



Impact of summer heat on male children's physiological responses during football training[☆]

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ABSTRACT

Background: As summer temperatures rise due to climate change, the Pediatrics Society calls for more research on children's core body temperature. This study aims to analyze these concerns by investigating the specific effects of heat exposure on children's physiological parameters such as body temperature during football training.

Methods: This case-crossover study investigated the effects of heat on several physiological parameters (e.g., ear and skin temperature) by monitoring 51 male children (aged 8–12 years) during outdoor football training sessions. Participants wore wearable sensors and were either part of a club football team (club: $n = 30$) or part of a football camp (camp: $n = 21$). Both groups were monitored twice. Club participants were monitored during two separate training days, one session in warm weather (≥ 25 °C) and one session in moderate weather (< 20 °C). Camp participants were monitored during two training sessions on the same warm summer day (≥ 25 °C). For both groups, urine density was measured before and after each training session to assess hydration status. A mixed linear regression was performed separately for the two settings.

Results: Ear and skin temperatures were significantly higher for both club and camp participants during the warm observation period compared to moderate outdoor temperatures. During training periods, outdoor temperature regularly exceeded 32.3 °C, a level at which the American College of Sports Medicine advises cessation of training. In this study, outdoor temperature had no impact on hydration status. The mixed linear regression models showed that outdoor temperature significantly influenced core and skin temperatures.

Conclusion: Our results showed a significant but safe increase in physiological parameters, like ear and skin temperatures, during summer football training, with no severe heat strain symptoms observed, highlighting the need for further research on long-term effects.

1. Introduction

The impact of climate change on human health, as highlighted by the World Health Organization (World Health Organization, 2023) is an undeniable reality that presents significant challenges. One of the notable consequences is the rising frequency of extreme weather events globally, including in Germany, such as prolonged hot summer days (> 30 °C), heat waves (multiple consecutive days with > 30 °C) and

tropical nights (temperature throughout the night > 20 °C) (Pansch et al., 2018; Eckstein et al., 2019). As climate change accelerates, vulnerable populations such as children are increasingly exposed to heat-related stress, particularly during outdoor sporting activities in the summer months (Sheffield et al., 2018).

In the federal state of Bavaria, Germany, football clubs are the most popular place for children to play sports. Approximately one in six children actively participates in a football club and regularly attends

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training sessions (Bavarian Authority for Statistics, 2021). These sessions usually start between 4 and 5 pm (CEST/CET) and last around 1.5 h. During the summer months of June to August, daily temperatures in Munich can peak during these training hours (Deutscher Wetterdienst, 2023). In addition, training pitches often lack shade. Artificial turf is a commonly used surface and can heat up significantly compared to natural grass. It can reach temperatures as high as 74.6 °C, which is 38 °C higher than natural grass under similar conditions (Bertling et al., 2021). A study on adult athletes demonstrated that both skin and perceived temperatures were higher on artificial turf compared to natural grass, although core body temperature did not differ significantly between the two surfaces (Singh et al., 2024).

Heat exhaustion typically occurs when the body's thermoregulatory responses are inadequate to preserve thermal homeostasis (Kenny et al., 2018). It is characterized by elevations in body temperature between 37 °C and 40 °C, accompanied by symptoms or signs of organ system failure, most frequently central nervous system dysfunction (Armstrong et al., 2007; Bouchama and Knochel, 2002; Glazer, 2005). There are large individual differences between the heat tolerance of children (Bergeron et al., 2011). Factors such as heat adaptation and individual general fitness are protective factors against heat exhaustion (Epstein, 1990; Kazman et al., 2013). Furthermore, results shown by Dougherty and colleagues show that for 9–12 year old boys, the critical limit for heat acclimation is shifted downwards for obese boys compared to well trained boys (Dougherty et al., 2010).

Our study aims to respond to the Pediatric Society's call for the development of heat safety guidelines and evidence-based prevention strategies by conducting empirical research on core body temperature measurements in children during various sports activities.

Previous studies have already examined the heat tolerance of children during sporting activity (Rivera-Brown et al., 2006; Rowland, 2008; Somboonwong et al., 2012). All three studies measured body temperature before and after exercise. Rivera-Brown and Rowland used rectal temperature in simulated conditions, while Somboonwong used ear temperature in a field study.

In the present study, we decided to measure body temperature continuously. Rectal thermometry, while regarded as the gold standard for core body temperature assessment, was deemed impractical for a field-based design involving children due to concerns regarding participant privacy and the potential disruption of regular training activities. Continuous temperature measurement via a non-invasive ear sensor was therefore selected to achieve high temporal resolution without necessitating additional pauses or interfering with the training process. Although the sensor had not previously been validated for use in pediatric populations during exercise, and specific data on its measurement accuracy were not available, potential measurement inaccuracies were considered acceptable within the framework of an intra-individual study design. This method allowed us to unobtrusively and continuously monitor body temperature, accurately tracking participants' temperature changes throughout the observation period without interfering with their activities. In contrast, spot measurements using ear thermometry would have disrupted the training and failed to capture the dynamic changes in body temperature. To the best of our knowledge, this approach has not been employed in previous studies, making this investigation a pilot study in the context of continuous, field-based temperature monitoring in children during exercise.

This study addresses the lack of data on thermoregulation in children during real-life sporting activities under heat exposure. The findings of this study may contribute to the development of evidence-based heat safety guidelines for youth sports and support pediatric health recommendations under rising climate-related stressors. Our hypothesis stated that *“Individual body temperature of children exercising on heat-exposed surfaces (>25°C) is equal compared to the one observed during moderate*

outdoor temperatures (<20°C).”

2. Materials and methods

2.1. Study design and observational setup

The study is set up as a case-crossover cohort study (Fig. 1). Because of potentially large individual differences between the heat tolerance of children, in our observational setup, only intraindividual differences were measured on different training days in order to investigate how the vital parameters behave at different outdoor temperatures. The detailed observational settings are described as follows.

2.1.1. First observational setting (clubs)

In the first part of the study, children were observed during their outdoor football training sessions. For each child, the observation was conducted twice, once during the summer months (June–August 2023), when the outdoor temperatures reached above 25 °C and once in spring and autumn (April–May and September–November 2023) when the outdoor temperatures dropped below 20 °C. In total, children from three different clubs in Munich, Germany, were examined (FT Gern, FC Teutonia München, SV, 1880 München). The training sessions of the teams generally lasted 90 min, but at least 75 min. The starting time was always between 4:30 and 5:30 p.m. (CEST/CET). The coaches were instructed to hold the two training sessions as identically as possible. No active influence was exerted by the study investigators on the football training sessions and the participants were not given any specific instructions. The training surface was either natural grass or artificial turf.

2.1.2. Second observational setting (camps)

In the second part, children were accompanied on two training sessions, which took place on 1 day as part of a football holiday camp. The first training session ran from 10:00–12:00 a.m. (CEST) and the second from 1:30–3:30 p.m. (CEST). The first training session should therefore have cooler outside temperatures than the second training session. In total, children from 2 different football camps were examined, but both were run by the same organization (MFS München). All other conditions were the same as in the first observational setup.

For the ease of understanding, the following nomenclature will be employed: “Club Normal” refers to training sessions with moderate temperatures, “Club Warm” to sessions with warm weather, “Camp Morning” to morning camp sessions, and “Camp Afternoon” to afternoon camp sessions.

2.2. Participants

Participants were eligible for inclusion based on the following criteria: (1) aged between 8 and 12 years; (2) member of a football club or participant in a football camp; (3) BMI <30; (4) no acute ear infection or any ear infection within the previous two weeks; (5) no severe chronic diseases; (6) no known metal allergies; and (7) consent obtained from both parents/legal guardians or single parent if applicable. Prior to enrolling their children in the study, parents/legal guardians were required to complete a questionnaire providing basic information about their children, including age, gender, height, and weight. Additionally, participants were asked to indicate, using an ordinal scale, how often the child engages in sports for at least 90 min per session each week: Never, 1–2 times, 3–5 times, or more than 5 times.

The study was carried out in accordance with the Code of Ethics of the Declaration of Helsinki for experiments involving human subjects and was reviewed and approved by the Ethics Committee of the Ludwig-Maximilians-Universität München (#23–0193).

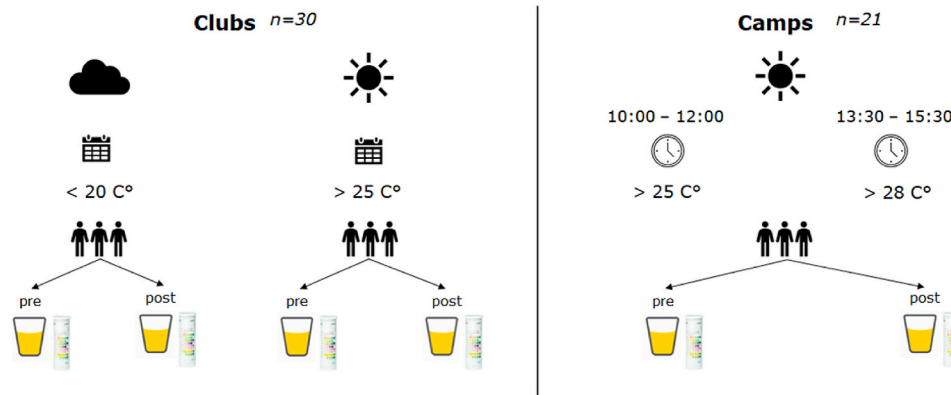


Fig. 1. Study test up for club participants (left) and camp participants (right).

2.3. Monitoring of the environmental conditions

We utilized a *QUESTemp 34 Heat Stress Monitor*® (Quest Technologies, Wisconsin, USA) to assess heat stress due to environmental conditions on the football pitch. Various parameters of outdoor temperature were measured using the Quest weather station, including air temperature, wet bulb temperature, globe temperature, and relative humidity, allowing for accurate calculation of the Wet Bulb Globe Temperature (WBGT) index. This is a composite measure of heat stress and should not be equated with standard air temperature. The WBGT index, in accordance with ISO 7243, served as our measure of outdoor heat stress due to its simplicity and established validity (Hosokawa et al., 2018; Standards, 2017). The device was placed on a tripod at a height of approximately 1 m and close to the training area, ensuring that it was away from any barriers that might block radiant heat or flow. Care was taken to ensure that the device accurately recorded the environmental conditions of the training area. Measurements were taken at 5 different locations, including 3 with grass surfaces and 2 with artificial surfaces. Strict measures were taken to ensure that the temperature readings were comparable. For instance, during training sessions in direct sunlight, the device was also placed in direct sunlight. Additionally, any bystanding objects were kept at least 3 m away from the device to avoid interference.

An important parameter for measuring heat exposure is wind speed (Lemke and Kjellstrom, 2012). However, it is not included in the WBGT index and was not measured on-site. To estimate wind speed during football training, data from the Munich city weather station were analyzed (DWD, ID = 3379).

2.4. Monitoring of physiological parameters

The study measured ear temperature and skin temperature and took urine samples.

A *cosinuss° C med*® ear sensor (Cosinuss GmbH, Munich, Germany) size S was utilized to monitor participants' ear temperature (ET) during the observations. The sampling interval was 1 s. Six receiving devices ("gateways") were placed around the football field to transmit data from the ear sensor to the *cosinuss° Health cloud* server. This data was stored on a secure, encrypted server in accordance with the General Data Protection Regulation (GDPR) to ensure the confidentiality and integrity of participant information.

Moreover, skin temperatures (ST) were monitored using *Thermochron iButton*® temperature loggers (CK electronic GmbH, Cologne, Germany). The skin sensors were placed at five different central and

peripheral locations (left/right infraclavicular, belly and left/right midhigh) (Wibowo et al., 2023).

Data for both ET and ST were included only if participants wore the respective measuring device for both measurement sessions and the data were evaluable. The duration of a club training was at least 75 min, while a camp training lasted at least 100 min.

In addition, participants' urine was analyzed using a *Combur 10*® test (Roche Diagnostic, Schweiz AG, Stadt, Switzerland), primarily to determine their hydration status. While club participants provided a urine sample before and after each training session, camp participants provided a urine sample before the first and after the second training session.

2.5. Data management

ST was continuously monitored using five sensors attached to the participants, recording temperatures at 1-min intervals throughout the study. For each minute, a median value was calculated from the five sensor readings to represent the ST, and the standard deviation (SD) of these median values was calculated to assess variability. Each sensor was corrected by an external calibration to ensure data accuracy. In cases where a sensor malfunctioned or was lost, data from that sensor was excluded from the median calculation, ensuring the median value accurately reflected the temperatures of the remaining, functioning sensors. For data cleaning, sections outside the observation period were removed to ensure the integrity of the dataset.

Participants' ET was consistently measured using the ear sensor, recording one value per second. For each minute, the median value was calculated from the 1-s readings. Consequently, the dataset for analysis consists of 1-min-readings for each participant. In cases where the sensor malfunctioned or was lost, the values for that time period were removed from the dataset, but the remaining data was still included in the analysis.

The measured ET was used as a proxy for core temperature. The body temperature of the participants was calculated from the measured skin and ear temperatures, representing the mass-weighted average temperature of body tissues. This was done using Burton's 1935 formula: $\text{Body Temp} = 0.64 \times \text{Core (Ear)} + 0.36 \times \text{Skin}$, which has proven to remain accurate and reliable to date (Lenhardt and Sessler, 2006).

The specific urine density (USG) values were determined from urine samples using a visual comparison of the test strip with the corresponding scale on the *Combur 10*® test kits. Each player received one value per urine sample. The means of the USG were then calculated, yielding two values per session: one before and one after the training

Table 1
Participant's characteristics at the time of the examination.

	Club (n = 30)	Camp (n = 21)
Age, years old	9 (± 1.7)	9 (± 1.8)
Height, m	1.42 (± 0.067)	1.43 m (± 0.12)
Weight, kg	32 (± 4.2)	33 (± 6.1)
BMI, kg/m ²	15.8 (± 1.72)	16.14 (± 2.23)

Data presented as means $\pm$ SD.

session for club participants, and one before the morning session and one after the afternoon session for camp participants.

2.6. Statistical analyses

We present numbers and percentages for categorical variables as well as mean/median and standard deviations for continuous variables. Normal distribution of variables was assessed using the Kolmogorov-Smirnov test.

As the ST, ET and the urine samples were found to be non-normally-distributed, median values are presented and non-parametric tests are applied. Specifically the Wilcoxon rank-sum test was used to compare measurements between groups.

As for environmental data, an unpaired *t*-test was conducted to examine whether wind speed and wind direction significantly differed between training days for club participants.

We fitted linear mixed-effects models to evaluate the effect of the weather conditions on children's skin and ear temperature during training sessions. Separate models were estimated for skin and ear temperature within two training contexts: club-based (warm vs. normal conditions) and camp-based (hot vs. warm conditions). Each model included the time as a continuous fixed effect, as well as a random slope and intercept for each participant to account for repeated measurements. Additional covariates included BMI, age, the surface type (grass vs. artificial) and for the club setting only also the season (spring vs. fall). Models were fitted using restricted maximum likelihood (REML), and degrees of freedom were estimated using Satterthwaite's approximation. All analyses were carried out with R Version 4.1.3.

3. Results

3.1. Participants' clinical characteristics

All data was collected during training sessions. Since only three girls participated in the study, they were excluded from the final cohort. In

the final cohort, we therefore included 51 participants who completed two training sessions, 31 for club and 20 for camp, respectively. Of all these participants the median age was 9 years (± 1.7). Overall, the median of the age-adapted BMI (Cole, 2000) was within the first interval of one standard deviation around the mean value. All participants reported engaging in physical activity lasting more than 90 min at least once per week, and 74 % engaged in such activity 3–5 times per week. [Table 1](#) provides an overview of the participant's basic data segregated in club and camp.

3.2. Monitoring of the environmental conditions

[Fig. 2](#) visualizes the representations of the measured 1-min WBGT medians of the different settings.

Of the 51 children in the final cohort, skin sensors malfunctioned or were not tolerated by three participants (two in the club setting and one in the camp setting), and ear sensors malfunctioned or were not tolerated by three other participants (all in the camp setting). As a result, the number of participants included in the analyses of ET and ST was reduced to 48. For the calculation of mean body temperature (BT), as presented in [Fig. 5](#), both ET and ST data were required for each participant, which further reduced the sample size to 45.

In Club Normal training sessions, the median WBGT recorded was 15.3 °C, while in Club Warm sessions it rose to 24.3 °C. Camp Morning sessions registered a slightly lower median WBGT of 26.6 °C compared to Camp Afternoon sessions, which measured a median WBGT of 28.5 °C. Club Normal and Camp Afternoon generally remained consistent throughout the observation period. However, the median WBGT in Camp Morning gradually increased over the session, whereas the median WBGT in Club Normal gradually decreased during the measurement period.

Unpaired *t*-test analysis of the hourly wind speed showed a significant difference ($p < 0.001$) between club training days, with median wind speeds of 3.1 m/s (SD 1.01) for Club Normal sessions and 2.4 m/s (SD 0.89) for Club Warm sessions. While the wind speeds differ significantly between these two training days, it is noteworthy that both measurements fall within the same Beaufort scale category, typically associated with low wind speeds ([World Meteorological Organization, 2019](#)).

3.3. Physiological parameters

Physiological parameters monitored included participants' median ET and median ST. Of 48 participants (94,1 %), the median ET was

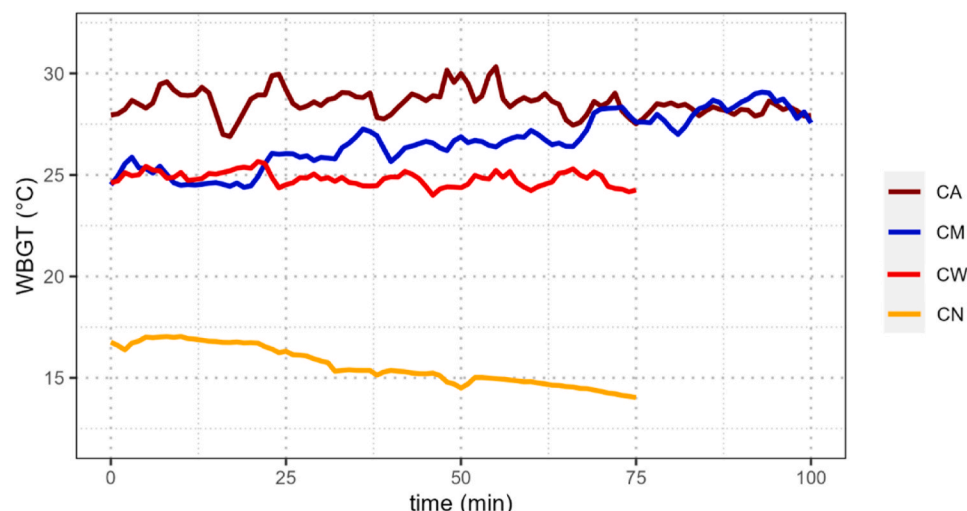


Fig. 2. Median Wet Bulb Globe Temperatures (WBGT) for the settings: Camp Afternoon (CA), Camp Morning (CM), Club Warm (CW) and Club Normal (CN) (n = 48).

Table 2
Median physiological parameters for the settings: Camp Afternoon, Camp Morning, Club Warm and Club Normal.

	Median Ear Temperature (°C)		Median Skin Temperature (°C)	
Camp Afternoon	36.9 (±0.49)	p < 0.001	35.5 (±0.99)	p < 0.001
Camp Morning	36.4 (±0.71)		34.3 (±1.08)	
Club Warm	36.5 (±0.42)	p < 0.001	33.8 (±1.45)	p < 0.001
Club Normal	35.5 (±0.46)		30.5 (±1.74)	

Wilcoxon rank sum test: Camp Afternoon against Camp Morning for ear temperature, Camp Afternoon against Camp Morning for skin temperature, Club Warm against Club Normal for ear temperature, Club Warm against Club Normal for skin temperature.

36.9 °C, 36.4 °C, 35.5 °C and 34.3 °C for Camp Afternoon, Camp Morning, Club Warm and Club Normal, respectively. Their median ST was 36.5 °C, 34.4 °C, 33.8 °C and 30.5 °C for Camp Afternoon, Camp Morning, Club Warm and Club Normal, respectively (see Table 2). The differences observed in each condition were found to be statistically significant ($p < 0.001$) based on the Wilcoxon rank sum test. As a visual representation, Figs. 3 and 4 show the 1-min median of ET and ST, respectively, for each observation condition, with gray shaded areas

representing the 95 %-confidence intervals. Table 2 shows the calculated median values for ET and ST over the entire training period in each setting. It also includes the p-values from the Wilcoxon signed rank test used to compare these median values between the different settings over the whole training period.

3.4. Correlation of ear and skin temperature in relation to outdoor temperature

To estimate the effect of outdoor temperature on ST and ET over the time of practice, we performed four separate mixed linear regression models. The results are shown in Table 3.

In the club-based models, warmer environmental conditions were strongly associated with higher ST (+2.97 °C, $p < 0.001$) and ET (+1.18 °C, $p < 0.001$). The seasonal comparison between fall and spring in the club setting did not reveal significant differences in ST or ET. In the camp-based training setting, both ST and ET were significantly higher under hot conditions compared to warm conditions (ST: +1.14 °C, ET: +0.44 °C; both $p < 0.001$). Training duration did not have a significant effect on either ST or ET. Body mass index (BMI), age, and type of surface (artificial vs. natural grass) were not significantly

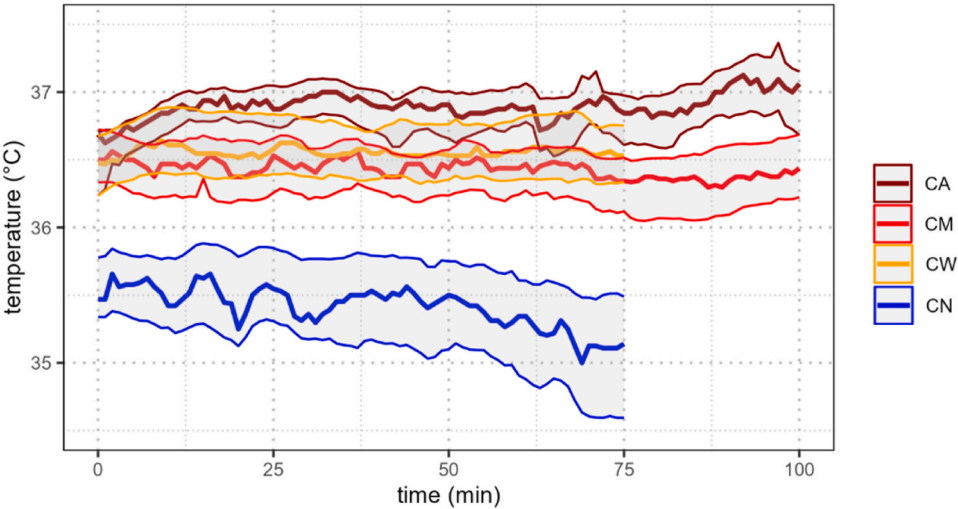


Fig. 3. One Minute Median Ear Temperature (ET) for the settings: Camp Afternoon (CA), Camp Morning (CM), Club Warm (CW) and Club Normal (CN) (n = 8).

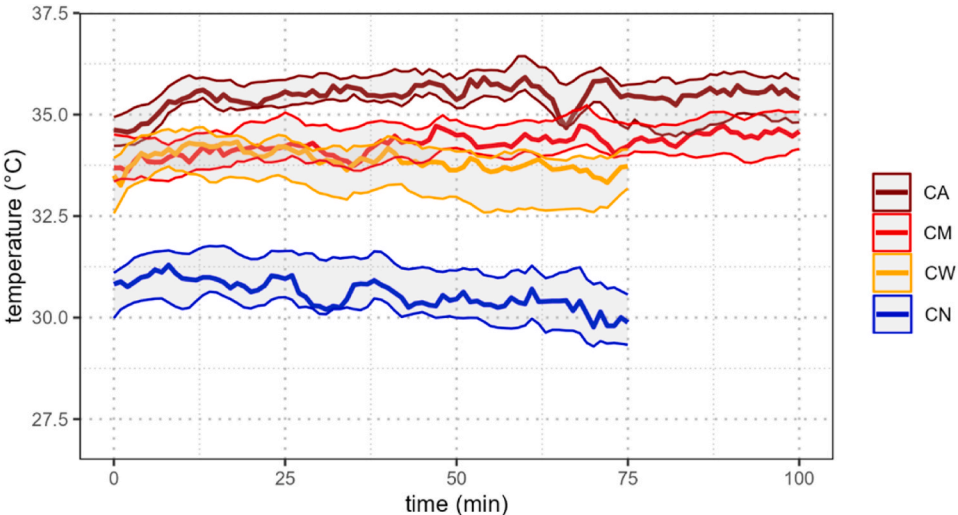


Fig. 4. One Minute Median Skin Temperature (ST) for the settings: Camp Afternoon (CA), Camp Morning (CM), Club Warm (CW) and Club Normal (CN) (n = 48).

Table 3
Mixed linear regression models.

Predictor	Skin Temperature, Club				Ear Temperature, Club				Skin Temperature, Camp				Ear Temperature, Camp			
	Estimate	Std. Error	t value	p value	Estimate	Std. Error	t value	p value	Estimate	Std. Error	t value	p value	Estimate	Std. Error	t value	p value
Intercept	29.79	3.29	9.054	<0.001	36.95	1.27	29.043	<0.001	33.03	1.06	31.29	<0.001	36.47	0.42	86.8	<0.001
duration	-0.0099	0.0024	-4.111	<0.001	-0.0029	0.0011	-2.748	0.012	0.0031	0.002	1.54	0.139	3.1E-05	0.0071	0.04	0.965
setting ^a	2.973	0.0309	96.245	<0.001	1.181	0.0132	89.733	<0.001	1.143	0.02	56.56	<0.001	0.443	0.008	57.99	<0.001
BMI	-0.032	0.139	-0.231	0.819	-0.022	0.056	-0.39	0.701	0.145	0.074	1.95	0.067	0.033	0.03	1.13	0.265
age	0.164	0.28	0.584	0.565	-0.124	0.109	-1.136	0.268	-0.12	0.149	-0.81	0.431	-0.068	0.059	-1.14	0.263
surface: grass (vs. Artificial)	0.657	0.644	1.02	0.319	0.251	0.236	1.064	0.299	0.057	0.357	0.16	0.874	0.111	0.142	0.78	0.44
season: spring (vs. Fall)	-0.385	0.704	-0.546	0.59	-0.179	0.26	-0.689	0.498								
Random Effects																
Intercept_SD	1.099				0.4544				0.64				0.616			
Duration_SD	0.0119				0.0051				0.0089				0.0034			
Residual_SD	0.977				0.403				0.641				0.641			

^a Club: warm vs. normal, Camp: hot vs. warm.

associated with either outcome in any setting. Random effects indicated substantial variability in baseline temperatures across individuals.

To explore the association between outdoor temperature (WBGT) and body temperature in more detail, Fig. 5 depicts the results of a linear regression with the actual temperature instead of only temperature setting. Each point represents a single measurement taken by a participant at minute 60 of each training session. The regressions in Fig. 5 show a significant positive correlation between both skin temperature ($p < 0.01$) and ear temperature ($p < 0.01$) and therefore also body temperature ($p < 0.01$) with outdoor temperature. Coefficients are highest for skin temperature with 0.35, indicating that with each increase in outdoor temperature, skin temperature increases by 0.35° . Estimates are lower for ear temperature (0.10) and body temperature (0.20), but are significant for each parameter. The dashed black line represents the WBGT value at which the American College of Sports Medicine (ACSM) recommends considering event relocation due to heat stress concerns (Roberts et al., 2023).

3.5. Urine samples

In the analysis of the urine samples using urine sticks, there were no signs of hematuria or proteinuria either before or after the training sessions. Additionally, no other abnormalities were detected in any of the urine samples.

In both club settings, an increase in the mean values of USG was observed before training compared to after training. For Club Normal the mean value increased from 1.016 to 1.024, and for Club Warm, it increased from 1.020 to 1.025. In the camp setting, the mean values remained very stable from the beginning to the end of the day. Because of the non-normal distribution of the data, a Wilcoxon-Rank test was performed for each setting. The test showed significant differences for the comparison before and after training on moderate temperature days and warm days (Wilcoxon; $p < 0.001$). However, no significant changes were observed for the camp setting.

4. Discussion

Our analysis revealed a positive correlation between outdoor temperature and ear and skin temperature in male children during training sessions. This suggests that rising ambient temperatures are associated with higher estimated mean body temperatures, as calculated using Burton's formula.

Fig. 5 focuses exclusively on temperatures measured in the 60th minute to minimize bias introduced by pre-training activity levels. By the 60th minute, we can assume a more comparable level of exertion among participants. The results illustrate a faster rise in skin temperature compared to ear respectively core temperature. This observation aligns with established knowledge regarding differences in thermoregulatory mechanisms between children and adults. Prepubertal children exhibit lower sweat production compared to adults, yet they can dissipate heat more effectively through convection due to a larger body surface area to mass ratio (Bar-Or et al., 1980; Rowland, 2008; Arlegui et al., 2021). Our results support the notion that skin temperature plays a key role in mediating body temperature stability in children during exercise, aligning with previous research on thermoregulatory differences.

The use of ear temperature as a proxy for body temperature in wearable devices is supported by existing research, which has demonstrated the value of physiological parameters as indicators of health status and diagnostic tools (Eggenberger et al., 2018). Recent validation of the Cosinuss[®] c-med in-ear sensor[®] showed high agreement with esophageal core temperature, outperforming rectal and bladder measures, which showed larger biases and lower reliability (Langenhorst et al., 2024). These findings support the use of in-ear sensors for intra-individual comparisons, particularly in dynamic thermal conditions. Additionally previous research on its predecessor, the Cosinuss[®]

Two in-ear sensor®, has shown the potential of the device for temperature measurement (Burgos et al., 2020; Ellebrecht et al., 2022; Wibowo et al., 2023), but also limitations in core body temperature assessment (Roossien et al., 2021). Although ET does not directly reflect core body temperature, it has been demonstrated to be a reliable proxy (Roossien et al., 2021).

The data from our study leads to the conclusion that the ET and the BT calculated from it underestimate the actual BT. For example, at an outside temperature of 15 °C (according to Fig. 4 in the 60th minute of the respective training session), the average ET value determined is 35.5 °C, while the calculated BT value is 33.7 °C. This already corresponds to hypothermia, although it can be ruled out that the average of the participants was actually in hypothermia.

Our findings indicate that while the outdoor temperature does correlate with the outdoor temperature, the training itself has no effect on the ET or ST (in fact, the results of the regression suggest a slight decrease over the time of training). However, the mixed model also showed mild to moderate individual variability for both the starting body temperature as well body temperature over time. It is already known from previous studies that the heat tolerance of children during sporting activities is dependent on a number of factors, including acclimatization, fitness level and the duration of the sporting session (Dougherty et al., 2010). For example, children who exercise a lot and are fit have an increased heat tolerance compared to children who rarely exercise (Sinclair et al., 2007). In the written survey of parents conducted prior to the study, it was indicated that the majority of children engage in sports activities more than three times per week for a duration of at least 90 min. Based on the findings of a Germany-wide epidemiological study, it can be assumed that the participants belong to the age group that engages in a comparatively large amount of sport (Finger et al., 2018) and are therefore likely to be relatively fit.

For our participants, the rather fit male children, our data show that they can effectively regulate their body temperature. We could not detect any pathological response, like muscle cramps, confusion, dizziness or a BT rise above a critical level.

However, the data set does not allow us to draw conclusions for other

groups, such as untrained male children or female children. Also, the age range was rather restricted to 8–12 years old. Follow-up studies should therefore examine core body-temperature responses and exertional heat-illness risks for other groups during outdoor activity.

It is essential to recognize that sustained exposure to elevated temperatures can pose health risks. For athletes, the risk of exertional heat stress becomes significant when exercise intensity is high and WBGT surpasses 28 °C (Armstrong et al., 2007). In many cases these temperatures were reached in the study's training sessions. The American College of Sports Medicine (ACSM) recommends limiting intense exercise when the WBGT exceeds 30 °C and warns that heat stress becomes unavoidable when the WBGT surpasses 32.3 °C, even for heat-acclimatized and physically fit individuals (Roberts et al., 2023).

Our results of our study are consistent with those of the 2019 Pediatrics Policy Statement (Bergeron et al., 2011), suggesting that boys who exercise regularly have a higher tolerance to heat stress and can therefore be active in high outdoor temperatures without an increased risk of heat-related illness.

Although, we recommend that coaches and club managers follow the ACSM guidelines, which means considering moving training to the evening hours if the outside temperature is hotter than 30 °C. It should be noted that this will not be feasible in many practical situations. Therefore, coaches must also ensure that children consume sufficient fluids and take adequate rest periods. The National Athletic Trainers' Association recommends consuming 3–5 ounces (90–150 ml) of fluid every 20 min (McDermott et al., 2017). Coaches should emphasize the importance of consistent fluid intake, especially in challenging environmental conditions. Taking enough drinking breaks is crucial, because research has shown that children often do not drink enough to fully replace the fluids they lose during exercise (Bar-Or et al., 1980; Bergeron et al., 2011; Decher et al., 2008). A study of 10–12 year old boys showed that dehydration occurred due to the children not drinking enough while exercising in hot climates (Bar-Or et al., 1980).

Another study investigated the hydration status of youth athletes at summer sport camps and revealed a high incidence of dehydration. Despite a good general knowledge of hydration concepts, the study

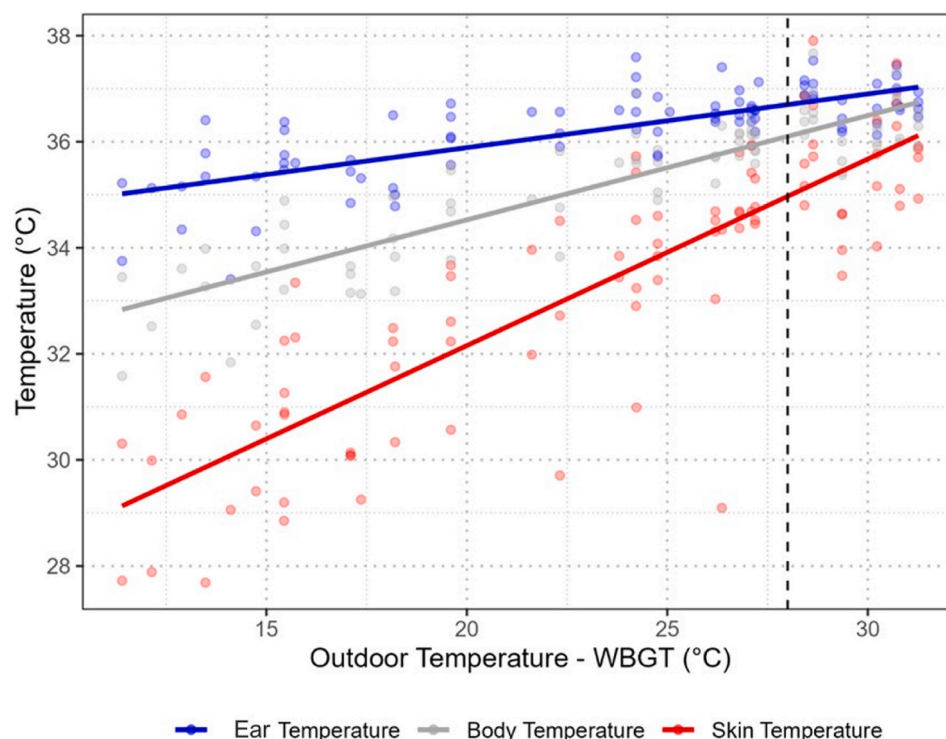


Fig. 5. Correlation between ear, body, and skin temperature and outdoor temperature at the 60th minute of each training session (n = 45).

participants did not drink enough fluid to maintain their hydration status during the training, with the most common barriers were lack of time to drink and forgetting to drink (Decher et al., 2008).

These results align with the results of our study. A significant difference in specific urine density was observed between pre- and post-training for both Club Warm participants and Club Normal participants. In contrast, no significant change in urine density was noted for camp participants. Since it was not the main target of this study, drinking breaks and fluid intake was not monitored. Still these results suggest that outdoor temperature do not have a significant effect on the hydration status of children after a football training session. Instead, it is more likely that the specific type of training and variations in coaching practices regarding hydration breaks and amount of fluid intake have a stronger influence.

5. Strength and limitations

This study breaks new ground by continuously monitoring male children's body temperature throughout physical activity using wearable technology in realistic outdoor conditions. This approach allows for a more comprehensive investigation of heat stress compared to previous studies which could only measure body temperature during breaks. The findings provide valuable insights for club officials and coaches, empowering them to develop effective heat stress management strategies for children.

While the generalizability of the results to the entire child population is limited due to the participation of only male subjects, the study successfully demonstrates the applicability of wearable sensors in outdoor settings. This paves the way for future research including young female participants.

The lack of measurement of fluid intake, the number of breaks taken, and the absence of a standardized training protocol represent confounding factors that could be potential points of criticism. To minimize the impact of these confounding factors, we selected an intra-individual design. In this setup, the training routine remained consistent, with the only variable being the outdoor temperature. This approach was intended to provide valid and reliable results.

The measurement of the USG is a valuable way to quickly and easily determine the hydration status during sports units (Decher et al., 2008; Shirreffs, 2003). However, it is not possible to diagnose dehydration simply by determining the USG. In a review article, however, it was found that there is no defined limit value for the USG, so that even maximum measurable values of 1.030 g/ml can be considered physiological (Zubac et al., 2018). This value is much more suitable as a progression parameter.

Wind conditions remained relatively stable over the course of our study. However, future research should further investigate the potential cooling effect of wind as a significant modifier.

According to the manufacturer, the device's ET measurements tend to underestimate the user's core temperature in outdoor settings. However the study design of within-subject comparisons with the same device model for both intra-individual measurements ensures reliable data on temperature changes. Recent validation by Langenhorst et al. (2024) confirmed a high agreement with esophageal core temperature, supporting the device's accuracy even under dynamic thermal conditions. This innovative application of wearable technology offers a valuable approach to advancing our understanding of thermoregulation.

In other studies, rectal and gastrointestinal temperature measurement have been demonstrated to be a reliable method for measuring body temperature (Bongers et al., 2018; González-Alonso et al., 1999; Moran and Mendal, 2002). However, the use of rectal temperature measurement is limited by the inability to obtain continuous readings, and it is probable that compliance with the gastrointestinal measurement using a capsule would have been lower. Consequently, the Cosinuss° c-med in-ear sensor was selected as a practical and non-invasive alternative.

Surface type (artificial vs. natural grass) was included as a between-subjects variable. However, as each participant consistently trained on only one surface, intra-individual comparisons were not possible. Therefore, the findings related to surface type should be interpreted with caution, as they may be influenced by individual-level confounding factors.

Using both spring and fall as reference periods for the moderate (club) condition may have introduced some variability due to differences in seasonal heat acclimatization and fitness levels. Although no significant differences in baseline ear or skin temperatures were found between spring and fall groups, subtle physiological adaptations that occurred over the summer cannot be ruled out.

The psychological effects of the heat on the test subjects were considered, both before and after the study. However, this proved to be challenging in one test run, as the children were influenced by the answers of the predecessor. Furthermore, the entire process would have required a significant amount of time, which would have prevented the examination of several children in one training session.

6. Conclusion

Our study highlights the significant impact of elevated outdoor temperatures on children's physiological responses during outdoor football activities, particularly noting the substantial increase in measured body and skin temperature under warm/hot conditions compared to moderate outdoor temperatures. As climate change continues to drive rising temperatures, implementing strategies to protect the health and well-being of children during outdoor sports has become essential.

The American College of Sports Medicine (ACSM) recommends cancelling competitions when temperatures exceed 28 °C and refraining from training when temperatures surpass 32.3 °C. In our study, however, the recorded outdoor temperatures frequently exceeded the 32.3 °C threshold for both the camp and club setups. This demonstrates that, in practice, these temperature limits are often surpassed. Nevertheless, our data indicated that no evidence of pathophysiological changes could be documented during and immediately after the exercise period.

While physiological parameters such as ear and skin temperature have risen with increasing outside temperatures, it is important to note that none of our participants exhibited heat-related symptoms such as critical elevated body temperatures, muscle cramps, confusion, or severe pain. The changes observed in the measured parameters remained within the age-appropriate normal range even after the physical exertion.

It is important to note that our study exclusively involved boys aged 8–12 who regularly engage in physical activity. Therefore, these findings cannot be generalized to the broader population within this age group. Further research is needed, particularly focusing on girls and less physically active boys, to better understand the impact of high temperatures on these groups.

A notable insight from our study is the lack of significant change in hydration status across different temperature conditions, suggesting that the type of training and coaching practices around hydration breaks are more influential. This underscores the importance of coaches ensuring regular hydration, not just during extreme heat but also in moderate conditions, to prevent dehydration.

As children can easily block out the feeling of thirst during sport, we refer to the NATA guidelines and recommend that coaches ensure that players drink at least 90–150 ml of fluid every 20 min, e.g. by ensuring that every child has drunk their water bottle at the end of training.

Proactive measures to reduce heat stress should include adjusting training times to cooler parts of the day, ensuring adequate shaded areas during practice, and enforcing regular hydration breaks regardless of the ambient temperature. These strategies can help mitigate the risks associated with heat stress, ensuring the safety and well-being of young

athletes.

By increasing awareness among coaches, club managers, and parents, and implementing these recommendations, we can better protect children from the adverse health effects of heat exposure during outdoor sports activities.

CRedit authorship contribution statement

Malte Satow: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Razan Wibowo:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Data curation. **Stephan Bose-O'Reilly:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Daniela Koller:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis. **Hein Daanen:** Writing – review & editing, Methodology. **Stefan Rakete:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Consent to participate

Informed consent was obtained from both parents or legal guardians of each participant included in the study, as well as from the participants themselves.

Ethics approval

The study was carried out in accordance with the Code of Ethics of the Declaration of Helsinki for experiments involving human subjects and was reviewed and approved by the ethics committee of the medical faculty of the Ludwig Maximilians University of Munich (#23–0193).

Consent for publication

Informed consent was obtained from all individual participants and both parents/legal guardians included in the study.

Availability of data and material

The data can be made available upon reasonable request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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