

What do thermal indices lack to help predict heat-related risk in elite Athletics?

David Bandiera ^{1,2} Frédéric Garrandes^{3,4} Jan Kowalski ⁵
Paolo Emilio Adami ^{3,4,6} Sebastien Racinais ² Andreas Matzarakis ^{7,8}
Yannis P Pitsiladis ^{1,9,10} Antonio Tessitore ¹ Stéphane Bermon ^{3,4}

► Additional supplemental material is published online only. To view, please visit the journal online (<https://doi.org/10.1136/bjsports-2025-110822>).

¹Department of Movement, Human and Health Sciences, Università degli Studi di Roma Foro Italico, Roma, Italy

²Environmental Stress Unit, CREPS Montpellier-Font Romeu, Montpellier, France

³Health and Science Department, World Athletics, Monaco

⁴Laboratoire Motricité Humaine Expertise Sport Santé (LAMHESS), Université Côte d'Azur, Nice, France

⁵JK Biostatistics AB, Stockholm, Sweden

⁶Physiology and Pharmacology Department "V. Erspamer", University of Rome La Sapienza, Rome, Lazio, Italy

⁷Faculty of Environment and Natural Resources, University Freiburg, Freiburg, Germany

⁸Democritus University of Thrace, Komotini, Greece

⁹Department of Biology, Hong Kong Baptist University, Hong Kong, Hong Kong

¹⁰Centre for Exercise Science and Medicine (CESAME), Hong Kong Baptist University, Hong Kong, Hong Kong

Correspondence to

Dr Stéphane Bermon;
stephane.bermon@worldathletics.org

Accepted 25 January 2026

Published Online First

17 February 2026



© Author(s) (or their employer(s)) 2026. No commercial re-use. See rights and permissions. Published by BMJ Group.

To cite: Bandiera D, Garrandes F, Kowalski J, et al. *Br J Sports Med* 2026;**60**:534–542.

ABSTRACT

Objectives This study aimed to characterise the frequency of exertional heat stroke (EHS), did-not-finish (DNF) and medical encounter (MED) outcomes in elite Athletics competitions, and to evaluate their association with environmental, individual and race-related variables. Particular attention was given to the wet bulb globe temperature (WBGT), a thermal index widely used by international federations to estimate athlete heat strain.

Methods Data were collected from 4938 athletes of both sexes participating in 80 World Athletics races held between 2019 and 2024 in five disciplines: long distance track events, marathon, racewalking, cross-country and trail-running. Spearman rank coefficient correlations, Pearson χ^2 tests and negative binomial (NB) regressions were used to explore associations between outcomes (EHS, DNF, MED) and environmental, individual and race-related variables. The predictive ability of these variables was assessed using leave-one-out cross-validation to identify the best-performing univariable and multivariable models.

Results EHS frequency was 8/1000 on average and 16/1000 when the WBGT was above 28.0°C, independent of sex ($p=0.297$) or discipline ($p=0.980$). DNF and MED were higher in marathon, racewalking and trail-running than shorter disciplines ($p<0.001$). Among variables, the mean radiant temperature showed the strongest univariable association with EHS ($R^2=0.11$, $p<0.001$), while WBGT association was weaker ($R^2=0.04$, $p=0.018$). Predictive accuracy was limited, with the best model having an error of 0.5 ± 0.7 EHS per race.

Conclusion The risk of EHS is particularly high during elite endurance events in Athletics. While EHS was greater with higher WBGT and radiant temperatures, neither provided sufficient predictive accuracy for heat-related risk in elite endurance athletes. Future models should consider other factors such as heat acclimatisation and recent illness to enhance predictive ability.

INTRODUCTION

Climate change and the globalisation of sport have increased the number of competitions held in hot environments.¹ Outdoor Athletics (track and field) is particularly exposed to environmental heat stress, as most international events take place in the Northern Hemisphere during summer.² This context demands specific preparation from athletes, such as heat acclimatisation, hydration, cooling

WHAT IS ALREADY KNOWN ON THIS TOPIC

- ⇒ Exertional heat stroke (EHS) is a leading cause of collapse and a life-threatening situation for athletes competing in the heat.
- ⇒ To anticipate the risk of EHS and implement mitigation strategies, international federations rely on environmental thermal indices.

WHAT THIS STUDY ADDS

- ⇒ EHS occurs in 8/1000 athlete exposures and up to 16/1000 in hot conditions (wet bulb globe temperature (WBGT) 28–29.9°C), with no differences by sex or endurance discipline.
- ⇒ Although a few models showed marginally improved prediction of EHS compared with WBGT, overall predictive ability remains poor.
- ⇒ Higher WBGT risk thresholds currently used by World Athletics are associated with an increased risk of EHS.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

- ⇒ WBGT flag categories must be considered when adapting the medical plan and the number of cold-water immersion baths to be provided.
- ⇒ Future studies should investigate whether athlete acclimation/acclimatisation and health status prior to the race improve EHS risk prediction.

strategies³ and tailored logistical planning from organisers.^{4,5}

Exertional heat illness (EHI), and especially exertional heat stroke (EHS), represents a major health risk for athletes competing in hot conditions.⁶ EHS is life-threatening if not managed promptly and effectively.⁷ The magnitude of EHI in Athletics is substantial: across seven international championships between 2009 and 2018, 24.7% ($n=132$) of all recorded illnesses ($n=534$) were heat-related, with the majority occurring in marathon (47.0%, $n=62$) and race walking (34.8%, $n=46$) events.²

The factors leading to EHI are multifactorial and not yet fully understood. However, EHI in athletes primarily results from the combination of elevated metabolic heat production, strong motivation-driven performances and hot environmental conditions.^{8,9} In addition, the absence of an adequate heat acclimatisation period or the presence of an infectious illness in the days preceding competition may further increase the risk of heat-related

illness.¹⁰ More broadly, heat stress can also lead to other adverse outcomes in Athletics, such as failure to finish the race (DNF) or medical encounters (MED), the latter referring to any admission to medical facilities regardless of cause.¹⁰

Anticipating heat stress risk is crucial for accurately estimating the medical needs during elite competitions (eg, number of medical staff, cold-water immersion facilities, emergency shuttles). To support this, organisers rely on thermal indices, which are quantitative indicators representing the impact of the thermal environment on individuals.¹¹ The most widely used index is the wet bulb globe temperature (WBGT),¹² adopted by several international federations including World Athletics, the International Cycling Union and World Triathlon.¹³ A coloured-flag system is used to further facilitate WBGT interpretation, classifying the level of heat stress risk. However, WBGT, as a climatic index, does not consider athletes' metabolic heat production, potentially underestimating heat stress in humid or low-airflow conditions.^{14 15} In an 8-year analysis of medical events at the Gothenburg half-marathon, WBGT showed a weaker relation ($R^2=0.56$, $p=0.033$) with the number of collapses compared with the universal thermal climate index (UTCI, $R^2=0.64$, $p=0.017$) and physiologically equivalent temperature (PET, $R^2=0.71$, $p=0.008$), suggesting that thermal indices considering metabolic heat production (ie, UTCI and PET) were more performant.¹⁶ However, a 30-year retrospective analysis of the temperate Twin Cities marathon (mean WBGT=7.4°C) revealed a significant quadratic association ($p=0.006$) between WBGT and medical stress (defined as the sum of DNF and MED), while the association with the PET was not significant ($p=0.71$).¹⁷

Since the ability of environmental, individual and race-related variables to accurately predict the risk of medical outcomes in elite athletes remains unclear, this study analysed data from World Athletics competitions to identify the factors associated with EHS, DNF and MED in elite athletes.

METHODS

Competitions

Fourteen Athletics competitions held between 2019 and 2024 were included in the analysis, encompassing World Athletics World Championships and the Olympic Games (table 1). In each competition, 2 to 12 races were analysed, representing a total of 80 races equally distributed between sexes. A median of 53 athletes (IQR: 39–83) started each race, resulting in a total of 4938 athlete exposures. An athlete exposure was defined as one athlete participating in one race during the competitions included in the analysis.¹⁸

Data collection and estimation

The variables retrieved from World Athletics competitions are listed in table 2. For each competition except for Tokyo 2020, the World Athletics' medical team recorded the number of EHS, DNF and MED. Outcomes at the Olympic Games of Tokyo were obtained from the study of Sugawara *et al.*¹⁹ EHS was diagnosed when athletes presented central nervous system dysfunction in conjunction with a rectal temperature $\geq 40^\circ\text{C}$, DNF referred to athletes who DNF the race, and MED to medical encounters, corresponding to admission to medical facilities for any reason.

For environmental variables, air temperature, relative humidity and wind speed were collected with a Kestrel 5400 portable environmental device at Doha 2019 (Nielsen-Kellerman Company, Boothwyn, USA), with a meteorological station at Antalya 2024 and Gdynia 2020 (Seiko, Ginza, Japan) and with a mobile meteorological station at the other competitions sites (Kunak

Technologies SL, Orkoien, Spain). The mean value between the start and the end of the race was extracted. When the wind was not measured on the field of play (Doha 2019, Gdynia 2020, Riga 2023, Antalya 2024, Paris 2024 marathon), it was extracted from the nearest meteorological station (wind at 10 m) and estimated to a value at 1.8 m with the wind profile power law.²⁰ Absolute humidity and dew point (ie, air temperature at which relative humidity reaches 100%) were calculated from air temperature and relative humidity on R statistical software (V.4.4.2)²¹ with the package “humidity”²² and “weathermetrics”.²³ The impact of solar radiation was assessed by calculating the mean radiant temperature (MRT) using the RayMan Model.²⁴

For thermal indices, WBGT was measured using a Kunak meteorological station equipped with a 15 cm black globe, in accordance with established guidelines.¹⁴ Exclusions included Doha 2019 and Antalya 2024, where a Kestrel 5400 was used, and Gdynia 2020, where WBGT was not measured. The heat index, a widely used public health indicator²⁵ reflecting the perceived temperature by combining air temperature and relative humidity, was calculated in its extended version from on-site measurements.²⁶ Additionally, more advanced thermal indices that account for human thermoregulatory responses and clothing insulation, such as the UTCI,²⁷ the PET²⁸ and its modified version (mPET),²⁹ were computed using the RayMan Model.²⁴ Although originally developed for the general population, these advanced indices account for heat exchanges between the human body and the environment (including heat production and dissipation through conduction, convection, radiation and evaporation). This comprehensive approach may provide a more accurate representation of athletes' thermal strain compared with indices based solely on environmental variables²⁵ (description of thermal indices in online supplemental material SM1).

For individual and race-related data such as the sex and average age of athletes, distance, winner race time, last finisher race time, average velocity and number of starters, details were obtained from the race sheets on the official website of World Athletics.³⁰ For model prediction, the nominal variable “sex” was one for female and 0 for male's races. The variable “slope” was 0 if the average racecourse slope gradient was $<1\%$ and 1 if $\geq 1\%$. “Run” was 1 for running disciplines and 0 for race walking disciplines. The spring delay was calculated as the number of days between the 20th of March or 23rd of September (competition held in the Northern and Southern hemispheres, respectively) and the date of the competition, to estimate natural acclimatisation status of athletes. If this number was negative, the first day of spring from the previous year was then used for the calculation. This variable was created to estimate the level of natural acclimatisation of the athletes, considering that competitions taking place in early spring (low delay spring value) could be more conducive to EHI than competitions during summer (high delay spring value) because athletes would not benefit from natural acclimatisation adaptations.

WBGT, sex and discipline influence

The influence of WBGT coloured-flag levels from World Athletics classification, sex and disciplines on EHS, DNF and MED was investigated with a Pearson's χ^2 test for count data (χ^2).³¹ The assumptions for the Pearson χ^2 test were met, with no expected cell count <1 and fewer than 20% of expected cell counts below 5. As recommended by the consensus on epidemiological studies in Athletics,¹⁸ the number of outcomes was expressed for 1000 athletes' exposure and the races were grouped under 5 Athletics disciplines: in stadium long distance (5000 m and 10 000 m) and

Table 1 Eighty races were investigated from 14 different World Athletics competitions

N	Type	Location	Dates	Races	WBGT (°C)
1	World Championships	Doha, Qatar	27 September 2019 to 6 October 2019	Marathon Racewalk 20 km Racewalk 50 km	20.9 (m), 28.5 (f) 27.9 (m), 28.2 (f) 27.9 (m, f)
2	World Half Marathon Championships	Gdynia, Poland	17 October 2020	Half-marathon	–
3	Olympic Games	Sapporo, Japan	23 August 2021 to 8 August 2021	Marathon Racewalk 20 km Racewalk 50 km	25.6 (m), 27.6 (f) 29.4 (m, f) 28.5 (m)
4	World Race Walking Team Championships	Muscat, Oman	4 March 2022 to 5 March 2022	Racewalk 10 km junior Racewalk 20 km Racewalk 35 km	27.5 (m), 25.6 (f) 24.5 (m), 24.8 (f) 24.7 (m), 25.0 (f)
6	World Championships	Eugene, Oregon, US	15 July 2022 to 24 July 2022	Marathon (f) Racewalk 20 km Racewalk 35 km 5000 m heat 5000 m final 10 000 m	11.9 (f) 24.0 (m), 22.6 (f) 13.0 (m), 14.0 (f) 25.2 (m), 27.7 (f) 27.0 (m), 21.8 (f) 19.6 (m, f)
7	World Mountain and Trail Running Championships	Chiang Mai, Thailand	4 November 2022 to 6 November 2022	Long trail 78 km Short trail 38 km Classic up down 11 km Classic up down junior 6 km	20.6 (m, f) 24.8 (m), 25.1 (f) 26.6 (m), 26.9 (f) 24.3 (m), 25.2 (f)
8	World Cross Country Championships	Bathurst, Australia	18 February 2023	10 km Junior 8 km or 6 km	21.7 (m), 24.0 (f) 27.9 (m), 28.9 (f)
9	World Mountain and Trail Running Championships	Innsbruck, Austria	6 June 2023 to 10 June 2023	Long trail 87 km Short trail 44 km Mountain classic 14 km Mountain classic junior 7 km	14.5 (m, f) 19.2 (m, f) 23.4 (m), 21.7 (f) 23.7 (m, f)
10	World Championships	Budapest, Hungary	19 September 2023 to 27 September 2023	Marathon Racewalk 20 km Racewalk 35 km 5000 m heat 5000 m final 10 000 m	25.8 (m), 26.0 (f) 20.5 (m), 25.1 (f) 25.9 (m), 26.1 (f) 25.3 (m), 26.6 (f) 25.8 (m), 24.9 (f) 28.0 (m), 23.0 (f)
11	World Road Running Championships	Riga, Latvia	1 October 2023	Half-marathon	15.6 (m, f)
12	World Cross Country Championships	Belgrade, Serbia	30 March 2024	10 km 8 km or 6 km junior	27.4 (m), 28.1 (f) 27.7 (m), 27.4 (f)
13	World Race Walking Team Championships	Antalya, Türkiye	21 April 2024	Racewalk 10 km junior Racewalk 20 km	15.9 (m), 21.0 (f) 25.1 (m), 23.7 (f)
14	Olympic Games	Paris, France	26 July 2024 to 11 August 2024	Marathon Racewalk 20 km 5000 m final 10 000 m	21.3 (m), 22.6 (f) 22.2 (m), 26.5 (f) 27.1 (m), 22.5 (f) 21.2 (m), 21.9 (f)

WBGT is indicated with (m) corresponding to the male race and (f) corresponding to the female race.
WBGT, Wet Bulb Globe Temperature.

out of stadium racewalking (from 10 to 50 km), marathon (full and half), cross-country (from 6 to 10 km) and trail running (from 6 to 87 km). All statistics were performed on R statistical software (V.4.4.2)²¹ and statistical significance was defined as $p < 0.05$.

Association and prediction

First, as the data were not normally distributed, associations between variables retrieved from Athletics World Championships (table 2) and the outcomes (ie, EHS, DNF and MED) were assessed using Spearman's rank correlation coefficient (r_s).

Second, negative binomial (NB) regressions were performed as the outcomes consisted of over-dispersed count data, thereby violating the assumptions of Poisson regression (variance larger than the mean, figure 1).

Thirdly, to assess the predictive ability of each variable, a leave-one-out cross-validation (LOOCV) was applied to the NB regressions. In this approach, the model (ie, NB regression between the variable and the outcome) is trained on all data points except

one, which is used for testing. The process is repeated for each data point, and absolute errors are averaged across all iterations, giving a mean absolute error (LOOCV MAE) and a standard deviation of the absolute error. This method provides an unbiased estimate of model performance on new data, especially in datasets with limited sample size ($n=80$).

Finally, multivariable NB models were run using the same LOOCV framework to assess whether combining variables improved predictive performance. Prior to model building, pairwise associations between continuous predictors (ie, variables in table 2, all non-parametric) were assessed using Spearman's rank correlations. Variables showing "strong" or "very strong" correlations ($r_s \geq 0.6$)³² were considered redundant and were not entered simultaneously into the same model. Within each correlated group, the variable with the lowest LOOCV MAE in univariable analyses was retained for multivariable modelling. All retained predictors were entered simultaneously into the multivariable NB models (no stepwise selection). Of note, the linearity assumption underlying NB regression was

Table 2 Environmental, individual and race-related variables retrieved from 80 World Athletics races

	Variable	Unity	Type	Collected/estimated
Environmental	Air temperature	°C	Continuous	Collected
	Relative humidity	%	Continuous	Collected
	Wind	m/s	Continuous	Collected/estimated
	Absolute humidity	g/m ³	Continuous	Collected
	Dew point	°C	Continuous	Collected
	Mean radiant temperature	°C	Continuous	Estimated
	Wet bulb globe temperature	°C	Continuous	Collected
	Universal thermal climate index	°C	Continuous	Estimated
	Physiologically equivalent temperature	°C	Continuous	Estimated
	Modified physiologically equivalent temperature	°C	Continuous	Estimated
Individual	Sex (female/male)		Nominal	Collected
	Age		Continuous	Collected
Race-related	Distance	km	Continuous	Collected
	Winner race time	min	Continuous	Collected
	Last finisher race time	min	Continuous	Collected
	Average velocity	m/s	Continuous	Collected
	Number of starters		Discrete	Collected
	Spring delay		Discrete	Collected
	Run (yes/no)		Nominal	Collected
	Slope (yes/no)		Nominal	Collected
Outcome	Exertional heat stroke		Discrete	Collected
	Did not finish		Discrete	Collected
	Medical encounters		Discrete	Collected

Some variables were directly collected on the field of play, while others were estimated with validated methods. The association between these variables and three different outcomes was investigated: the number of athletes diagnosed with exertional heat stroke, those who did not finish and medical encounters, corresponding to athletes admitted to medical facilities regardless of cause.

not formally assessed and therefore represents a methodological limitation.

Patient and public involvement

No patient or public involvement was needed for this research.

Equity, diversity and inclusion statement

All athletes registered for the World Athletics championships were included, with no exclusion based on sex, ethnicity, socio-economic status or marginalisation. The author team comprised 9 men, including 1 junior and 4 experienced researchers, 1 biostatistician, 1 biometeorologist and 2 medical doctors. Five

different nationalities are represented within the research team (France, Sweden, Italy, Germany, Greece).

RESULTS

WBGT, sex and discipline influence

Across all events, 41 EHS, 484 DNF and 466 MED were recorded. This corresponds to a frequency of 8/1000 athletes' exposure for EHS, 98/1000 for DNF and 94/1000 for MED.

However, these frequencies varied with environmental conditions as higher WBGT level was associated with higher risk of EHS (p=0.003), DNF and MED (both p<0.001, table 3). When WBGT was <21°C (white flag), the EHS frequency was 2/1000

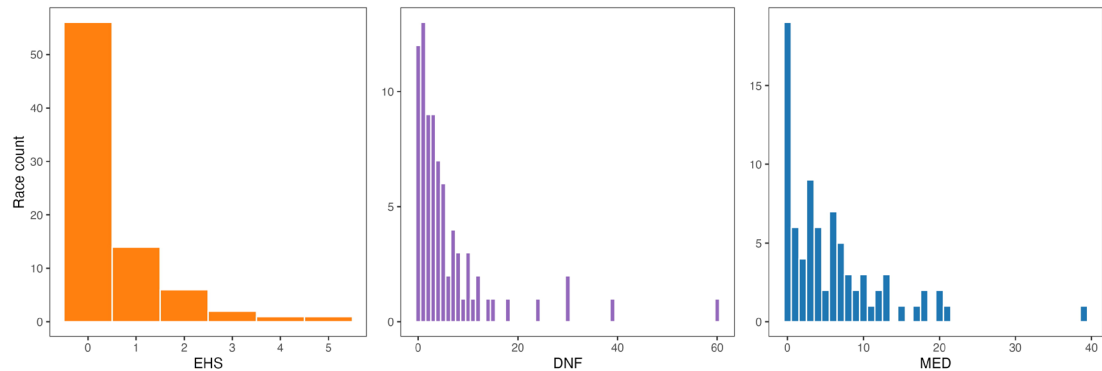


Figure 1 Histograms showing the number of athletes diagnosed with exertional heat stroke (EHS), those who did not finish (DNF) and medical encounters (MED), corresponding to athletes admitted to medical facilities regardless of cause. 80 World Athletics races are depicted, and the data for the three outcomes are overdispersed since the variances are larger than the means.

Table 3 Association between wet bulb globe temperature levels (white, green, orange, red, black), sex (female, male) and discipline (marathon, racewalking, trail, xcountry, long) on the number of athletes diagnosed with exertional heat stroke, those who did not finish and medical encounters, corresponding to athletes admitted to medical facilities regardless of cause

		Group	Athletes with outcome	Athletes without outcome	Frequency/1000	RR	Df	χ^2	P value
EHS	WBGT	Black $\geq 30^\circ\text{C}$	–	–	–		3	13.8	0.003
		Red 28–29.9°C	8	493	16	10.5			
		Orange 25–27.9°C	20	1558	13	8.3			
		Green 21–24.9°C	11	1311	8	5.5			
		White $< 21^\circ\text{C}$	2	1310	2				
	Sex	Female	22	2229	10	1.4	1	1.1	0.297
		Male	19	2668	7				
	Discipline	Marathon	10	1093	9	1.2	4	0.4	0.980
		Racewalking	9	1267	7	0.9			
		Trail	13	1439	9	1.2			
		xcountry	6	700	9	1.1			
		Long	3	398	8				
DNF	WBGT	Black $\geq 30^\circ\text{C}$	–	–	–		3	57.9	< 0.001
		Red 28–29.9°C	72	429	144	1.1			
		Orange 25–27.9°C	164	1414	104	0.8			
		Green 21–24.9°C	69	1253	52	0.4			
		White $< 21^\circ\text{C}$	172	1140	131				
	Sex	Female	236	2015	105	1.1	1	2.2	0.140
		Male	248	2439	92				
	Discipline	Marathon	174	929	158	5.3	4	90.7	< 0.001
		Racewalking	120	1156	94	3.1			
		Trail	148	1304	102	3.4			
		xcountry	30	676	43	1.4			
		Long	12	389	30				
MED	WBGT	Black $\geq 30^\circ\text{C}$	–	–	–		3	34.5	< 0.001
		Red 28–29.9°C	80	421	160	1.7			
		Orange 25–27.9°C	163	1415	103	1.1			
		Green 21–24.9°C	92	1230	70	0.7			
		White $< 21^\circ\text{C}$	124	1188	95				
	Sex	Female	255	1996	113	1.4	1	17.3	< 0.001
		Male	211	2476	79				
	Discipline	Marathon	166	937	151	20.1	4	103.1	< 0.001
		Racewalking	104	1172	82	10.9			
		Trail	161	1291	111	14.8			
		xcountry	32	674	45	6.1			
		Long	3	398	8				

Df, degree(s) of freedom; DNF, did not finish; EHS, exertional heat stroke; MED, medical encounters; RR, rate ratio; WBGT, Wet Bulb Globe Temperature; χ^2 , Chi 2 test.

while between 28.0–29.9°C (red flag), it rose to 16/1000. No races were conducted with WBGT $\geq 30^\circ\text{C}$ (black flag) (figure 2).

There was no significant association between sex and EHS ($p=0.297$) or DNF ($p=0.140$), whereas female had 1.4 more risk of MED than male ($p<0.001$, table 3). Also, there was no significant association between the discipline and EHS ($p=0.98$), while the association was significant for DNF and MED ($p<0.001$, table 3).

Association and prediction

Among all the variables, PET showed the strongest correlation with EHS ($r_s=0.42$, $p<0.001$), followed by MRT ($r_s=0.41$, $p<0.001$) and UTCI ($r_s=0.34$, $p=0.002$), whereas the correlation with WBGT was lower ($r_s=0.21$, $p=0.061$). MRT yielded the strongest NB regression ($R^2=0.11$, $p<0.001$) and was the best predictor (lowest prediction error of 0.60 ± 0.69 EHS cases per race) followed by PET and UTCI (table 4). WBGT showed a slightly higher error of 0.71 ± 0.69 (table 4, figure 2).

A longer distance was associated with higher number of DNF and MED (respectively $r_s=0.72$ and $r_s=0.69$, both $p<0.001$), as well as both a longer last finisher race time ($r_s=0.69$, $r_s=0.72$, both $p<0.001$) and winner race time (both $r_s=0.67$, $p<0.001$, table 4). Age was the best predictor for both DNF (error of 4.39 ± 6.70) and MED (4.01 ± 4.25 , table 4). Association results of each variable listed in table 2 can be found in online supplemental materials for EHS (SM2), DNF (SM3) and MED (SM4).

Regarding multivariable association, the best models predicting outcomes were composed of the following variables:

- ▶ $\log(\text{EHS}) = -9.13 + 0.17 * \text{dew point} + 0.50 * \text{slope} + 0.76 * \text{run} + 0.11 * \text{MRT}$.
- ▶ $\log(\text{DNF}) = -3.35 + 0.02 * \text{number of starters} + 0.08 * \text{absolute humidity} + 0.08 * \text{age}$.
- ▶ $\log(\text{MED}) = -2.84 + 0.43 * \text{sex} + 0.03 * \text{number of starters} + 0.11 * \text{dew point} + 0.02 * \text{age} + 0.16 * \text{run}$.

Those models led to predictive errors of 0.54 ± 0.71 case per race for EHS, 3.89 ± 6.12 for DNF and 3.56 ± 4.10 for MED.

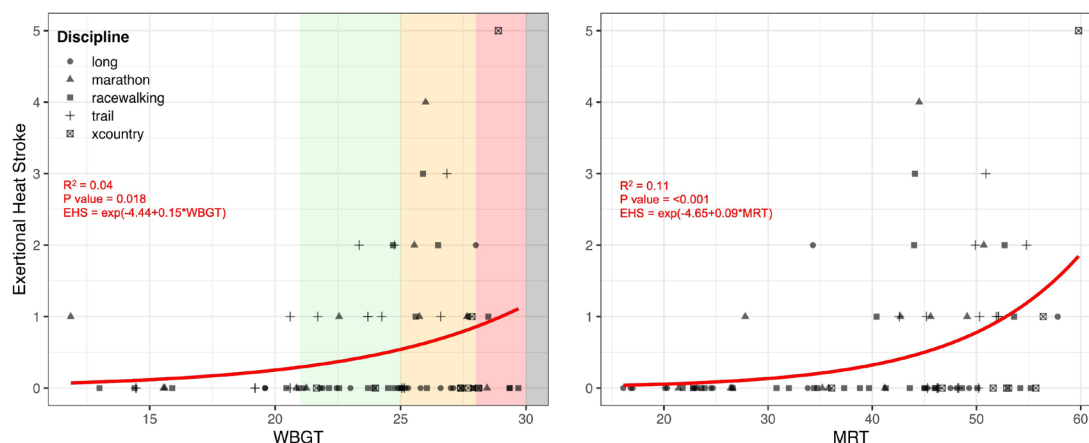


Figure 2 Association between exertional heat stroke (EHS) count and the Wet Bulb Globe Temperature (WBGT, left) or Mean Radiant Temperature (MRT, right). Among the variables retrieved, MRT demonstrates the strongest association, explaining 11% of EHS variability, while WBGT explains 4%. Red line: negative binomial regression, R^2 : McFadden's R^2 .

DISCUSSION

EHS frequency in elite athletes

The first key finding of this study is the high frequency of EHS among elite athletes averaging 8 cases per 1000 exposures, which increases to 16 per 1000 in hot environmental conditions (WBGT 28–29.9°C) (table 3). In comparison, EHS rates in mass-participation marathons under cooler conditions (ambient air temperature 5–20°C) are considerably lower, ranging from 0.4 to 1.3 per 1000 exposures.^{33–35} Even in competitions known for their high rates of heat illness, such as the Falmouth Road Race,

the reported EHS frequency is 2.1 per 1000, peaking at 6.6 per 1000 during the 2003 heat wave.^{36 37} Although fewer studies are available due to the lack of proper EHS diagnosis,⁸ the risk of EHS also appears to be generally lower in other sports and in the military. For example, American football shows a frequency of 4.2 per 1000 exposures, which is higher than tennis, football (soccer) or field hockey but still below that observed in elite Athletics in our study.³⁸ While in the military, the reported average EHS frequency in the US Army is approximately 0.3 per 1000 person-years.^{8 39} These comparisons highlight the uniquely

Table 4 Univariable association between variables retrieved from Athletics races and the number of athletes diagnosed with exertional heat stroke, those who did not finish the race and medical encounters

	Variable	Correlation			Negative binomial regression				
		Rank	Coefficient	P value	Coefficient	P value	R^2	MAE	LOOCV MAE
EHS	PET	1	0.42	<0.001	0.09	<0.001	0.10	0.61	0.63
	MRT	2	0.41	<0.001	0.09	<0.001	0.11	0.58	0.60
	UTCI	3	0.34	0.002	0.15	<0.001	0.09	0.63	0.65
	mPET	4	0.24	0.030	0.05	0.013	0.03	0.70	0.72
	WBGT	5	0.21	0.061	0.15	0.018	0.04	0.69	0.71
	Age	6	0.17	0.130	0.01	0.893	0.00	0.72	0.74
DNF	Distance	1	0.72	<0.001	0.05	<0.001	0.14	4.08	4.47
	Last finisher race time	2	0.69	<0.001	0.00	<0.001	0.06	4.90	5.83
	Winner race time	3	0.67	<0.001	0.01	<0.001	0.08	5.15	6.65
	Age	4	0.61	<0.001	0.15	<0.001	0.08	4.25	4.39
	Number of starters	5	0.55	<0.001	0.02	<0.001	0.07	4.95	5.19
	Average velocity	6	−0.31	0.006	−0.37	0.001	0.02	5.33	5.51
	WBGT	13	0.08	0.474	−0.05	0.136	0.01	5.67	5.84
MED	Last finisher race time	1	0.72	<0.001	0.00	<0.001	0.04	4.98	5.97
	Distance	2	0.69	<0.001	0.04	<0.001	0.07	4.34	4.70
	Winner race time	3	0.67	<0.001	0.01	<0.001	0.04	5.31	6.90
	Number of starters	4	0.66	<0.001	0.02	<0.001	0.05	4.81	5.15
	Age	5	0.61	<0.001	0.10	<0.001	0.03	3.92	4.01
	Average velocity	6	−0.50	<0.001	−0.46	<0.001	0.03	4.03	4.14
	WBGT	17	0.04	0.707	0.01	0.880	0.00	4.90	5.02

Spearman rank correlation coefficients and negative binomial regression were performed, and the predictive ability of variables was investigated with a leave-one-out cross-validation (LOOCV). In the table, variables are ranked according to the strength of their Spearman rank correlation coefficients, and their association with WBGT are always included.

DNF, did not finish; EHS, exertional heat stroke; LOOCV MAE, MAE from LOOCV; LOOCV SDAE, standard deviation of absolute error from LOOCV; MAE, Mean Absolute Error; MED, medical encounters; mPET, modified physiologically equivalent temperature; MRT, mean radiant temperature; PET, physiologically equivalent temperature; R^2 , McFadden's R^2 ; UTCI, universal thermal climate index; WBGT, Wet Bulb Globe Temperature;

high EHS risk associated with elite-level Athletics competitions. This specificity must be carefully considered by local organising committees when planning events, ensuring the deployment of adequate medical resources and prehospital care systems to effectively manage EHS.⁴⁷

Sex and discipline influence

The frequency of EHS does not differ significantly between male and female athletes ($p=0.297$, table 3), a finding consistent with previous research on EHI in elite athletes across various disciplines, including track and field,² cycling⁴⁰ and beach volleyball.⁴¹ While sex differences in EHI risk have been reported among amateur runners,^{35 42 43} this disparity may be less pronounced in elite populations. It is likely that comparable levels of intense physical exertion associated with high metabolic heat production and a similarly strong performance-driven motivation in both sexes contribute to the equal EHS risk observed during elite competitions.^{44 45} Promoting heat preparedness through educational materials regardless of sex is therefore crucial.⁴⁶

On the other hand, sex was associated with MED, with female athletes more frequently seeking medical attention ($RR=1.4$, table 3) despite similar rates of EHS and DNF. Available data on medical care utilisation among male and female athletes remain limited and inconclusive.⁴⁷ Additionally, in this study, MED outcomes do not differentiate the underlying causes (eg, injury vs illness), which limits the interpretability of these findings.

No significant difference was observed between disciplines for EHS frequency ($p=0.980$, table 3). This finding reinforces the notion that long-duration events such as the marathon or race walking are not the only disciplines at risk of EHS in elite Athletics.^{44 48} Consequently, shorter but more intense disciplines such as 10 000 m and 5000 m should receive the same medical attention for heat stroke risk as longer endurance events.

In contrast, race discipline is significantly associated with both DNF and MED frequencies ($p<0.001$, table 3). Disciplines involving longer distances such as the marathon, racewalking and trail races are linked to higher rates of DNF and MED, consistent with the positive correlations observed between these outcomes and race distances (table 4, $p<0.001$). Longer events place greater physiological and cognitive demands on athletes, increasing the risk of withdrawal or medical complications.⁴⁹ Additionally, elite athletes running longer distances are more likely to voluntarily withdraw when they are no longer in contention for podium positions, thereby avoiding unnecessary physiological stress and optimising recovery for future events.⁵⁰

EHS association and prediction

The WBGT flag system is informative, as higher severity flags correspond to increased EHS frequency ($p=0.003$, figure 2). However, there is considerable variability within each level, resulting in a weak overall association between WBGT and EHS ($R^2=0.04$, $p=0.018$). When used alone, WBGT yielded a mean absolute error on new data (LOOCV MAE) of 0.7 ± 0.7 EHS cases per race, which is higher than the mean number of EHS per race (0.5 ± 1.0), limiting its utility for predicting EHS frequency. Among recreational runners, the relationship between WBGT and EHS remains inconsistent; some studies report moderate to strong coefficients of determination ($R^2=0.41$ – 0.91),^{16 37 42 45 51} while others find no significant association.⁴³ Therefore, the reliability of WBGT appears to be case-dependent, and its use should ideally be supported by prior association analyses with heat-related outcomes before being relied on for decision-making.

MRT emerged as the strongest univariable predictor of EHS ($R^2=0.11$; LOOCV MAE: 0.6 ± 0.7 , table 4), emphasising the influence of solar radiation over air temperature, humidity or wind.⁵² PET and UTCI outperformed WBGT ($R^2=0.10$, 0.09 vs 0.04 , respectively), which is consistent with previous findings in recreational settings.¹⁶ However, all thermal indices demonstrated limited predictive ability, likely due to their design for the general population who typically exhibit lower metabolic heat production and wear clothing that differs from that of athletes.^{25 48} The best multivariable model reached a LOOCV MAE of 0.5 ± 0.7 EHS cases, which remains insufficient for accurate prediction given the race average cases of 0.5 ± 1.0 . All together, these results indicate that currently retrieved environmental, individual and race-related variables (table 2) are not sufficient to predict EHS frequency. It is suggested that including factors such as athletes' acclimation/acclimatisation status or recent illness history may improve prediction ability.^{6 10 41} Such information could be collected using two simple questions addressed to the endurance athletes in the days preceding the race:

- Q1: Have you specifically trained in a natural or artificial hot environment ($\geq 30^\circ\text{C}$) for at least 5 days in the 30 days prior to your competition? (Yes/No).
- Q2: Have you experienced symptoms of illness such as fever, diarrhoea or vomiting within the 10 days prior to your competition? (Yes/No).

The responses to these questions would provide an estimate of the athletes' acclimation/acclimatisation status and general health condition before the event. A higher proportion of acclimated athletes and a lower proportion of those reporting recent illness could indicate a reduced overall risk of EHS within the race.

DNF and MED association and prediction

In contrast, individual and race-related variables allow for a more measured prediction of DNF and MED outcomes. Specifically, multivariable models achieve LOOCV MAEs of 3.9 ± 6.1 DNF and 3.6 ± 4.1 MED, both lower than their corresponding mean race frequency of 6.1 ± 9.4 and 5.8 ± 6.7 , respectively. Indeed, it has been well identified that age has a direct impact on DNF and MED in elite athletes.⁴⁷ A higher incidence of injuries has been reported among older athletes (>30 years) during competition. The increased injury risk in this population may be explained by the cumulative training load and microtrauma sustained over multiple seasons, as well as age-related tissue degeneration.⁵³

These findings therefore support the potential utility of such models for tailoring medical logistics and resource allocation during elite competitions.

Strengths and limitations

A strength of our study is that most environmental variables were measured directly in the field of competition rather than estimated from nearby stations (table 2), improving ecological accuracy and capturing microclimate variations that can significantly affect athletes' responses. The measuring system was consistently placed in direct sunlight as close as possible to the athletes: between the track and the stands for stadium sessions and at the finish line for other events. It was installed several days before races and was therefore stabilised to ambient conditions before the first measurement was recorded.

A limitation is that the study focused on the most severe form of EHI, namely EHS. Thus, milder and more frequent conditions such as heat exhaustion or heat-related performance decrements

were not considered and still have important implications for athletes' performance and safety. On the other hand, EHS assessments were conducted by medical professionals, ensuring high validity and reliability in the diagnosis.

Also, the dataset does not encompass the full range of possible climatic conditions. Consequently, certain environmental variables (eg, air temperature, relative humidity, MRT or wind speed) may have been overrepresented or underrepresented, potentially influencing their apparent association with EHS, MED or DNF.

Clinical implications

The uniquely high risk of EHS in elite Athletics competitions highlights the importance that event organisers must place on providing adequate medical and pre-hospital care on site. A dedicated area, referred to as a heat deck, allowing one or multiple cold-water immersion for the treatment of EHS, should be included in the medical tent. It is fundamental to staff this area with physicians trained in the diagnosis and treatment of EHS and equipped with the necessary material (ie, rectal thermometer with flexible long probe, rigid or inflatable bathtub, water, ice, mesh, stretcher).⁷ Our findings indicate that no variable provides substantially better prediction of EHS than the WBGT, which therefore remains the most practical reference tool for decision-making. In this specific context of elite endurance competition and with a limited number of participants at the World Championships (15 to 170 starters), we recommend adjusting the capacity of the heat deck to WBGT flag categories and expected EHS cases (figure 2): preparation for 2 EHS cases under a white flag, 3 under a green flag, 5 under an orange flag and 6 under a red flag, while events under a black flag should be cancelled. It is important to note that these recommendations are specific to elite endurance competitions and cannot be directly applied to mass-participation events, where thousands of amateur athletes are involved and the EHS frequency differs.

CONCLUSION

Medical outcomes from 80 elite athletics races representing 4938 race entries were analysed. EHS occurs with notably high frequency (8/1000 on average and 16/1000 in hot conditions), regardless of sex or discipline. Dropouts and MED are more common in marathon, racewalking and trail running as compared with shorter events. Although higher WBGT flag levels are associated with increased EHS frequency, WBGT has limited predictive value, and no other variable performs substantially better. Overall, the environmental and personal variables considered in this study contribute only slightly to predicting EHS, suggesting that most of the variance is likely underpinned by other personal variables (eg, acclimatisation, underlying illness, inflammatory status, previous episodes), some of which have yet to be discovered, representing an important area of future study.

Social media David Bandiera, LinkedIn @david-bandiera-5b2207159

Contributors FG, PEA and SB conducted environmental and medical data collection during World Athletics competitions. DB and FG performed race data extraction, environmental data estimation and data analyses. Data analyses were discussed by DB, FG, JK, SR, AM, YPP, AT and SB. DB and FG drafted the manuscript, and all co-authors contributed substantially to interpreting the results and approved the manuscript. All authors understand that they are accountable for all aspects of the work and ensure the accuracy and integrity of this manuscript. SB is the guarantor of the manuscript.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval Not applicable.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request. Environmental data have been collected on the field of play with meteorological station. Individual and race-related details are available online at <https://worldathletics.org/competition/calendar-results?>. Medical data, including exertional heat stroke and medical encounter counts, is not publicly available to protect athletes' privacy.

Supplemental material This content has been supplied by the author(s). It has not been vetted by BMJ Publishing Group Limited (BMJ) and may not have been peer-reviewed. Any opinions or recommendations discussed are solely those of the author(s) and are not endorsed by BMJ. BMJ disclaims all liability and responsibility arising from any reliance placed on the content. Where the content includes any translated material, BMJ does not warrant the accuracy and reliability of the translations (including but not limited to local regulations, clinical guidelines, terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

ORCID iDs

David Bandiera <https://orcid.org/0000-0003-2618-1922>
Jan Kowalski <https://orcid.org/0000-0001-5414-6556>
Paolo Emilio Adami <https://orcid.org/0000-0001-5975-5342>
Sebastien Racinais <https://orcid.org/0000-0003-0348-4744>
Andreas Matzarakis <https://orcid.org/0000-0003-3076-555X>
Yannis P Pitsiladis <https://orcid.org/0000-0001-6210-2449>
Antonio Tessitore <https://orcid.org/0000-0002-3542-0991>
Stéphane Bermon <https://orcid.org/0000-0002-9529-2901>

REFERENCES

- Smith KR, Woodward A, Lemke B, *et al*. The last Summer Olympics? Climate change, health, and work outdoors. *The Lancet* 2016;388:642–4.
- Hollander K, Klöwer M, Richardson A, *et al*. Apparent temperature and heat-related illnesses during international athletic championships: A prospective cohort study. *Scand J Med Sci Sports* 2021;31:2092–102.
- Esh CJ, Carter S, Galan-Lopez N, *et al*. A Review of Elite Athlete Evidence-Based Knowledge and Preparation for Competing in the Heat. *J of SCI IN SPORT AND EXERCISE* 2024;6:218–37.
- Racinais S, Hosokawa Y, Akama T, *et al*. IOC consensus statement on recommendations and regulations for sport events in the heat. *Br J Sports Med* 2023;57:8–25.
- Bermon S, Adami PE. Meteorological Risks in Doha 2019 Athletics World Championships: Health Considerations From Organizers. *Front Sports Act Living* 2019;1:58.
- Casa DJ, DeMartini JK, Bergeron MF, *et al*. National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses. *J Athl Train* 2015;50:986–1000.
- Hosokawa Y, Racinais S, Akama T, *et al*. Prehospital management of exertional heat stroke at sports competitions: International Olympic Committee Adverse Weather Impact Expert Working Group for the Olympic Games Tokyo 2020. *Br J Sports Med* 2021;55:1405–10.
- Périard JD, DeGroot D, Jay O. Exertional heat stroke in sport and the military: epidemiology and mitigation. *Exp Physiol* 2022;107:1111–21.
- Roberts WO, Armstrong LE, Sawka MN, *et al*. ACSM Expert Consensus Statement on Exertional Heat Illness: Recognition, Management, and Return to Activity. *Curr Sports Med Rep* 2023;22:134–49.
- Racinais S, Havenith G, Aylwin P, *et al*. Association between thermal responses, medical events, performance, heat acclimation and health status in male and female elite athletes during the 2019 Doha World Athletics Championships. *Br J Sports Med* 2022;56:439–45.
- de Freitas CR, Grigorieva EA. A comparison and appraisal of a comprehensive range of human thermal climate indices. *Int J Biometeorol* 2017;61:487–512.
- YAGLOU CP, MINARD D. Control of heat casualties at military training centers. *AMA Arch Ind Health* 1957;16:302–16.
- Bandiera D, Racinais S, Garrandes F, *et al*. Heat-related risk at Paris 2024: a proposal for classification and review of International Federations policies. *Br J Sports Med* 2024;58:860–9.
- Budd GM. Wet-bulb globe temperature (WBGT)—its history and its limitations. *J Sci Med Sport* 2008;11:20–32.
- Racinais S, Alonso JM, Coutts AJ, *et al*. Consensus recommendations on training and competing in the heat. *Br J Sports Med* 2015;49:1164–73.
- Thorsson S, Rayner D, Palm G, *et al*. Is Physiological Equivalent Temperature (PET) a superior screening tool for heat stress risk than Wet-Bulb Globe Temperature (WBGT)?

- index? Eight years of data from the Gothenburg half marathon. *Br J Sports Med* 2021;55:825–30.
- 17 Schroeder AN, Suriano ZJ, Kliethermes SA, *et al.* Using Wet Bulb Globe Temperature and Physiological Equivalent Temperature as Predictive Models of Medical Stress in a Marathon: Analysis of 30 Years of Data From the Twin Cities Marathon. *Clin J Sport Med* 2023;33:45–51.
 - 18 Timpka T, Alonso J-M, Jacobsson J, *et al.* Injury and illness definitions and data collection procedures for use in epidemiological studies in Athletics (track and field): consensus statement. *Br J Sports Med* 2014;48:483–90.
 - 19 Sugawara M, Manabe Y, Yamasawa F, *et al.* Athlete Medical Services at the Marathon and Race Walking Events During Tokyo 2020 Olympics. *Front Sports Act Living* 2022;4:872475.
 - 20 Touma JS. Dependence of the Wind Profile Power Law on Stability for Various Locations. *J Air Pollut Control Assoc* 1977;27:863–6.
 - 21 R Core Team. R: a language and environment for statistical computing. R Foundation for Statistical Computing; 2024. Available: <https://www.R-project.org>
 - 22 Humidity CJ. Calculate water vapor measures from temperature and dew point. 2019. Available: <https://github.com/caijun/humidity>
 - 23 Anderson GB, Bell ML, Peng RD. Methods to calculate the heat index as an exposure metric in environmental health research. *Environ Health Perspect* 2013;121:1111–9.
 - 24 Fröhlich D, Gangwisch M, Matzarakis A. Effect of radiation and wind on thermal comfort in urban environments - Application of the RayMan and SkyHelios model. *Urban Climate* 2019;27:1–7.
 - 25 Havenith G, Fiala D. Thermal Indices and Thermophysiological Modeling for Heat Stress. *Compr Physiol* 2015;6:255–302.
 - 26 Lu YC, Roms DM. Extending the Heat Index. *Journal of Applied Meteorology and Climatology* 2022;61:1367–83.
 - 27 Jendritzky G, de Dear R, Havenith G. UTCI—why another thermal index? *Int J Biometeorol* 2012;56:421–8.
 - 28 Höppe P. The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. *Int J Biometeorol* 1999;43:71–5.
 - 29 Chen YC, Matzarakis A. Modified physiologically equivalent temperature—basics and applications for western European climate. *Theor Appl Climatol* 2018;132:1275–89.
 - 30 World Athletics. Events calendar | World Athletics. World Athletics competitions; 2025. Available: <https://worldathletics.org/competition/calendar-results> [Accessed 20 May 2025].
 - 31 Agresti A. Statistical Methods for the Social Sciences. Pearson; 2018.
 - 32 Prion S, Haerling KA. Making Sense of Methods and Measurement: Spearman-Rho Ranked-Order Correlation Coefficient. *Clin Simul Nurs* 2014;10:535–6.
 - 33 Breslow RG, Collins JE, Troyanos C, *et al.* Exertional Heat Stroke at the Boston Marathon: Demographics and the Environment. *Med Sci Sports Exerc* 2021;53:1818–25.
 - 34 Roberts WO. A 12-yr profile of medical injury and illness for the Twin Cities Marathon. *Medicine & Science in Sports & Exercise* 2000;32:1549–55.
 - 35 Divine JG, Daggy MW, Dixon EE, *et al.* Case Series of Exertional Heat Stroke in Runners During Early Spring: 2014 to 2016 Cincinnati Flying Pig Marathon. *Curr Sports Med Rep* 2018;17:151–8.
 - 36 DeMartini JK, Casa DJ, Belval LN, *et al.* Environmental conditions and the occurrence of exertional heat illnesses and exertional heat stroke at the Falmouth Road Race. *J Athl Train* 2014;49:478–85.
 - 37 Stearns RL, Hosokawa Y, Belval LN, *et al.* Exertional Heat Stroke Survival at the Falmouth Road Race: 180 New Cases With Expanded Analysis. *J Athl Train* 2023;59:304–9.
 - 38 Gamage PJ, Fortington LV, Finch CF. Epidemiology of exertional heat illnesses in organised sports: A systematic review. *J Sci Med Sport* 2020;23:701–9.
 - 39 Maule AL, Scatliffe-Carrion KD, Kotas KS, *et al.* Heat exhaustion and heat stroke among active component members of the U.S. Armed Forces, 2019–2023. *MSMR* 2024;31:3–8.
 - 40 Racinais S, Nichols D, Travers G, *et al.* Health status, heat preparation strategies and medical events among elite cyclists who competed in the heat at the 2016 UCI Road World Cycling Championships in Qatar. *Br J Sports Med* 2020;54:1003–7.
 - 41 Racinais S, Alhamoud M, Nasir N, *et al.* Epidemiology and risk factors for heat illness: 11 years of Heat Stress Monitoring Programme data from the FIVB Beach Volleyball World Tour. *Br J Sports Med* 2021;55:831–5.
 - 42 Belval LN, Giersch GEW, Adams WM, *et al.* Age- and Sex-Based Differences in Exertional Heat Stroke Incidence in a 7-Mile Road Race. *J Athl Train* 2020;55:1224–9.
 - 43 Breslow RG, Shrestha S, Feroe AG, *et al.* Medical Tent Utilization at 10-km Road Races: Injury, Illness, and Influencing Factors. *Med Sci Sports Exerc* 2019;51:2451–7.
 - 44 Périard JD, Eijssvogels TMH, Daanen HAM. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. *Physiol Rev* 2021;101:1873–979.
 - 45 Grundstein AJ, Hosokawa Y, Casa DJ, *et al.* Influence of Race Performance and Environmental Conditions on Exertional Heat Stroke Prevalence Among Runners Participating in a Warm Weather Road Race. *Front Sports Act Living* 2019;1:42.
 - 46 Galan-Lopez N, Esh CJ, Leal DV, *et al.* Heat Preparation and Knowledge at the World Athletics Race Walking Team Championships Muscat 2022. *Int J Sports Physiol Perform* 2023;18:813–24.
 - 47 Edouard P, Dandrieux P-E, Iatropoulos S, *et al.* Injuries in Athletics (Track and Field): A Narrative Review Presenting the Current Problem of Injuries. *DtschZSportmed* 2024;75:132–41.
 - 48 Racinais S, Moussay S, Nichols D, *et al.* C during the UCI Road Cycling World Championships in the heat. *Br J Sports Med* 2019;53:426–9.
 - 49 Edouard P, Junge A, Sorg M, *et al.* Illnesses during 11 international athletics championships between 2009 and 2017: incidence, characteristics and sex-specific and discipline-specific differences. *Br J Sports Med* 2019;53:1174–82.
 - 50 Hanley B. Pacing, packing and sex-based differences in Olympic and IAAF World Championship marathons. *J Sports Sci* 2016;34:1675–81.
 - 51 Zhang X, Ren K, Ding X, *et al.* Modified physiological equivalent temperature for monitoring heat stress: 20-year data from the falmouth road race. *In Review* [Preprint] 2024.
 - 52 Otani H, Kaya M, Tamaki A, *et al.* Effects of solar radiation on endurance exercise capacity in a hot environment. *Eur J Appl Physiol* 2016;116:769–79.
 - 53 Edouard P, Depiesse F, Branco P, *et al.* Analyses of Helsinki 2012 European Athletics Championships injury and illness surveillance to discuss elite athletes risk factors. *Clin J Sport Med* 2014;24:409–15.