C., Beaumont, J. S., Boeckman, J., van Geffen, B., & Vanos, J. K. (2022). Analysis of potential hydration opportunities during future football tournaments based on data from the 2018 FIFA World Cup. *Sci Med Footb*, *8*(1), 32-36. https://doi.org/10.1080/24733938.2022.2137574

Wegmann, M., Faude, O., Poppendieck, W., Hecksteden, A., Fröhlich, M., & Meyer, T. (2012). Pre-cooling and sports performance: a meta-analytical review. *Sports Med*, *42*(7), 545-564. https://doi.org/10.2165/11630550-000000000-00000

Weiner, B. J., Lewis, C. C., Stanick, C., Powell, B. J., Dorsey, C. N., Clary, A. S., Boynton, M. H., & Halko, H. (2017). Psychometric assessment of three newly developed implementation outcome measures. *Implementation Sci*, *12*. https://doi.org/10.1186/s13012-017-0635-3

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis* (Second Edition ed.). Springer.

Williams, C. A., & Blackwell, J. (2012). Hydration Status, Fluid Intake, and Electrolyte Losses in Youth Soccer Players. *Int J Sports Physiol Perform*, *7*(4), 367-374. https://doi.org/10.1123/ijspp.7.4.367

Winter, I., Burdin, J., & Wilson, P. B. (2024). Reliability and minimal detectable change of the MX3 hydration testing system. *PLoS ONE*, *19*(11). https://doi.org/10.1371/journal.pone.0313320

World Meteorological Organization. (2023). *The Global Climate 2011-2020. A decade of accelerating climate change.* https://library.wmo.int/idurl/4/68585

World Triathlon. (2022). *World Triathlon Competition Rules*. Retrieved February 14, 2024 from https://www.triathlondeutschland.de/sites/default/files/documents/2023-05/World-Triathlon_Competition-Rules_2023_20230208.pdf

Yeargin, S. W., Dompier, T. P., Casa, D. J., Hirschhorn, R. M., & Kerr, Z. Y. (2019). Epidemiology of Exertional Heat Illnesses in National Collegiate Athletic Association Athletes During the 2009–2010 Through 2014–2015 Academic Years. *J Athl Train*, *54*(1), 55-63. https://doi.org/10.4085/1062-6050-504-17

Zhang, H., Arens, E., Huizenga, C., & Han, T. (2010). Thermal sensation and comfort models for non-uniform and transient environments, part III: Whole-body sensation and comfort. *Build Environ*, *45*(2), 399-410. https://doi.org/10.1016/j.buildenv.2009.06.020

Zhang, W., Ren, S., & Zheng, X. (2022). Effect of 3 min whole-body and lower limb cold water immersion on subsequent performance of agility, sprint, and

intermittent endurance exercise. *Front Physiol*, *13*, Article 981773. https://doi.org/10.3389/fphys.2022.981773

Zhang, Y., Nepocatych, S., Katica, C. P., Collins, A. B., Casaru, C., Balilionis, G., Sjökvist, J., & Bishop, P. A. (2014). Effect of Half Time Cooling on Thermoregulatory Responses and Soccer-Specific Performance Tests. *Monten J Sports Sci Med*, *3*(1), 17-22.

Zhou, C., Hopkins, W. G., Mao, W., Calvo, A. L., & Liu, H. (2019). Match Performance of Soccer Teams in the Chinese Super League – Effects of Situational and Environmental Factors. *Int J Environ Res Public Health*, *16*(21). https://doi.org/10.3390/ijerph16214238

Appendix

Appendix A – Ethical Approval (Study 1-5)

UNIVERSITÄT DES SAARLANDES

Universität des Saarlandes | Der Vorsitzende der Ethikkommission der Fakultät für Empirische Humanwissenschaften und Wirtschaftswissenschaft | Prof. Dr. Cornelius König | Postfach 15 11 50 | D-66041 Saarbrücken

Edgar Schwarz
Sportwissenschaft Geb. 8.2
Universität des Saarlandes
66123 Saarbrücken

Universität des Saarlandes
Fakultät für Empirische Humanwissenschaften und Wirtschaftswissenschaft

Der Vorsitzende der Ethikkommission
Prof. Dr. Cornelius König

Postfach 15 11 50
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ckoenig@mx.uni-saarland.de
www.uni-saarland.de/ao

Datum 20.7.2023
Betreff Ethik-Antrag

Dear Mr. Schwarz,

The Ethic Committee of the Faculty for Human and Business Sciences of Saarland University has reviewed your proposal 23-14 „Improving health, safety and performance of footballers playing in the heat“ and decided to approve it.

Sincerely,

Cornelius König

Appendix B – Clinical Trial Register (Study 4)

Current Version | Version History | Download

DRKS00032208

Testing a simple cooling intervention to improve health, safety and performance of footballers playing in the heat

Organizational Data

DRKS-ID:
DRKS00032208

Recruitment Status:
Recruiting complete, study complete

Date of registration in DRKS:
2023-07-25

Last update in DRKS:
2024-07-25

Registration type:
Prospective

Acronym/abbreviation of the study

No Entry

URL of the study

No Entry

Brief summary in lay language

The study examines two soccer games in hot temperatures. One team is cooled in the first game, and the other team is cooled in the second game. This cooling consists of a combination of cold drinks, slush ice, ice towels, and fans, and takes place 10 minutes before each game and at halftime, as well as during 3-minute extra breaks per half. The effects of these cooling measures on core body temperature, heart rate, fluid loss, hydration status, running performance, other game statistics, subjective feelings of exertion, heat sensation and well-being of the players will be observed and compared to the game without cooling. To control for the placebo effect, participants in the game without cooling are given a drink that is supposed to improve heat resistance and thus have similar effects to cooling. However, the drink is actually exactly the same as the one from the cooling intervention, only with a different taste, and not cooled. Afterwards, participants are asked about their opinion on the cooling intervention.

Appendix C – UEFA Medical Research Grant (Study 4)

TO
Universität des Saarlandes
66123 Saarbrücken
Germany

For the attention of
Edgar Schwarz

Our reference	Date
MEDICAL/GMOY	20 July 2023

UEFA Medical Research Grant Programme 2023 – Letter of Confirmation

Dear Mr. Schwarz,

We are pleased to inform you that your application for the UEFA Medical Research Grant Programme 2023 has been voted successful. For your research project, UEFA will grant you the amount of €14755,-. The UEFA MRGP encourages universities and scientists to develop their research into medical and health topics in European football. It is for anyone pursuing or already holding a doctorate who is analysing European football from a medical and health point of view. Once completed, the research is shared with the 55 UEFA member associations and is used for growth and development purposes. The purpose of this research grant programme is to improve strategic decision-making in European football through medical and health related research.

The total amount of the UEFA research grant is €14755,- payable in three instalments. The detailed breakdown of the payments can be found in the Declaration signed by the Researcher.

We ask you to acknowledge receipt of this grant and indicate your acceptance of the terms discussed above. We look forward to receiving your progress report by 30 November 2023, so that we can discuss the future development of this project. In the meantime, you have our very best wishes for continued success.

Yours faithfully,

Dr. Zoran Bahtijarević
Chief Medical Officer

UEFA Route de Genève 46, CH-1260 Nyon 2, Switzerland
Tel. +41 848 00 27 27, Fax. +41 848 01 27 27 UEFA.com

Appendix D – Invitation Letter Club Tigres UANL (Study 4)

SINERGIA DEPORTIVA
S.A. DE C.V.
ESTADIO UNIVERSITARIO , PUERTA 13
SAN NICOLÁS DE LOS GARZA, N.L.
C.P. 66455

Dear Edgar Schwarz:

Hereby Tigres UANL invites the Saarland University and the University of Technology Sydney to conduct the research project 'Improving health, safety and performance of footballers playing in the heat' within the Club Tigres UANL organisation. We are happy to support you and your teammates.

Dr.Roberto Alfredo Freeze Cornejo
Head of medical services Club Tigres UANL

Dr .Agustin Jaime Alanis Flores
Team Doctor Tigres UANL U-18

14 /9/2023
San Nicolas De Los Garza, Nuevo León, Mexico

Appendix E – Participant Information Sheet and Consent (Study 4)

Sportmedizin Saarbrücken

UNIVERSITÄT DES SAARLANDES

Institut für Sport- und Präventivmedizin
Bereich Klinische Medizin
Ärztlicher Direktor: Univ.-Prof. Dr. med. Tim Meyer

Hoja informativa & formulario de consentimiento:
'Improving health & performance of footballers playing in the heat.'
Mejora de la salud y el rendimiento de los futbolistas que juegan con calor.

Objetivo de este estudio:
Cuando juegan al fútbol en climas cálidos, los jugadores pueden luchar contra los efectos nocivos de este clima. Esta investigación comparará los efectos de dos intervenciones que contrarrestan estos efectos cuando se juega al fútbol. Estas intervenciones serán:
1 Enfriamiento: Los jugadores recibirán toallas frías y bebidas frías en dos ocasiones antes del partido, durante las pausas de enfriamiento en cada mitad y en el descanso.
2 Bebida especial: Los jugadores recibirán una bebida diseñada específicamente para mejorar el rendimiento en el calor, que combina ingredientes importantes (hidratos de carbono, electrolitos, minerales) para aumentar la tolerancia al calor.

Procedimientos:
Los participantes jugarán dos partidos experimentales dentro de la práctica de equipo. Antes, habrá una sesión de familiarización en la que se explicarán todos los procedimientos a los jugadores. Durante esa sesión de familiarización, los jugadores recibirán una pastilla para medir su temperatura central. Se les pedirá que se introduzcan la pastilla al levantarse los días de las pruebas. Mientras la pastilla esté dentro del cuerpo está prohibido que los participantes se hagan una resonancia magnética. En caso de urgencia médica que requiera imágenes, se puede utilizar un TAC como herramienta de diagnóstico. Por lo demás, la píldora no plantea ningún riesgo para la salud. Los jugadores se presentarán en las instalaciones de entrenamiento a las 8 de la mañana. Tras su llegada, los jugadores recibirán un desayuno antes de comenzar las pruebas de referencia. Las pruebas de referencia consistirán en medir el peso corporal desnudo, medir la osmolalidad de la saliva, realizar breves cuestionarios y aplicar composiciones de sudor, GPS y dispositivos de medición de la frecuencia cardiaca. A continuación, los jugadores se someterán al procedimiento habitual de un día de partido, que incluye un calentamiento, un partido de 90 minutos, dos intervenciones de preenfriamiento, una intervención de enfriamiento en el descanso y dos pausas de enfriamiento adicionales en cada tiempo. Para controlar el consumo de líquidos y la pérdida de sudor, los jugadores deberán beber únicamente de su botella individual y no derramar ni escupir agua al suelo. Si los jugadores necesitan ir al baño, se les pide que midan su peso corporal antes y después de ir al baño. Después del partido se repetirán las mismas pruebas que antes del partido.

Mediciones:
Temperatura central: medida mediante una pastilla ingerible (BodyCap), que los jugadores deben consumir la mañana del partido.
Estado de hidratación: medido a partir de una muestra de saliva de la lengua (MX3)
Composición del sudor: medida a partir de un parche de sudor en el brazo (MX3)
Consumo de líquidos/pérdida de sudor: medido a partir del seguimiento de botellas de agua individuales y del cambio de masa corporal desnuda.
GPS: medido con dispositivos GPS portátiles (WIMU)
Frecuencia cardiaca: medida con cinturones pectorales de frecuencia cardiaca (Sigma)
Sensación térmica: medida con una escala subjetiva
Grado de agotamiento percibido: medido en una escala subjetiva.
Valoración de la fatiga: medida en una escala subjetiva

Anonimato de los datos:
Los datos registrados en este proyecto serán anónimos y no se podrá rastrear a ningún jugador individual. Los resultados del proyecto se publicarán en artículos de revistas revisadas por pares, pero no se incluirá información individual de los participantes.

Responsabilidades del investigador - Derechos de los participantes
Como sujeto, usted es libre de retirar su consentimiento para participar en cualquier momento.
Los investigadores responderán en todo momento a cualquier pregunta que pueda tener en relación con el estudio. Las preguntas relativas al estudio pueden dirigirse a:
Edgar Schwarz, Saarland University, +49 1786084818, edgar.schwarz@uni-saarland.de

Lieferanschrift: Universität des Saarlandes, Campus B8 2, 66123 Saarbrücken
(0681) 302 - 70400 sportmed@mx.uni-saarland.de
(0681) 302 - 4296 www.Sportmedizin-Saarbrücken.de

Sportmedizin Saarbrücken

UNIVERSITÄT DES SAARLANDES

Institut für Sport- und Präventivmedizin
Bereich Klinische Medizin
Ärztlicher Direktor: Univ.-Prof. Dr. med. Tim Meyer

Institut für Sport- und Präventivmedizin
Universität des Saarlandes, Postfach 151150, 66041 Saarbrücken

Hoja informativa & formulario de consentimiento:
Improving health & performance of footballers playing in the heat.
Mejora de la salud y el rendimiento de los futbolistas que juegan con calor.

Yo, _____, he leído la información contenida en este formulario de consentimiento y en la hoja informativa que lo acompaña, y todas las preguntas que he formulado han sido respondidas satisfactoriamente.

Estoy de acuerdo en participar en este proyecto, consciente de que puedo retirarme en cualquier momento sin ser objeto de ninguna sanción o trato discriminatorio.

Estoy de acuerdo en que se me ha explicado suficientemente la finalidad de esta investigación y los posibles riesgos o molestias que conllevan los procedimientos de las pruebas.

Estoy de acuerdo que se publiquen los datos de este estudio siempre que no se utilicen mi nombre y datos confidenciales.

He leído los criterios antes mencionados, se me han explicado por escrito los procedimientos y entiendo mis derechos como participante.

_____ _____
firma del participante fecha

_____ _____
firma del of investigador fecha

Lieferanschrift: Universität des Saarlandes, Campus B8 2, 66123 Saarbrücken
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