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Heat stress risk in elite endurance Athletics: policy evaluation, epidemiology, and physiological monitoring approaches

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SCIENTIFIC WORK

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- 2024 **Bandiera D**, Racinais S, Garrandes F, Adami PE, Bermon S, Pitsiladis YP, Tessitore A. *Heat-related risk at Paris 2024: a proposal for classification and review of International Federations policies*. Br J Sports Med. 2024 Jul 25;58(15):860-869. doi: 10.1136/bjsports-2024-108310. (Q1)
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- 2025 **Bandiera D**, de Bardonnèche J, Janry P, Calas-Étienne S, Aubin JC, Tessitore A, Pitsiladis Y, Racinais S. *Validation of the iButton and Flex sensors for measuring skin temperature*. Eur J Appl Physiol. 2025 Oct 18. doi: 10.1007/s00421-025-06020-9. (Q2)
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<https://www.frontiersin.org/journals/physiology/articles/10.3389/fphys.2025.1717275/full>
- 2026 **Bandiera D**, Garrandes F, Kowalski J, Adami PE, Racinais S, Matzarakis A, Pitsiladis YP, Tessitore A, Bermon S. *What do thermal indices lack to help predict heat-related risk in elite Athletics?* Br J Sports Med. 2026 Feb 17:bjsports-2025-110822. doi: 10.1136/bjsports-2025-110822. (Q1)
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Presentation in scientific conferences

Oral presentation

- 2025 **Bandiera D**, Garrandes F, Matzarakis A, Adami PE, Racinais S, Pitsiladis YP, Tessitore A, Bermon S. *Improving risk prediction for heat stroke and race dropouts in athletics: beyond the WBGT*. Nomination for the ECSS Young Investigators Award. 30th Annual Congress of the European College of Sport Science (ECSS), July 2025, Rimini, Italia.

Poster presentation

- 2023 **Bandiera D**, Pitsiladis YP, Adami PE, Bermon S, Racinais S, Tessitore A. *A call for a new heat stress index to better safeguard athletes from exertional heat illnesses and impaired performance*. XIV Congresso Nazionale della Società Italiana delle Scienze Motorie e Sportive (SISMeS), November 2023, Napoli, Italia.

Invited presentation

- 2024 **Bandiera D**. *Paris temperatures - Protecting the athletes' health and performance: What are the International Federations heat policies?* Olympic Games medical meetings on sport medicine & sport physiotherapy, July 2024, Paris, France.
- 2025 **Bandiera D**. *Can we improve risk prediction for exertional heat stroke in elite athletes?* Global Summit on Athletics Science & Medicine, September 2025, Tokyo, Japan.
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Attendance to scientific conferences

- 2023 28th Annual Congress of the European College of Sport Science (ECSS), July 2025, Paris, France.
- 2024 7th International Olympic Committee (IOC) World Conference on Prevention of Injury and Illness in Sport, March 2024, Monaco.
- 2024 HKBU in Paris - Science, Technology, AI and Sport, July 2024, Paris, France.
- 2024 Institut National du Sport de l'Expertise et de la Performance (INSEP) Medical and Para-medical symposium, November 2024, Montpellier, France.
- 2024 2nd Symposium on Performance and Environmental Stress, December 2024, Font-Romeu, France.
- 2025 Using Environmental Stressors to Achieve Peak Performance: From Evidence to Avenues to Explore, March 2025, Paris, France.

Collaboration work in scientific conferences

- 2024 James C, Muniz-Pardos B, Comeras-Chueca C, Guppy F, Angeloudis K, Comadran E, Pitsiladis A, Rico Meneses M, Verdoukas, P, Miller M, Zelenkova I, Casajus J, Iglesias DP, **Bandiera D**, Tessitore A, Perazzetti A, Martusciello F, Migliorini S, Pitsiladis YP. *Real-time thermoregulatory and biomechanical monitoring to prevent heat illness in international triathlon*. 29th Annual Congress of the European College of Sport Science (ECSS), July 2024, Glasgow, Scotland. Oral presentation.
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- 2026 Xu S, Adami PE, Asanuma F, **Bandiera D**, Bermon S, Fujita Mamika, Garrandes F, Kawakami E, Kimura N, Kobayashi K, Mizokami T, Yamaguchi A, Hosokawa Y. *Sweat Sodium Concentration In Elite Marathoners At The World Athletics Championships Tokyo 2025*. American College of Sports Medicine (ACSM) Annual Meeting, May 2026, Salt Lake City, USA. Poster presentation.

Article reviewing activities

- 2025 Journal of Applied Physiology (JAP)
- 2025 International Journal of Sports Physiology and Performance (IJSPP)
- 2026 British Journal of Sport Medicine (BJSM)

Athlete monitoring during competition

- 2023 *Adidad Road to Record*, live monitoring of physiological and biomechanical variables in 30 elite athletes (5 km, 10 km and half marathon), April 2023, Herzogenaurach, Germany
- 2023 *SAFRA Singapore Bay Run & Army Half Marathon*, live monitoring of physiological variables in 162 soldiers (10 km and half marathon), September 2023, Singapore.
- 2024 *Olympic Games*, live monitoring of physiological and biomechanical variables in 13 elite athletes (cycling, race walking, 800m, boxing), July 2024, Paris, France.

- 2024 *Marathon for all*, live monitoring of physiological and biomechanical variables in 25 recreational athletes (marathon), August 2024, Paris, France.
- 2025 *World Athletics Championship*, measures of sweat and blood sodium concentration, whole body sweat loss and heat acclimation survey in 37 elite athletes (race walking and marathon), Tokyo 2025, Tokyo, Japan.

Other article in preparation or revision

- Hosokawa Y, Adami PE, Asanuma F, **Bandiera D**, Berman S, Fujita M, Kawakami, Kimura EN, Kobayashi K, Mizokami T, Xu S, Yamaguchi A, Garrandes F. *Endurance Athletes' Knowledge and Practices in Heat Acclimatization and Nutrition for World Championships Tokyo 2025*. In preparation.
- Sakamoto Y, Alhadad S, Xiaohan Z, Tan BY, Ang WH, Law L, Prakaash S, Racinais S, Muniz-Pardos B, **Bandiera D**, Comadran E, Iglesias DP, Pitsiladis YP, Lee JKW. *Physiological demands and contributors to variance of body core temperature in 162 tropical recreational runners during distance running in a warm-humid environment*. Accepted in the Medicine & Science in Sports & Exercise journal.
- **Bandiera D**, Di Domenico H, Samozino P, Racinais S, Rupp T. *No differences between cold and hot water immersion for neuromuscular recovery, sprint mechanics and delayed onset muscle soreness after a simulated football game*. Under revision in the Journal of Sports Sciences.
- Racinais S, Iglesias DP, Devic A, Le Van P, Salt M, **Bandiera D**, Grant ME, Bahr R, Engerbrechtsen L, Pitsiladis YP, *A legacy from Paris 2024 to LA 2028: Ice requirements at the summer Olympic and Paralympic Games*. In preparation.

Outreach activities

- 2023 **Bandiera D**, “*Coup de chaud en course à pied*” (*Exertional heat stroke in running*), On your Marks Podcast #26, December 2023, online.
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- 2024 **Bandiera D**, Martin S, Rubio J, Racinais S. “*Quinzaine scientifique: l'exercice sous la chaleur*” (*Science fortnight: exercise under the heat*). Presentation and quiz for young athletes on heat training, heat stroke and heat therapy. “Centre de Ressources d'Expertise et de Performance Sportive” (CREPS) Montpellier, January 2024, Montpellier, France.

- 2025 **Bandiera D**, Martin S, Racinais S. *“Quinzaine scientifique: la récupération” (Science fortnight: the recovery in sport)*. Presentation and quiz for young athletes on hydration strategies, sleep, nutrition and mental fatigue. CREPS Montpellier, January 2025, Montpellier, France.
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- 2025 **Bandiera D**, Rubio J, Racinais S. *“La Thermorégulation du sportif” (“Thermoregulation of the athlete”)*. Liflet for coaches and athletes on the physiological basis of thermoregulation in athletes. CREPS Montpellier, May 2025, Montpellier, France.
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LIST OF ABBREVIATIONS

C	Convective heat exchange
DNF	Athletes that Did-Not-Finish the race
E	Evaporative heat loss
EHI	Exertional Heat Illness
EHS	Exertional Heat Stroke
HI	Heat Index
IFs	International Federations
K	Conductive heat exchange
LOOCV	Leave-One-Out Cross-Validation
M	Metabolic energy
MED	Athletes admitted to medical facilities regardless of cause
mPET	modified Physiological Equivalent Temperature
NB	Negative Binomial
PET	Physiological Equivalent Temperature
R	Radiant heat exchange
rh	Relative humidity
S	Body heat storage
SRC	Sweat Rate Calculator
sweat [Na ⁺]	Sweat Sodium Concentration
T _{bg}	Black Globe Temperature
T _{db}	Dry-Bulb Temperature
T _{wb}	Wet-Bulb Temperature
UTCI	Universal Thermal Climate Index
W	Mechanical work
WBGT	Wet Bulb Globe Temperature
WBSL	Whole Body Sweat Loss

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ABSTRACT

Background:

Athletics is a global sport practiced by millions of individuals and followed by a large international audience. Although environmental conditions are documented during the bidding process for World Athletics elite events, they do not appear to constitute a determining criterion in the selection of host cities. In addition, World Athletics Championships are systematically scheduled during the summer months, when environmental conditions are most likely to induce significant heat strain. Climate change is further contributing to rising global surface temperatures and increasing the frequency, severity, and unpredictability of heatwaves. Moreover, metabolic heat production from contracting skeletal muscles represents a major internal source of heat production in elite athletes. This high rate of heat production combined with impaired heat dissipation under strenuous environmental conditions results in marked elevations in thermal strain in endurance elite athletes participating to World Athletics competitions.

This thermal strain poses substantial challenges for the organization of outdoor sporting events and the protection of athlete health. Indeed, thermal strain can impair performance and expose athletes to serious health risks. Importantly, exertional heat stroke (EHS) represents the most severe form of heat-related illness and may be fatal if not promptly and adequately treated. International Federations (IFs) are therefore required to anticipate and mitigate heat-related risks to ensure safe competition environments for athletes.

Accordingly, this thesis aimed to evaluate heat stress risk in elite endurance athletes. Chapter 1 examined the heat policies implemented by major IFs and evaluated their relevance in relation to the heat-related risks associated with each sport. Chapter 2 investigated the incidence of EHS in elite Athletics competitions and its association with environmental, individual, and race-related variables. In addition, Chapters 3 and 4 validated innovative wearable sensors designed for real-time assessment of whole-body sweat loss (WBSL), sweat sodium concentration ($[Na^+]$), and skin temperature, with the objective of improving the understanding of elite athletes' thermoregulatory responses.

Methods:

A scoping review was conducted in Chapter 1 to identify and characterise the heat-related policies implemented by all IFs participating in the Paris 2024 Olympic Games. Extracted data

included the thermal indices used, environmental monitoring procedures, decision thresholds, and implemented mitigation strategies.

Chapter 2 consisted in a data mining approach. Environmental, individual and race-related data from 80 elite endurance races occurring between 2019 and 2024 were analysed. The relation between these variables and medically diagnosed EHS, did-not-finish athletes and medical encounters were investigated to better determine thermal risk.

Chapters 3 and 4 investigated the validity of a sweat sensor (S1, Flowbio, London, UK) and a skin temperature device (Flex, BodyCap, Caen, France). These wearables were tested on 23 recreationally active adults (11 males, 12 females) cycling in moderate intensity (1.9 ± 0.4 W/kg) in dry (40°C ; 36 % rh, 2 m/s airflow) and humid (30°C ; 81 % rh, 2 m/s) hot conditions following a cross-over design. The S1 was compared to the LAQUAtwin (Horiba Advanced Techno, Kyoto, Japan) and to the gold standard flame photometry for sweat $[\text{Na}^+]$. For WBSL, the S1 was compared to the gold standard scale-based method. The accuracy of the Flex sensor was compared with that of the iButton Hygrochron DS1923 (Analog Devices, Wilmington, USA).

Results:

Fifteen sports included in the Paris 2024 Olympic Games programme were classified as presenting a high, very high, or extreme heat stress risk (33%). World Athletics and most International Federations at-risk use the Wet Bulb Globe Temperature (WBGT) thermal index to estimate environmental heat strain.

In elite endurance Athletics competitions, the frequency of EHS averaged 8 cases per 1000 athlete exposures and increased to 16 cases per 1000 exposures under hot environmental conditions (WBGT $28\text{--}29.9^{\circ}\text{C}$). The association between WBGT and EHS frequency was weak ($R^2 = 0.04$, $P = 0.018$). However, WBGT risk categories currently used by World Athletics were informative, as higher WBGT risk thresholds was associated with progressively higher EHS risk ($P = 0.003$). Importantly, none of the other thermal indices, nor individual, race-related, or hyperlocal environmental variables, demonstrated a substantially stronger association with EHS occurrence than WBGT.

The S1 sweat sensor demonstrated acceptable accuracy for sweat sodium concentration, showing no difference compared with the LAQUAtwin ($P = 0.952$) and an averaged difference of -10 mmol/L compared with flame photometry ($P < 0.001$). It also provided accurate WBSL estimates, with no significant difference compared with the scale-based method (mean difference of 0.047 kg, $P = 0.624$).

For skin temperature assessment, the base surface of the iButton was more accurate than its top ($P < 0.001$). During exercise, the Flex sensor measured higher skin temperatures than the base surface of the iButton, with a mean difference of 0.41°C .

Conclusions:

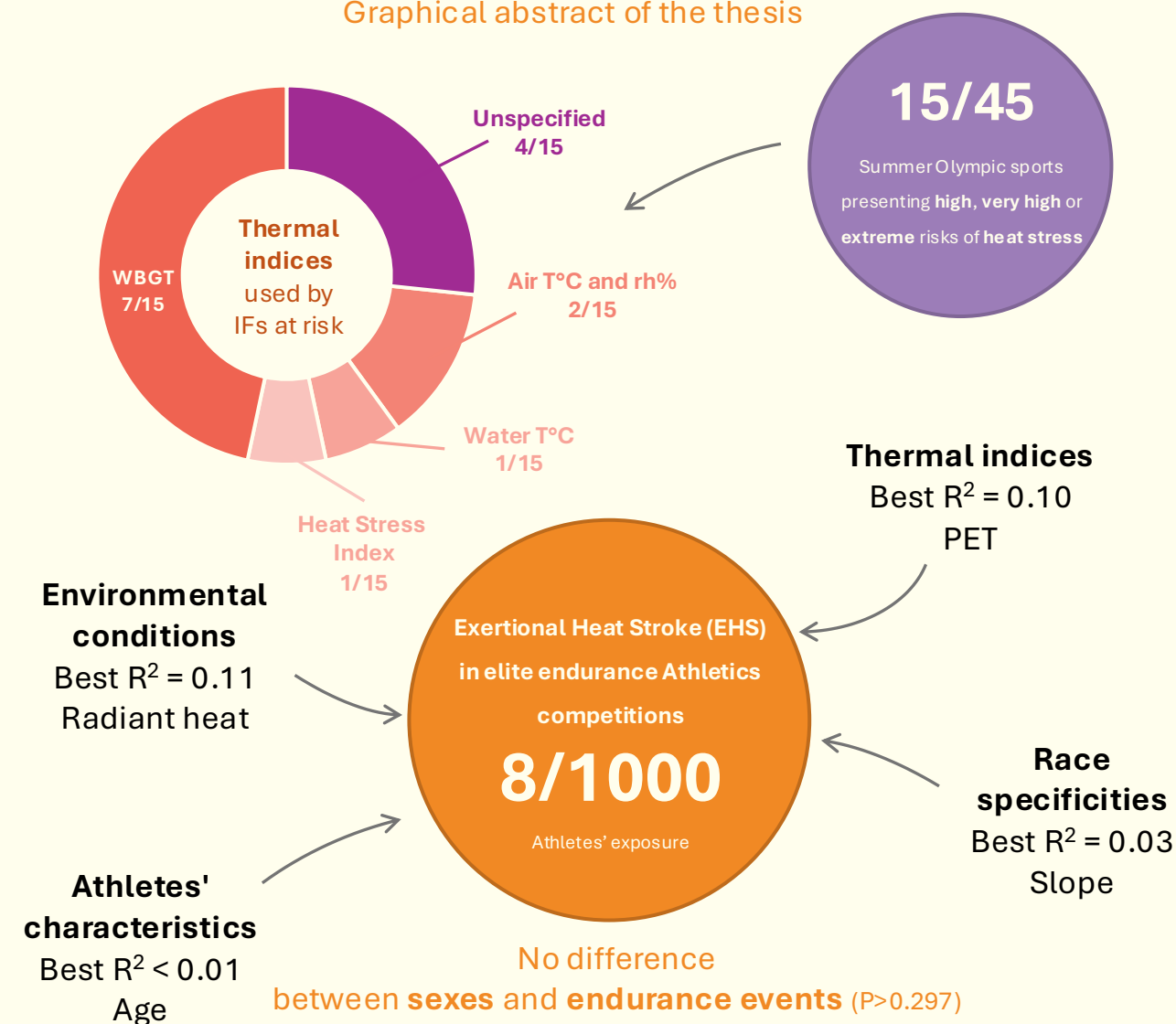
IFs governing sports exposed to significant heat stress risk should implement robust and evidence-based heat policies to protect athletes from heat-related dangers. In elite endurance Athletics competitions, the frequency of EHS is particularly high and warrants specific attention from organisers to ensure adequate on-site medical resources and pre-hospital care capacity.

The WBGT should not be considered a predictive tool of individual thermal strain in elite Athletics endurance athletes, but rather a preparation guide for EHS risk. Local organising committees should therefore allocate medical and material resources according to the worst-case WBGT category anticipated for competition.

In addition, validated wearable technologies such as sweat sensors or skin temperature device offer substantial opportunities to better understand the thermal strain endured by athletes during competitions. Integrating these physiological measurements with individual modifiers such as acclimation and health status could allow a more precise estimation of EHS risk than current thermal indices. This framework may provide a more mechanistically grounded basis for pre-competition thermal risk assessment in elite Athletics competitions.

Heat stress in elite endurance Athletics events

Graphical abstract of the thesis



= not able to predict **EHS**

Acclimation

Health status



Prepare heat deck for elite competitions based on **WBGT flag levels** ($P = 0.003$)

- 2 EHS outcome
- 3 EHS outcome
- 5 EHS outcome
- 6 EHS outcome
- Event schedule changes or postponement

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INTRODUCTION

1. Context

1.1. Athletics

1.1.1. History and globalisation

Athletics encompasses a collection of competitive running, walking, jumping, and throwing events (Britannica Encyclopedia 2025). The most common types of Athletics competitions are track and field, road running, cross-country and race walking. It is often regarded as the oldest form of organised competition, with the earliest known Athletics event dating back to 3800 BC in Memphis (Egypt) where running races of approximately 800 metres were reportedly held between two pillars (Museum of World Athletics 2025). Athletics was also a central component of the ancient Olympic Games, first organised in Olympia (Greece) in 776 BC, and it featured prominently in the first modern Olympic Games in Athens in 1896. During that inaugural edition, 63 male athletes from nine nations competed across 12 Athletics events. Although global interest in Athletics had been limited before these Games, this event marked the beginning of worldwide enthusiasm for the sport.

On 17 July 1912, following the closing ceremony of the Stockholm Olympic Games, the International Amateur Athletic Federation (IAAF) was founded as the international federation of Athletics, being the world governing body for the track and field disciplines (World Athletics 2025b). At its inception, the IAAF governed only men's competitions, and it was only in 1936 that it officially incorporated women's Athletics (Britannica Encyclopedia 2025). Over the following decades, both track and field and the IAAF evolved in parallel with the social and economic changes of the 20th century. In 2001, the organisation's name was changed to the International Association of Athletics Federations to reflect the growing professionalisation of the sport, and in 2019, it was renamed World Athletics (World Athletics 2025b).

Today, World Athletics serves as the international governing authority for Athletics, overseeing the global growth and development of the track and field disciplines (World Athletics 2021). It is responsible for the standardisation of rules and regulations, the organisation of international competitions and the ratification of official world records. The organisation also strives to broaden accessibility to Athletics, encourage people to exercise, and contribute to a healthier and fitter world. Currently, 214 national member federations are affiliated with World Athletics (World Athletics 2025g). Each national federation serves as the governing body for Athletics within its respective country, with only one member federation per nation permitted. All members must adhere to the constitution and regulations of World Athletics. With its broad international reach, World Athletics is among the largest sporting federations in the world, with more member federations than the United Nations.

As the leading sport of the Olympic Games, Athletics holds a central position in global sport culture and embodies the Olympic spirit of universality (World Athletics 2025b). The World Athletics Championships rank among the most-watched sporting events worldwide, surpassed only by the Olympic Games and the FIFA World Cup in global audience and impact. Athletics events regularly fill stadiums with tens of thousands of spectators and attract television audiences numbering in the millions. World Athletics as its governing body therefore bears a global responsibility to ensure that all affiliated events are fair, accurately measured, and safely conducted, upholding the highest standards of integrity and organisation in every competition.

1.1.2. Health and Science department

The Health & Science department of World Athletics (World Athletics 2025f) is composed by two medical doctors and one scientific manager, forming a multidisciplinary team responsible for athlete health and scientific oversight within the federation. The department's missions are threefold:

1. to deliver high-standard health services to athletes and their support personnel during World Athletics competitions, including site visits and the verification of local health procedures,
2. to conduct and promote scientific research programs addressing emerging challenges in Athletics practice and regulations such as heat stress and injury prevention,
3. to develop and implement preventive and educational initiatives, notably through its role as co-founder of the World Academy for Endurance Medicine.

The department produces technical documents and competition medical guidelines that set minimum standards for health services at major events (Adami et al. 2020). Through its activities, the Health & Science Department acts as a vital interface between scientific research and medical practice, ensuring that evolving knowledge is translated into concrete operational policies and educational materials.

The Health & Science department of World Athletics has founded the present thesis, which was commissioned to enhance the department's capacity to describe and characterise heat-related risks during international Athletics competitions. Indeed, the climate change and globalisation of sport have increased the number of competitions held in hot countries (Bermon and Adami 2019) and multiples cases of heat-related illnesses have been reported in elite athletes (Hollander et al. 2021).

1.1.3. International competitions

World Athletics governs a wide range of disciplines that compose the global Athletics programme. These include endurance in stadium events, such as the 5000 m and 10000 m

track races; and out of stadium events road races, including the half marathon and marathon; race walking events contested over a variety of distances; and off-road disciplines, such as cross-country running. In recent years, the scope of World Athletics has expanded to include trail and mountain running, reflecting the growing popularity of endurance sports held in natural environments. The federation co-organised the World Mountain and Trail Running Championships in 2022 in Chiang Mai (Thailand) followed by Innsbruck-Stubai (Austria) in 2023, and Canfranc (Spain) in 2025 (World Athletics 2025d). These endurance events induce strenuous physiological demands for athletes (sustained and elevated intensity) that make them particularly vulnerable to environmental heat stress (Racinais et al. 2022).

The international Athletics calendar is structured around a recurring cycle of major events (World Athletics 2025e). The main competitions are the Summer Olympic Games held every four years organised by the International Olympic Committee, and the World Athletics Championships organised by World Athletics, staged biennially in odd-numbered years to avoid Olympic years. Additional biennially staged events organised by World Athletics are the World Athletics Indoor Championships, World Athletics Relays, World Athletics U20 Championships, World Athletics Road Running Championships, World Athletics Race Walking Team Championships and World Athletics Cross Country Championship (World Athletics 2021). All these international competitions organised by World Athletics are defined as a World Athletics series event. Beyond these multi-year cycles, elite athletes also compete annually in the Diamond League circuit and major city marathons including Tokyo, London, Berlin, Boston, Chicago, and New York, collectively known as the World Marathon Majors. These competitions not only provide ranking points and financial incentives but also serve as qualification opportunities for global championships.

1.1.4. Bidding process

World Athletics operate a formalised bidding process when selecting host cities for World Athletics series event. Candidate cities must first submit a “Pre-Qualification Form”, that assess their capacity to meet several guarantees including infrastructure readiness, financial and logistical capability, national security and governance integrity (World Athletics 2023). In addition, the form requires cities to respond to environmental-related criteria, specifically addressing the following questions:

“B.5.3. Is the Host City subject to any of the following extreme weather conditions during the month in which the WAS Event [World Athletics series event] is proposed to take place:

B.5.3.1. Extreme heat and/or relative humidity (i.e. WBGT' >28°C when competitions or training are taking place): Yes/No

If needed, please provide more information in the box below.

B.5.3.2. Extreme cold and wind (i.e. Wind chill calculated temperature $<-5^{\circ}\text{C}$ when competitions or training are taking place): Yes/No

B.5.3.3. Other extreme meteorological phenomena such as tornadoes, typhoons, hurricane, sandstorm, or tsunami, if yes please explain: Yes/No

¹ Wet Bulb Globe Temperature (WBGT) is a measure of the heat stress in direct sunlight, which takes into account: temperature, humidity, wind speed, sun angle and cloud cover (solar radiation)”

These questions illustrate that environmental stress is explicitly included among the evaluation criteria for host city selection. However, there remains limited transparency regarding the relative weighting of environmental risk compared with factors such as infrastructure, finance, or political stability. Moreover, no specific environmental thresholds (e.g., temperature limits) are defined above which candidate cities are disqualified. This lack of clear criteria may have serious consequences: when major championships are awarded to cities with hot climates, athletes can be exposed to substantial environmental stress that poses risks to their health and performance (Junge et al. 2026; Racinais et al. 2023).

1.1.5. Seasonality

The governing body of World Athletics explicitly calls for configuring the summer season to end with a global championship (northern-hemisphere seasonality), creating a consistent season-long narrative (World Athletics 2024). In line with this, a new global championship in non-World Championship years have been launched and will appear for the first time in September 2026 in Budapest (Hungary) under the name of “World Athletics Ultimate Championship” (World Athletics 2025h). The late summer period has traditionally represented the peak of athletes’ training and performance cycles, as most competitions (i.e. Diamond League Final, national championships) are organized around this timeframe. Historically, all twenty editions of the World Athletics Championships have been organised between mid-July and early October, firmly establishing a long-standing seasonal tradition (World Athletics 2025a).

However, the timing of these major events also means that competitions are often held under the most strenuous environmental conditions of the year. The exposure to elevated air temperature, humidity, radiant heat and/or low air movement during summer can compromise performance and pose serious health risks, especially for endurance athletes (Casa et al. 2015). This issue has prompted growing concern within the scientific community and among sporting authorities. Both researchers and World Athletics President Lord Sebastian Coe have publicly advocated for rethinking the Athletics calendar to mitigate heat stress and reduce the

risks associated with competing in extreme summer conditions (Smith et al. 2016; The Independent and Clifford 2025).

1.1.6. Scheduling

World Athletics have the final authority to set a detailed timetable for all World Athletics series event (World Athletics 2021). The factors that are accounted to deliver this planning are time differences between the host country and key international television markets, the television market of the host country, spectator appeal, athlete requirements and ticket sales. Therefore, the broadcasting constraint and spectator availability seems to be prioritized to decide the starting times of the events. In recent editions of the World Athletics Championships, the competition days were typically divided into two stadium sessions: a morning session often starting around 09:00 a.m. local time, containing heats, qualifiers, and some field events, and an evening session beginning in the early evening, around 07:00 p.m. (World Athletics 2025c).

In contrast, road events such as the marathon and race walk are typically scheduled earlier in the morning, around 08:00 a.m., to take advantage of cooler conditions. Depending on the level of heat risk assessed by the World Athletics Health & Science Department, start times may be adjusted accordingly to ensure athlete safety. This was recently the case at the 2025 Tokyo World Athletics Championships, where the marathon and race walk events began 30 minutes earlier, starting at 07:30 a.m., to benefit from lower ambient temperatures (BBC 2025). The World Athletics Championships of Doha in 2019 (Qatar) were also the first to be held in an air-conditioned stadium, while the road races were scheduled late at night (start time around 11:30 and 11:59 p.m.) to maximize the chance of lower thermal strain (Bermon and Adami 2019).

World Athletics is responsible for governing several international competitions that are organized across the globe. The World Championships are systematically scheduled during the summer months, when environmental conditions are most likely to cause heat stress (e.g., Tokyo 2025, Budapest 2023, Doha 2019). Despite mitigation strategies such as event rescheduling, athletes are still exposed to considerable heat stress.

1.2. The danger of heat

1.2.1. Climate change

Over the past century, human activities have driven climate change through the emission of greenhouse gases, primarily carbon dioxide and methane (IPCC 2023). The global mean surface temperature has increased by 1.1 °C during 2011-2020 compared to the pre-industrial period (1850-1900), which represents the earliest timeframe with near-global temperature records (IPCC Working Group I 2023)(Figure 1). This temperature elevation encompasses both oceanic and terrestrial surfaces. However, the warming is more pronounced over land where Athletics events occur, with an average increase of 1.59 °C.

The conclusions of the 6th assessment report of the Intergovernmental Panel on Climate Change state that *“human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming”* (IPCC 2023). The rate of warming since 1970 has been faster than during any other 50-year period over the past two millennia. Of note, current greenhouse gases emissions originate mainly from the energy sector (34%), industry (24%), and agriculture (22%) (IPCC Working Group III 2022).

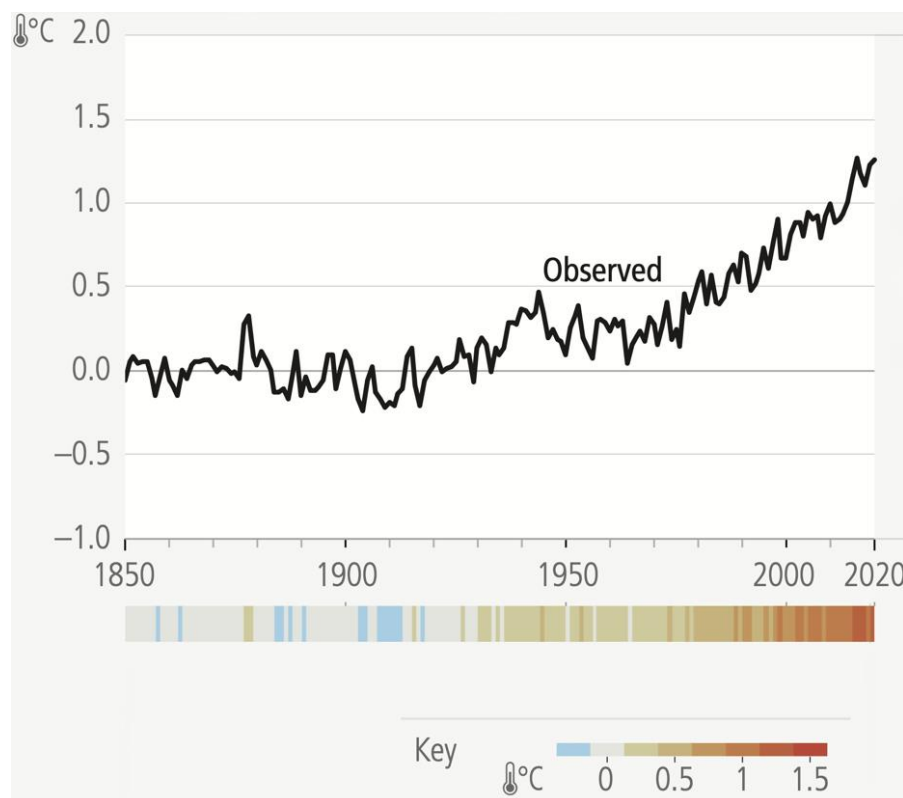


Figure 1: Evolution of climate change

Global surface temperature increased by 1.1 °C by 2011-2020 compared to the pre-industrial period due to human activities. Figure 2.1 of the IPCC Synthesis Report of 2023 (IPCC 2023).

Beyond the gradual increase in average surface temperature, a particularly concerning manifestation of climate change for sporting events is the increased frequency, intensity, and duration of heatwaves observed since the 1950s (Sun, Hu, and Zhang 2018). Heatwaves cause sudden and severe increases in ambient temperature, drastically altering environmental conditions for athletes and event organisers. Their unpredictability complicates the safe planning of outdoor competitions.

For instance, at the Tokyo Olympic Games in 2021 (Japan), organisers relocated the marathon and race walk events from Tokyo to the city of Sapporo, 800 km further north, based on historical climatological averages. Indeed, Tokyo's August conditions between 2010 and 2020 averaged 30.0 °C with 75 % relative humidity (rh), while Sapporo's historical averages were milder with 27.1 °C and 75 % rh (Sugawara et al. 2022). However, during the competition window in early August 2021, Sapporo experienced an unanticipated heatwave which produced very strenuous conditions for athletes: consecutive daytime air temperatures exceeded 30 °C and humidity remained above 60 % rh (Yamasaki and Nomura 2022).

Similarly, during the 2023 World Athletics Championships in Budapest, the local organising committee had based its contingency plan for heat-related risks on the most severe conditions recorded over the previous decade. Yet, the event coincided with an unexpected heatwave affecting much of Europe, with ambient temperatures and humidity exceeding 35 °C and 90 % rh (Esh et al. 2024). The severity and unpredictability of heatwave therefore challenge the organization of outdoor Athletics events and pose risks for athletes health (Casa et al. 2015).

1.2.2. Projections

Exposure to high heat stress poses serious risks to human health as it increases morbidity and mortality (Ebi et al. 2021). It is estimated that an average of 546 000 deaths are every year caused by the heat worldwide (Romanello et al. 2025). As heatwaves become more frequent and intense with ongoing climate change, the number of people exposed, including vulnerable populations, outdoor workers, soldiers, and athletes, is projected to rise dramatically in the coming decades. A study by Mantzios et al. found that 25% of endurance running competitions held worldwide between 1936 and 2019 took place in moderate, high or extreme heat (i.e., 1258 races, including marathon, racewalking, 5000 m, 10000m, and 3000m steeplechase events). This figure rises to 50% when the marathon events are excluded (Mantzios et al. 2022).

Projections from the IPCC suggest that global surface temperatures will continue to rise throughout the 21st century under nearly all emission scenarios (IPCC Working Group III 2022). Based on current governmental policies implemented as of 2020 to reduce the emission of greenhouse gases, the global temperature is expected to increase by 3.2 °C by 2100. We

can therefore expect even more extreme conditions in the decades to come, and greater risks for the populations exposed.

1.2.3. Exertional heat illnesses

In exercising individuals, heat stress can lead to a spectrum of conditions collectively known as exertional heat illness (EHI) (Casa et al. 2015) (Figure 2). In contrast to classic heat stroke, which typically affects children and the elderly, EHI occurs in fit and healthy athletes during or shortly after sustained aerobic exercise performed in temperate to hot environments (Leon and Bouchama 2015).

The mildest form of EHI is exercise-associated muscle heat cramps, characterized by involuntary and painful contractions of skeletal muscles during or after exercise.

Heat exhaustion represents a more advanced stage of moderate EHI, defined by an inability to continue exercising or maintain cardiac output, often accompanied by moderate-to-severe elevation in core temperature (below 40.5 °C). Symptoms include fatigue, dizziness, headache, nausea, hypotension, tachycardia, and, in some cases, collapse (Casa et al. 2015; Leon and Bouchama 2015).

Athletes can also suffer from heat injury, which refers to moderate-to-severe EHI, involving organ (kidney, liver) and tissue (gut, skeletal muscle) injury during exertion, generally associated with core temperatures elevation (below 40.5 °C).

The most severe manifestation of EHI is exertional heat stroke (EHS). EHS is a life-threatening condition characterized by central nervous system dysfunction (e.g., ataxia, confusion, irritability) and core temperatures above 40.5 °C (Casa et al. 2015). Of note, the temperature threshold remains debated, with some authors suggesting that EHS can be diagnosed from 40 °C (Armstrong et al. 2007; Yankelson et al. 2014). Importantly, core temperature alone is not diagnostic, as athletes can reach values exceeding 40-40.5 °C during exercise without any symptoms of EHI (Maron, Wagner, and Horvath 1977; Racinais et al. 2019; Singh et al. 2023). To be classified as EHS, both an elevated core temperature (above 40-40.5 °C) and central nervous system dysfunction must be present. EHS leads to multi-organ and tissue damage that, if untreated, can rapidly progress to collapse and death.

Overall, EHS can be described as a combination of high metabolic heat production in working muscles, a saturation of thermoregulatory capacity, and a performance-driven motivation that pushes the athletes to sustain elevated intensity despite severe physiological strain (Périard, DeGroot, and Jay 2022; Roberts et al. 2023). However, the difficulty in the anticipation of EHS lies in the fact that some athletes present those characteristics without developing an EHS. This suggests that EHS likely results from a complex interaction between these known factors

and potentially additional, yet unidentified, contributors. Consequently, the relationships between these factors and the occurrence of EHS need to be investigated.

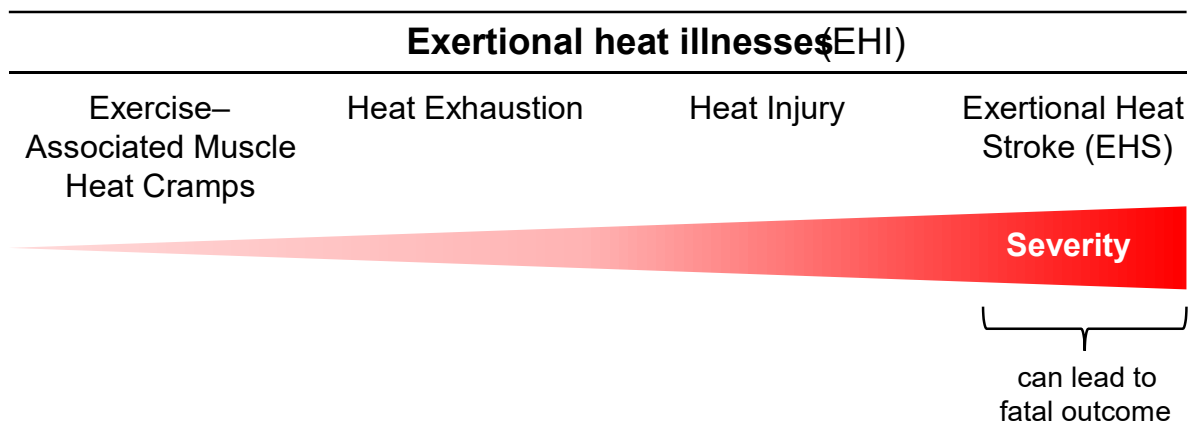


Figure 2: Spectrum of exertional heat illnesses (EHI)

The most severe form of EHI is the exertional heat stroke (EHS). EHS is lethal if not treated promptly and adequately.

1.3. Regulation of body heat

1.3.1. Heat production and dissipation

The occurrence of EHS reflects the limitation of the body's thermoregulatory system to maintain the core temperature within safe ranges. Understanding the physical and physiological mechanisms of thermoregulation is therefore crucial to explain how heat is produced and dissipated during exercise.

During exercise, metabolic heat production from contracting skeletal muscles represents a major internal source of heat production, particularly in elite athletes. Indeed, the human body is inherently inefficient at converting metabolic energy (i.e., energy stored in carbohydrates, lipids and protein substrates) into mechanical work such as running (Hill 1922). Only a fraction of the total metabolic energy expended contributes to external mechanical work, while the remaining portion is released as heat, and called the metabolic heat production. Mechanical efficiency of running is relatively high, with reported values around 60%, compared to around 30% for other activities such as cycling (Kyröläinen, Komi, and Belli 1995; Storniolo et al. 2022; Whipp and Wasserman 1969). This greater efficiency is partly due to the elastic energy storage and return provided by the stretch-shortening cycle of the lower-limb muscles and tendons during running (Di Prampero et al. 1986). Nevertheless, approximately 40% of the total metabolic energy expended for running is still converted into heat. Also, because running involves the support and propulsion of the body's full weight, its energetic cost is high and thus induces important energy expenditure. In elite athletes, the magnitude of metabolic heat production therefore leads to a substantial increase in body temperature, which is partially dissipated to the surrounding environment through thermoregulatory mechanism (Périard, Eijssvogels, and Daanen 2021).

While high ambient temperature is often used to describe environmental conditions leading to thermal strain, body temperature regulation is in fact influenced by four environmental parameters: ambient air temperature, relative humidity, radiant heat, and air movement (wind speed) (Cramer et al. 2022). These environmental parameters impact heat transfers between human and the environment through four physical processes: conduction, convection, radiation, and evaporation. The rate of body heat storage (S) of an athlete can therefore be represented as follow (Cramer and Jay 2019):

$$S = (M - W) \pm K \pm C \pm R - E \quad (\text{equation 1})$$

where M represents the metabolic energy production and W the external mechanical work, K the conductive heat exchange, C the convective heat exchange, R the radiant heat exchange, and E the evaporative heat loss.

Conduction refers to heat transfer through direct contact between the skin and a solid surface (e.g., shoes). In the context of exercise, conductive heat transfer is generally negligible compared to other mechanisms.

Radiation involves the transfer of electromagnetic energy between the skin and surrounding objects of different temperatures. Heat transfer by radiation increases as the temperature of these external objects rises. For athletes exercising outdoors, the primary source of radiant heat is the sun, with greater solar exposure (i.e., fewer clouds) leading to higher radiant heat gain (Honjo et al. 2018).

Convection represents heat transfer between the skin and a moving fluid, being air or water in the sporting context. It increases with body or air movement and is directly proportional to both the temperature gradient between the skin and the environment and the velocity of the air current. Convection is one of the two main mechanisms of heat loss during exercise. This mechanism is most effective when ambient temperature remains below the skin temperature but loses efficiency as air temperature approaches that of the skin (Foster et al. 2022).

Evaporation of sweat from the skin surface is the primary mechanism of heat dissipation during exercise in strenuous conditions (Cramer et al. 2022). Each gram of fully evaporated sweat removes 2426 Joules of heat, making evaporation the most efficient means of cooling the body (Wenger 1972). The efficiency of this process depends on the water vapour pressure gradient between the skin and the environment. High ambient humidity reduces this gradient, thereby limiting the rate at which sweat can evaporate from the skin. As a result, a greater proportion of sweat drips off without contributing to heat loss, leading to reduced evaporative efficiency and increased thermal strain. This mechanism explains why competitions in tropical environments, characterised by high humidity, pose particularly elevated heat-related risks for athletes (Vanos and Grundstein 2020).

Finally, clothing acts as a barrier between the skin and the environment, potentially influencing conductive, convective, radiant, and evaporative heat exchanges (Havenith et al. 2012; Ioannou et al. 2021). In Athletics, however, race outfits are typically lightweight and specifically designed to maximize heat dissipation. For instance, sleeveless tops, tight-fitting shorts, and breathable fabrics have been developed to facilitate convection and evaporation. As a result, the impact of clothing on thermoregulation is optimized in Athletics, compared to other sports where heavier or more insulating attire is worn (i.e., equestrian, sailing) (Racinais et al. 2023).

1.3.2. Thermoregulation system

Given the strong influence of environmental parameters on heat exchange, it is essential to understand the physiological mechanisms that allow athletes to maintain thermal balance during exercise in the heat.

Humans are homeothermic organisms, meaning that they maintain a stable internal body temperature through coordinated physiological responses (Kenny and Flouris 2014). The set of mechanisms that allow the body to maintain its core temperature within an optimal range despite environmental or metabolic perturbations is called thermoregulation. This regulation relies on two complementary systems: autonomic responses (involuntary), which adjust heat production and dissipation through physiological pathways, and behavioural responses (voluntary), which involve conscious actions such as seeking shade or adjusting clothing (Périard and Racinais 2019).

To achieve thermal balance, the human body is equipped with thermoreceptors, which are specialized sensory structures that detect changes in temperature (Périard, Eijssvogels, and Daanen 2021). These are divided into two main categories: central thermoreceptors, which monitor core body temperature and are primarily located in the brain, spinal cord, and abdominal viscera; and peripheral thermoreceptors, situated in the skin and mucous membranes, which detect variations in ambient temperature. Together, these receptors transmit continuous feedback to the central nervous system. The hypothalamus integrates this thermal information and orchestrates appropriate effector responses such as sweating and skin blood flow adjustments to maintain homeothermy (Hardy 1961).

1.3.3. Autonomic responses

The autonomic response is initiated by the hypothalamus following the detection of temperature changes by thermoreceptors. These thermal signals are transmitted unconsciously to the thermoeffectors through the autonomic nervous system. The thermoeffector's responses most relevant to sport and exercise in hyperthermic condition include eccrine sweat secretion and cutaneous vasodilation (Périard and Racinais 2019).

The first thermoeffectors activated in response to heat stress are the cutaneous blood vessels. Indeed, skin blood flow can increase up to 16-fold between thermoneutral and hyperthermic conditions (Lossius, Eriksen, and Walløe 1993). Blood acts as a cooling fluid, transferring the heat produced by working muscles to the skin, where it is dissipated into the ambient environment by convection. Under heat stress, cutaneous blood flow first increases through the withdrawal of sympathetic vasoconstrictor activity. As the thermal strain intensifies, an additional rise in skin perfusion occurs through active vasodilatory mechanisms (Kamijo, Lee,

and Mack 2005). At rest, in thermoneutral conditions, approximately 0.5 L/min of blood (i.e., 5-10 % of cardiac output) is directed toward the skin circulation (Lossius, Eriksen, and Walløe 1993). However, during heat stress, skin blood flow can increase up to 8 L/min through an elevation and redistribution of cardiac output, representing 20-30% of maximal cardiac output in highly trained athletes (i.e., 30-40 L/min) (Ekblom and Hermansen 1968). This redistribution occurs at the expense of working skeletal muscles blood flow. Consequently, an elevated heart rate is required to maintain the same blood flow, which constitute the higher cardiac strain observed in hyperthermic condition compared to thermoneutral one (González-Alonso and Calbet 2003).

As thermal strain continues to increase, the second major mechanism promoting heat loss is eccrine sweat secretion. Eccrine sweat glands are tubular structures consisting of a coiled duct leading to a pore at the skin surface (Sato et al. 1989). Sweat is extracted from the glands to the skin via these pores and is composed of 99% of water (Robinson and Robinson 1954). As mentioned previously, the evaporation of sweat molecules from the skin surface induces a substantial transfer of heat from the body to the environment, thereby limiting the rise in skin temperature (Wenger 1972). Sweat evaporation is thus the most effective autonomic thermoregulatory mechanism during exercise for dissipating body heat (Cramer et al. 2022).

Whole-body sweat rate shows large interindividual variabilities in athletes (Baker 2017). It commonly ranges from 0.5 to 2.0 L/h, while values exceeding 3.0 L/h may occur in some individuals, particularly during long and intense exercise and/or environmental heat stress (Baker et al. 2016; Barnes et al. 2019). This variability reflects the fact that sweat rate is primarily driven by the evaporative requirement for heat balance (Gagnon, Jay, and Kenny 2013). Greater metabolic heat production, as occurs with higher exercise intensity, longer exercise duration, or a larger active muscle mass, increases the need for evaporative cooling and therefore increases sweat rate. Body fat may also influence heat storage by acting as an insulating layer reducing the dissipation of metabolic heat production (Foster et al. 2020). Moreover, aerobic fitness and heat acclimation usually enhance sweating responses by lowering the threshold for sweating onset and increasing sweat gland sensitivity (Périard, Eijssvogels, and Daanen 2021). Sex-related differences may also contribute to sweat-rate variability, although they should be interpreted carefully because they are partly explained by differences in metabolic heat production and body composition. When men and women exercise at the same relative intensity, men often produce more absolute metabolic heat and therefore show greater evaporative heat loss. When metabolic heat production is experimentally matched, sex differences in sweating are reduced, although women may exhibit lower local sweat rate and sweat gland output at high requirements for heat loss (Gagnon and Kenny 2012). This suggests that sex may influence sweating responses, but its independent

effect is smaller when body morphology and metabolic heat production are accounted for. Finally, individual sweat gland function, including regional gland density, cholinergic sensitivity, and output per gland, further contributes to interindividual athlete variability (Notley, Mitchell, and Taylor 2023). This large variability has direct practical implications, as standardized hydration recommendations are unlikely to match the needs of all athletes. Therefore, sweat losses should ideally be assessed individually under conditions representative of training or competition (Shirreffs and Sawka 2011).

1.3.4. Behavioural responses

In addition to autonomic adaptations, behavioural responses are also activated by the hypothalamus when an increase in body temperature is detected. This response is conscious and mediated by the somatic nervous system. In individual exercising, behavioural thermoregulation to reduce body temperature encompasses a wide range of voluntary actions, such as reducing muscular work, seeking for shaded areas, or removing a layer of clothing (Flouris and Schlader 2015).

Interestingly, behavioural adjustments reduce the need to rely on autonomic responses and have been proposed as the first line of defence in reducing thermal strain (Andreas D. Flouris 2011). This concept is based on the idea that autonomic thermoregulatory mechanisms have limited capacity for heat dissipation, whereas behavioural strategies offer numerous and flexible means to prevent or restore thermal homeostasis.

While the general population can adopt various behavioural strategies during exercise to minimize the elevation core temperature, with reducing muscular work being among the most efficient, elite athletes cannot do so, as their primary aim is to sustain maximal muscular output. In athletes, behavioural adaptations often involves pre-cooling interventions implemented in the hours preceding competition, such as cold-water immersion, application of cold towels, or the use of ice vests (Bongers, Hopman, and Eijsvogels 2017). During races, clothing is generally minimal to maximise heat dissipation, and athletes often rely on cold-water or ice-slurry ingestion, head or face dousing, and, when permitted by the discipline, neck collars (e.g., in race walking) (Racinais, Ihsan, et al. 2021). However, driven by strong performance motivation, athletes tend to prioritise maintaining effort over implementing behavioural cooling responses. Consequently, autonomic thermoregulatory mechanisms are pushed to their physiological limits (i.e., eccrine sweating and cutaneous vasodilation).

1.4. Overview and research questions

Climate change is driving a progressive rise in global surface temperatures, which amplify the frequency, severity, and unpredictability of heatwaves (IPCC 2023). These environmental changes pose substantial challenges for the organisation of outdoor sporting events (Racinais et al. 2023), many of which are scheduled in hot cities during summer, precisely when conditions are most conducive to severe heat strain in athletes (Bermon and Adami 2019). Indeed, athletes metabolic heat production is elevated, and these environmental conditions impair heat dissipation (Périard and Racinais 2019). Despite these constraints, the international sports federations (IFs) retain the responsibility to ensure that their competitions proceed under safe conditions (Adami et al. 2020), and reserve the right to postpone or cancel events, as excessive thermal strain can markedly impair athletes' performance and precipitate serious health risks (Leon and Bouchama 2015).

The first objective of this thesis, addressed in Chapter 1, was to classify the summer sports included in the Paris 2024 Olympic Games according to their level of heat-related risk. Furthermore, the regulatory policies implemented by the corresponding IFs were examined to identify the strategies currently employed to mitigate athlete heat strain and prevent heat-related illness. Indeed, EHS represents the most severe form of heat-related illness and is potentially fatal if not treated promptly and appropriately, underscoring the importance of robust and evidence-based regulations (Casa et al. 2015).

Building on this foundation, Chapter 2 focused specifically on elite athletes competing in endurance events to evaluate the frequency of EHS, of athletes that did-not-finish (DNF) and of athletes admitted to medical facilities regardless of cause (MED) during major World Athletics competitions. This chapter also investigated whether the occurrence of EHS, DNF and MED differed according to athletes' sex or practised discipline. In addition, to better characterise EHS, the relationship between hyperlocal environmental parameters measured during the competition, individual, and race-related factors with the frequency of EHS were investigated.

Beyond the description and characterisation of EHS, this thesis also aimed to improve the measurement of thermoregulatory responses in athletes during competition. Thermoregulatory systems are often challenged near their physiological limits during competition, and monitoring those responses could allow a better understanding of athletes' heat-dissipation capacities. In this context, because eccrine sweat secretion and cutaneous vasodilation represent the two primary physiological mechanisms for heat dissipation (Cramer et al. 2022), sensors allowing to measure these responses were investigated.

In Chapter 3, the validity of the innovative S1 sensor (Flowbio, London, UK) designed to measure whole-body sweat loss and sweat sodium concentration during exercise was evaluated. Its precision was quantified against gold-standard methods, and the practicality of its use in a sport-related condition was discussed.

Finally, Chapter 4 examined the validity of the Flex sensor (BodyCap, Caen, France). The validity of the skin-temperature sensor was assessed both by a controlled heated plate and on human skin during exercise to characterise its accuracy and limitations. Additionally, this chapter investigated best-practice recommendations for the use of traditional skin-temperature sensors to improve reliability in applied settings.

The research questions investigated in the thesis were summarised in Table 1.

Table 1: Research questions investigated in the thesis

Chapter	Study	Research questions
Chapter 1	Title: “Heat-related risk at Paris 2024: a proposal for classification and review of International Federations policies” Journal: British Journal of Sports Medicine Status: Published Date: July 2024	→ Which sports and disciplines included in the Paris 2024 Olympic Games pose the greatest risk in hot weather? → What are the heat-related policies implemented by the 32 IFs governing these sports? → What are the mitigations strategies employed by the 32 IFs to protect athletes against the heat?
Chapter 2	Title: “What do thermal indices lack to help predict the heat-related risk in elite Athletics?” Journal: British Journal of Sports Medicine Status: Published Date: February 2026	→ What is the frequency of EHS, DNF and MED outcomes in elite Athletics competitions? → What is the association between environmental, individual and race-related parameters and EHS, DNF and MED outcomes? → How the policy used by World Athletics to prevent heat-related illnesses should be applied?
Chapter 3	Title: “Sweat sodium composition and sweat loss estimation through wearable sensors and predictive equations in dry and humid hot conditions” Journal: Frontiers in Physiology Status: Published Date: January 2026	→ What is the validity of the innovative S1 sensor (Flowbio, London, UK) for measuring sweat sodium concentration and whole body sweat rate during exercise in hot conditions? → What is the validity of the recently developed algorithm “sweat rate calculator” (Jay et al. 2024a) for measuring whole body sweat rate in hot conditions? → Is the validity of these tools impacted by hot humid environmental conditions, compared to hot and dry conditions?
Chapter 4	Title: “Validation of the iButton and Flex sensors for measuring skin temperature” Journal: European Journal of Applied Physiology Status: Published Date: October 2025	→ What is the validity of the innovative Flex sensor (BodyCap, Caen, France) for skin temperature measurement? → On which side the traditional iButton hygrochron DS1923 (Analog Devices, Wilmington, USA) should be attached to the skin for reliable temperature measurement? → What is the influence of a higher surface temperature on the accuracy of the Flex and iButton hygrochron measurements?

2. Experimental protocols

2.1. Scoping review

Chapter 1 presents a scoping review conducted to identify and characterise the heat-related policies implemented by major IFs. To obtain a representative and coherent sample of sport-governing bodies, all IFs participating in the Paris 2024 Olympic Games were included ($n = 32$) (International Olympic Committee 2024). This selection ensured broad coverage of international sport while restricting the scope to IFs with comparable global influence and organisational structures to World Athletics.

For each IF, publicly available documents written in English (e.g., competition regulations, medical guidelines, environmental monitoring protocols) were systematically screened to identify components of their heat policies. Extracted data included the thermal indices used, environmental monitoring procedures, decision thresholds, and implemented mitigation strategies.

Thermal indices identified within the policies were categorised based on their number of environmental and individual input variables (e.g., ambient temperature, humidity, activity, clothing), following the classification framework proposed in the biometeorology literature (De Freitas and Grigorieva 2015). Mitigation strategies were listed into grouped categories (e.g., timetable adjustments, cooling provisions, shaded areas).

To complement the analysis of existing heat policies, a categorisation of heat-stress risk was performed for all sports included in the Paris 2024 Olympic Games programme ($n = 45$). All authors of the scoping review independently performed a blinded rating of each event using a 5-point scale ranging from 1 (low risk of heat stress) to 5 (extreme risk of heat stress) as recommended by the International Olympic Committee consensus statement on sport events in the heat (Racinais et al. 2023). The author list comprised medical doctors who were experts in recognising and treating heat stroke, as well as experienced environmental physiologists specialising in heat mitigation strategies for Olympic events. An initial classification was proposed by the first author based on five predefined factors: competition venue (i.e., outdoor or indoor), exercise duration, exercise intensity, exercise type (i.e., continuous or intermittent), and clothing or equipment requirements (i.e., hindering effect for heat dissipation). All authors then independently reviewed and modified the classification according to their expertise. The final score for each event corresponded to the mean of all authors' ratings. For sports comprising multiple events, the final sport classification was determined by the event with the highest heat stress risk level. Sports categorised as having high, very high, or extreme heat-

stress risk were deemed particularly relevant to this thesis topic, and their heat policies were further discussed.

This approach necessarily included subjective elements, as no validated framework currently exists for reporting heat policies and categorising heat stress risk across Olympic sports. Furthermore, the review relied on publicly available English-language policies available at the time of the search (as of January the 18th, 2024). Although it is believed that IFs are using English as the main language for external communication, it cannot be excluded that non-English policies, unpublished documents, or more recent policy updates may not have been captured.

2.2. Data mining approach

2.2.1. Medical and environmental data collected by World Athletics

For the conduction of this thesis, World Athletics provided a dataset comprising medical encounters and environmental conditions recorded during 14 World Championships since 2019. This unique set of data aimed at describing the occurrence of EHS in elite athletes and examining its association with multiple environmental, individual, and race-related parameters, with the long-term goal of improving the ability to predict such events. The dataset included 80 races, equally distributed between sexes. Races were classified into 5 Athletics disciplines: in-stadium long-distance (5000 m and 10000 m), and out-of-stadium racewalking (10-50 km), marathon (half and full), cross-country (6-10 km), and trail running (6-87 km). Across these events, an average of 62 ± 34 athletes started each race, resulting in 4 938 individual race exposures.

For each race, the dataset included three outcome variables:

1. Exertional heat stroke cases (EHS), diagnosed on-site by trained medical personnel according to current clinical standards: central nervous system dysfunction combined with a core temperature $>40^{\circ}\text{C}$ (Armstrong et al. 2007). This constitutes a major strength of the dataset, as EHS is often underdiagnosed in competitive sport settings (Périard, DeGroot, and Jay 2022)
2. Medical encounters (MED), defined as athletes admitted to medical facilities for any reason
3. Athletes that did not finish the race (DNF)

Environmental conditions were measured on-site in the field of play using portable meteorological stations (Kunak, Kunak Technologies SL, Orkoien, Spain; or Kestrel 5400, Nielsen-Kellerman Company, Boothwyn, USA). Parameters included ambient temperature, relative humidity, and the Wet Bulb Globe Temperature (WBGT), the thermal index routinely used by World Athletics (Adami et al. 2020).

2.2.2. Additional performance and environmental parameters

From this original dataset, several parameters that could be linked with race outcomes were calculated and/or estimated.

First, publicly available information from the World Athletics website was integrated into the dataset, including athletes' age, race distance, the winner's and last finisher's times, and average race velocity (World Athletics 2025a). Advanced thermal indices as the Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), and modified PET

(mPET) were derived from on-site meteorological data and race-level contextual variables. The Heat Index (HI) was computed from measured temperature and relative humidity. Because the original HI formulation by Steadman (1979) yields biased values when applied outside its intended temperature-humidity range (i.e., typically when conditions are either very hot and humid or very cold and dry), the extended HI proposed by Lu and Roms (2022) was computed (Lu and Roms 2022; Steadman 1979). This extended formulation preserves the physiological basis of the Steadman model while broadening its applicability to extreme environmental conditions by avoiding extrapolation beyond the original limits. A description of these thermal indices can be found in Table 2.

In addition, dew point temperature was calculated from measured air temperature and relative humidity, and absolute humidity was derived from relative humidity, as these parameters have been associated with exertional heat illness risk (Racinais, Alhammoud, et al. 2021). To obtain the four key environmental parameters (ambient air temperature, relative humidity, radiant heat, and air movement) for each race, mean radiant temperature was estimated using the RayMan model (Fröhlich, Gangwisch, and Matzarakis 2019) based on the geographical coordinates of each race (latitude, longitude, altitude). Wind speed was recorded directly by the on-site meteorological station when available; otherwise, it was retrieved from the closest official meteorological station using an online database (Cedar Lake Ventures Inc 2025). In the latter case, wind speed measured at 10 m was converted to its equivalent at 1.8 m, using the standard power-law wind profile (Touma 1977).

2.2.3. Categorical parameters

Several categorical variables were constructed to classify races according to the type of discipline and acclimatisation status. The “run” parameter was assigned a value of 1 for running disciplines and 0 for race-walking disciplines, and “slope” was assigned a value of 1 when the average course gradient was superior or equal to 1%, and 0 when inferior to 1%.

Finally, a variable was developed to represent athletes’ level of natural seasonal heat acclimatisation, based on the assumption that competitions held early in spring expose athletes to greater heat-stress risk due to limited natural acclimatisation (Racinais, Alhammoud, et al. 2021). A “spring delay” was therefore calculated as the number of days between the first day of spring and the competition date. For races in the Northern Hemisphere, the reference date was 20 March, whereas for races in the Southern Hemisphere, it was 23 September. When this difference was negative, the first day of spring from the previous year was used.

In total, 21 parameters were included in the data set and the association between these environmental, individual or race-related parameters with EHS, MED or DNF was investigated.

Table 2: Description of thermal indices commonly used in biometeorology

T_{air} : air temperature; v_a : windspeed; p_a : water vapor pressure; RH: relative humidity; MRT: mean radiant temperature; T_{wb} : wet bulb temperature; T_g : globe temperature; T_{db} : dry bulb temperature. *Adapted from Grundstein A, Vanos J, Br J Sports Med 2020, doi: 10.1136/bjsports-2020-102920.*

	Wet Bulb Globe Temperature (WBGT)	Heat Index	Physiological Equivalent Temperature (PET)	modified PET (mPET)	Universal Thermal Climate Index (UTCI)
	Measure of heat stress in direct sunlight	Index developed to represent how hot environmental conditions feel to the human body	Index indicating the indoor air temperature that would produce the same core and skin temperatures	Index indicating the indoor air temperature that would produce the same core and skin temperatures	Equivalent temperature based on human physiological response
Aim & Usage	$0.7 \times T_{wb} + 0.2 \times T_g + 0.1 \times T_{db}$	Requires air temperature and humidity	Requires environmental conditions	Requires environmental conditions	Requires environmental conditions
	Specific instrumentation required.	Calculated with an equation.	Calculated with a specific software	Calculated with specific software.	Calculated with specific software.
	Designed for soldiers	Designed for the public	Designed for the public	Designed for the public	Designed for the public
Meteorological Inputs	- T_{wb} - T_g - T_{wb}	- T_{air} - RH (shaded area and light wind assumed)	- T_{air} - p_a or RH - v_a at 1.5m - MRT	- T_{air} - p_a or RH - v_a at 1.1m - MRT	- T_{air} - p_a or RH - v_a at 10m - MRT or T_g
Activity assumptions	Activity not directly considered	“Low to moderate” activity assumed Individual of 1.7 m, 67 kg	Activity of 40 W/m ² = seated person Individual of 1.8 m, 75kg	Activity of 135 W/m ² = walking at 4 km/h Individual of 1.8 m, 75kg	Activity of 135 W/m ² = walking at 4 km/h Individual of 1.9 m, 74 kg
Clothing Assumptions	Clothing not directly considered	Trousers and short-sleeved shirt (0.5 clo)	Trousers, shirt, light jacket (0.9 clo)	Adaptively modeled as a function of air temperature	Adaptively modeled as a function of air temperature
Notes on Applicability	Heat stress in the military, occupational health.	Public health guidance, weather forecasts, heat stress warnings. An extension of the original model was used in the present thesis allowing its application to a wider range of temperature and humidity.	Equivalent temperature index, stationary model.	Updated from PET: clothing and activity modifications.	Climate impact assessment, ambulatory individuals, wide range of climate conditions.

2.3. Cross-over design

Chapters 3 and 4 stem from a common experimental protocol designed to validate two wearable sensors intended to improve the measurement of thermoregulatory responses in athletes. Specifically, the study evaluated a sweat-sensing device (S1, Flowbio, London, UK) and a skin temperature sensor (Flex, BodyCap, Caen, France) in controlled hot conditions.

The experiments were conducted at the “Centre de Ressources d’Expertise et de Performance Sportive” (CREPS) of Montpellier (France) which houses an environmental chamber capable of standardising heat, humidity, and altitude. The protocol was performed in collaboration with the “Environmental Stress Unit” of the institute, a specialised department dedicated to the implementation of heat and altitude training camp in athletes, and to the research on thermal strain and hypoxia in sport.

All participants provided written informed consent prior to inclusion (Appendix 1), and the protocol received ethical approval from the University of Montpellier Research Ethics Committee (2023-023; Appendix 2), in accordance with the Declaration of Helsinki.

Recreationally active adults were recruited from Bachelor’s and Master’s sport science programmes at the University of Montpellier (Appendix 3). Each participant completed two exercise trials in the environmental chamber in a randomised order, with at least 24 h of rest between sessions and identical testing times of day. The trials consisted of:

1. Hot-dry condition: 39.9 ± 0.3 °C; $36 \pm 3\%$ rh, 2 m/s airflow
2. Hot-humid condition: 30.1 ± 0.2 °C; $81 \pm 1\%$ rh, 2 m/s airflow

Participants cycled on an ergometer equipped with a power output sensor (Wattbike Pro, Nottingham, UK) at an intensity corresponding to 80% of their age-predicted maximal heart rate ($220 - \text{age}$), monitored with a H10 chest strap (Polar, Kempele, Finland). The exercise duration and intensity were selected to ensure sufficient sweating for collecting two consecutive absorbent sweat patches from each upper arm.

S1 devices were secured on both upper arms using a strap, positioned just below the deltoid tuberosity on a flat, cleaned skin surface to ensure full sensor-skin contact. Local sweat composition was assessed using the absorbent patch method at the same anatomical sites (Baker et al. 2009). Sweat sodium concentration was measured using a portable sodium analyser (LAQUAtwin, Horiba Advanced Techno, Kyoto, Japan) and validated against a laboratory gold-standard flame photometry method (Baker 2017). Additionally, whole body sweat loss estimated by the S1 and by an online sweat rate calculator (Jay et al. 2024b) was compared with the reference scale-based method (Cheuvront and Kenefick 2017).

The accuracy of the Flex sensor was compared with that of the iButton Hygrochron DS1923 (Analog Devices, Wilmington, USA), a device widely used in sport science for measuring skin temperature. Both sensors were positioned side-by-side and affixed with Leukotape (BSN medical GmbH, Hamburg, Germany) at three body sites: (1) left forearm, (2) chest (beneath the left portion of the chest strap), and (3) left anterior thigh.

3. Statistical analyses

All statistical analyses were performed using R statistical software (version 4.4.2) (R Core Team 2024), with the significance level set at $P < 0.05$. Chapter 1 consisted of a scoping review, therefore, no statistical analyses were conducted for this component of the thesis.

- **Correlation coefficients**

In Chapters 2 and 3, correlation coefficients were computed to evaluate linear relationships between numerical variables. Data normality was assessed using the Shapiro-Wilk test (package *rstatix*). Pearson's correlation coefficients were performed when the assumption of normality was met, otherwise, Spearman's rank correlation coefficient were used. In Chapter 2, correlations were used to assess associations between environmental, individual and race-related parameters and three outcome variables: EHS, MED, DNF. In Chapter 3, correlations were calculated to examine the relationships among sweat sodium concentration, whole body sweat loss and core temperature measured during laboratory-based trials.

Correlation analyses were implemented using a custom function developed in R (example of Pearson's correlation script in Appendix 4). For each variable pair, the data were combined into a two-column data frame, and only complete observations were retained to avoid bias introduced by missing values. Correlation coefficient was calculated to quantify the strength and direction of the association, and statistical significance was assessed under the null hypothesis of no linear relationship. To complement the correlation analysis, simple linear regression models ($y \sim x$) were fitted for each variable pair. From these models, the regression equation and coefficient of determination were extracted to describe the form of the relationship and the proportion of variance explained. Visual representations of associations were generated using the *ggplot2* package, with scatterplots overlaid with fitted least-squares regression lines to facilitate interpretation.

- **Pearson's Chi-squared test for count data**

Pearson's Chi-squared tests were used to examine associations between categorical variables and outcomes in Chapter 2. Specifically, Chi-squared analyses were conducted to assess the influence of sex, Athletics discipline, and environmental heat-risk category (WBGT colour flag) on the occurrence of EHS, MED, and DNF outcomes.

For each test, contingency tables were constructed using observed counts of outcomes (e.g., presence vs absence of EHS) across categories of the explanatory variable. Pearson's Chi-squared test was then applied to evaluate whether the distribution of outcomes differed significantly between groups. The assumptions for the Pearson's Chi-squared test were met, with no expected cell counts below 1 and fewer than 20% of expected cell counts below 5.

To complement the Chi-squared test, outcome incidence rates were calculated and expressed as the number of cases per 1000 athlete exposures as recommended by the consensus on epidemiological studies in Athletics (Timpka et al. 2014), and rate ratio were computed to quantify the magnitude of association between groups.

All Chi-squared analyses were implemented using a custom function developed in R (Appendix 5). This function automated the construction of contingency tables, selection of the appropriate correction method, computation of incidence rates and rate ratio, and export of the results into structured spreadsheet files for reporting and further interpretation.

- **Negative binomial regression with leave-one-out cross-validation**

In Chapter 2, the relationships between environmental, individual and race-related parameters and EHS, DNF and MED outcomes were explored using regression-based approaches. Previous literature has reported that the associations between environmental stress indicators and heat-related outcomes may be non-linear, limiting the relevance of simple correlation analyses (Schroeder et al. 2023). Moreover, EHS, DNF and MED were count variables, and preliminary examination of outcome distributions indicated clear overdispersion, characterised by variances exceeding their respective means. Therefore, Poisson regressions were deemed inappropriate, and negative binomial (NB) regression models were employed instead, as they explicitly account for overdispersion in count data (Hilbe 2011).

While the primary aim of this thesis was to describe and characterise heat-related risks in elite Athletics, an exploratory analysis was also performed to assess the potential of environmental, individual and race-related parameters to predict EHS, DNF and MED outcomes. Therefore, NB regression models were evaluated using a leave-one-out cross-validation (LOOCV) approach (Figure 3). In this framework, the model was “trained” on all observations except one (i.e., the regression was applied to all races except one), which was then used as a test case. The trained model was used to predict the value for the excluded observation, and the difference between the predicted and actual result was recorded (i.e., the model was “tested”). This procedure was repeated until each observation had served once as the test case. Model performance was quantified by computing the mean absolute error across all iterations (i.e., the average of the absolute differences between the predicted and actual results), along with the standard deviation of these differences. The model exhibiting the lowest mean absolute error and the smallest associated standard deviation was considered the most performant. By systematically testing actual data, LOOCV provided an unbiased estimate of each model’s predictive ability.

Leave-One-Out Cross Validation (LOOCV)

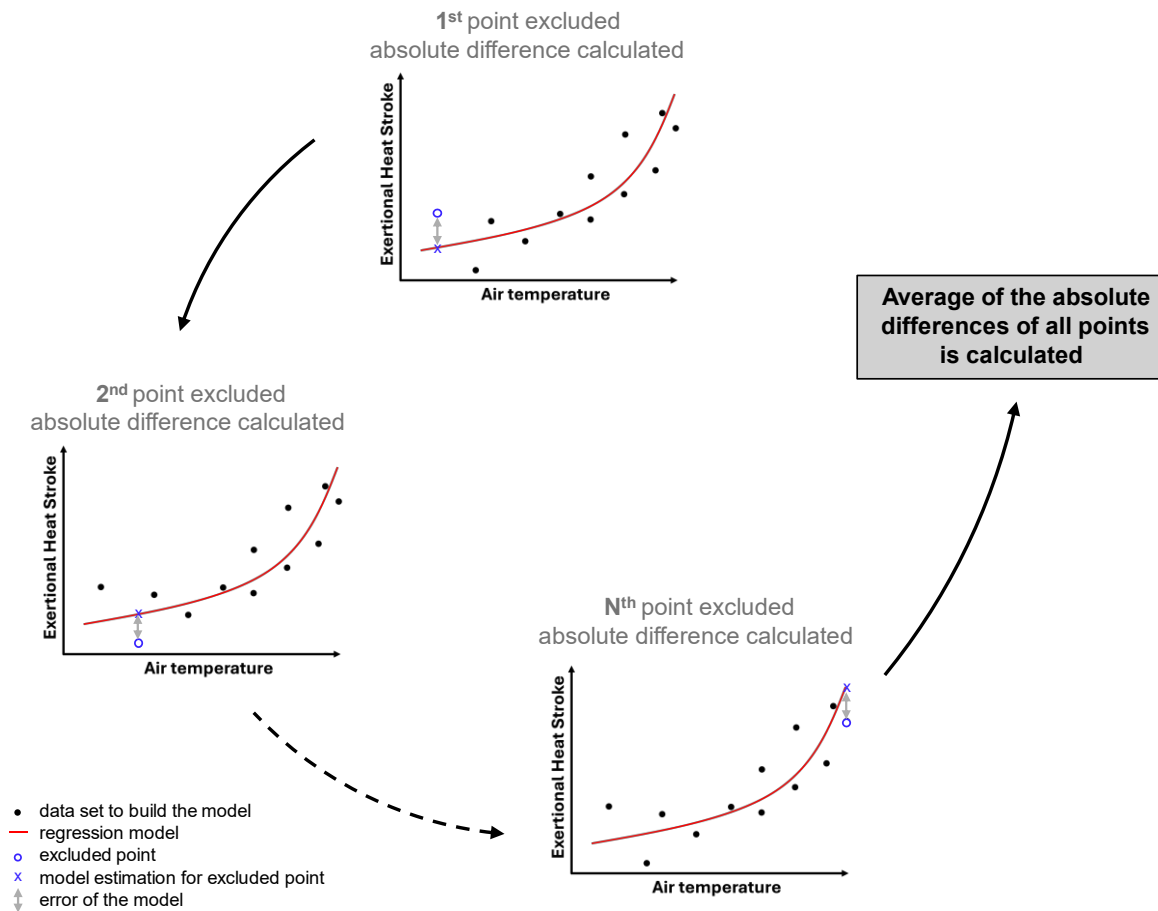


Figure 3: Schematic illustration for leave-one-out cross-validation (LOOCV) procedure

LOOCV allows to assess the ability for a variable (here the temperature) to predict an outcome (the number of EHS). The regression model (in red) is fitted to all data points except one (blue circle). The absolute difference (grey arrow) between the model estimation for the excluded point (blue cross) and the real value of this excluded point (blue circle) is measured. This procedure is repeated for all points. The mean absolute error is calculated for each variable as the average of these differences.

This procedure was conducted for regressions with a single predictor (univariable NB regression). In addition, regressions including multiple predictors simultaneously (multivariable NB regression) were also performed to increase the likelihood of identifying a well-fitting model.

A custom R function was developed to perform NB regressions with LOOCV for each model (Appendix 6). NB regression models were fitted using the *MASS* package. For each model, key metrics including the formula of the regression, Akaike Information Criterion, McFadden's pseudo coefficient of determination and mean absolute error were recorded. All possible combinations of predictors were evaluated. To reduce computation time, model evaluation was parallelised using the *parallel* package, with models fitted concurrently across available

computer's central processing units. Models that failed to converge were automatically excluded from further analysis. Final results were compiled into a single table and exported for further interpretation.

- **Bias and Bland-Altman analysis**

For Chapters 3 and 4, a custom R function was developed to assess the validity of the S1 and Flex sensors (Appendix 7). Several complementary agreement metrics were used, including the calculation of the average of the differences (or systematic “bias”), the average of the absolute differences, and the average of the relative differences with their associated standard deviations between the sensor and the reference device. The concordance correlation coefficient (Lin 1989) was also calculated for agreement between methods (package *DescTools*) and interpreted as follow: poor (< 0.90), moderate (0.90-0.95), substantial (0.95-0.99), and almost perfect (> 0.99) (McBride 2005).

In addition, Bland-Altman analyses were performed to provide a graphical assessment of differences between methods (Bland and Altman 1986). For each comparison, the bias and the 95% limits of agreement, defined as the bias $\pm$ 1.96 times the standard deviation of the differences, were calculated and displayed with the *ggplot2* package.

- **Linear mixed-effects model**

In Chapter 3, in addition to the metrics listed above, the validity of the S1 sensor under hot-dry and hot-humid conditions was assessed using linear mixed-effects models. Measurement method and environmental condition were included as fixed effects, while participant identity was specified as a random effect with the *lme4* package in R. This modelling framework accounted for repeated measurements within participants (i.e., two sweat samples collected on each upper arm during the trial) and accommodated unbalanced data structures (i.e., some samples were excluded before analyses). Post hoc pairwise comparisons were performed using the Tukey method to control for multiple testing via the *emmeans* package (Appendix 8).

- **Paired comparison**

In Chapter 3, exercise responses between hot-dry and hot-humid conditions and in Chapter 4 the accuracy of wearable devices, were compared using paired statistical tests. A custom function in R was developed to apply these tests (Appendix 9). Data normality was assessed using the Shapiro-Wilk test (package *rstatix*). When the assumption of normality was met, paired Student's t-tests were performed; otherwise, paired Wilcoxon signed-rank tests were conducted. To quantify the magnitude and practical relevance of observed differences, effect sizes were calculated and interpreted as negligible (<0.20), small (0.20-0.49), moderate (0.5-0.79), and large ($\geq$ 0.8) for parametric test (Cohen 1988) and negligible (<0.10), small (0.10-

0.29), moderate (0.30-0.49) and large (≥ 0.5) for non-parametric ones (Tomczak and Tomczak 2014). A report was generated for each comparison (packages *grDevices*, *gridExtra*, *ggplot2*) including graphs and key metrics as the normality, p-value and effect size.

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CHAPTER 1

HEAT-RELATED POLICIES OF MAJOR INTERNATIONAL FEDERATIONS

1. Overview

In accordance with the International Olympic Committee's recommendations, IFs are required to anticipate and mitigate heat-related risks in order to protect athletes' health during competitions (International Olympic Committee 2025). IFs have developed heat policies, referring to the regulations and guidelines that account for the influence of the thermal environment on athletes' heat strain during competition. In the first chapter of this thesis, a scoping review was therefore conducted on the heat policies implemented by the majors IFs.

The heat policy of World Athletics consists of monitoring and interpreting environmental conditions in order to estimate the level of heat-stress risk faced by athletes (Adami et al. 2020). To achieve this, World Athletics relies on a thermal index, defined as a quantitative indicator intended to represent the impact of the thermal environment on individuals (De Freitas and Grigorieva 2017). Thermal indices have long been used in biometeorology to describe thermal stress (Macpherson 1962). However, their application in sport science has emerged more recently (Armstrong et al. 2007), driven by the increasing globalisation of sport and the growing exposure of athletes to strenuous environmental conditions associated with climate change (Racinais et al. 2023). A recent systematic review identified more than 300 existing thermal indices, incorporating various environmental parameters (e.g., ambient air temperature, relative humidity) and, in some cases, individual characteristics (e.g., body size, body mass, and clothing) (Ioannou et al. 2022).

The thermal index adopted by World Athletics is the Wet Bulb Globe Temperature (WBGT) (Yaglou and Minard 1957). Developed in the 1950s by the U.S. Army and Marine Corps following several heat-related casualties during military training, WBGT was designed to quantify environmental heat stress. This index is now widely used across multiple fields, including the military, industry, biometeorology, and sport (Havenith and Fiala 2015). Its measurement requires specific instrumentation placed in direct sunlight and integrates multiple environmental factors into a single index. Conceptually, WBGT combines the responses of the four main components of the thermal environment (Budd 2008): ambient air temperature, relative humidity, radiant heat, and air movement.

The WBGT is calculated as follow: $WBGT(^{\circ}C) = 0.7 \times T_{wb} + 0.2 \times T_{bg} + 0.1 \times T_{db}$. The black globe temperature (T_{bg}) is measured at the centre of a sealed, matte-black, thin-walled globe with a diameter of 15 cm (ISO 7243 1989). T_{bg} is highly sensitive to radiant heat and increases markedly under strong solar radiation, while wind enhances convective cooling and reduces its value. As such, it reflects the combined influence of radiant heat, air temperature, and wind speed. The wet-bulb temperature (T_{wb}) is obtained using a naturally ventilated thermometer

covered with a wetted wick and exposed to ambient thermal radiation (ISO 7243 1989). As such, T_{wb} is primarily driven by ambient water vapour pressure. Lower relative humidity facilitates evaporation, resulting in lower T_{wb} , whereas higher humidity limits evaporative cooling. Wind increases evaporative heat loss, while radiant heat contributes to warming the sensor. The dry-bulb temperature (T_{db}) corresponds to the ambient air temperature measured in a shielded environment, and serves as a reference compared to T_{bg} and T_{wb} as it is protected from radiation (Parsons 2006). By integrating these components, WBGT responds to all four elements of the thermal environment and conforms to the principles of thermodynamics that also apply to human. However, its response does not necessarily mirror that of the human body, due to fundamental differences in size and shape and the absence of metabolic heat production or clothing (Hatch 1973).

Based on this thermal index, World Athletics has established a standardised operational procedure to monitor environmental heat stress during events. Several weeks before major international competitions, the Health & Science team of World Athletics installs a weather station (KUNAK, Kunak Technologies SL, Orkoien, Spain) at the competition venue, positioned as close as possible to the athletes' field of play (Figure 4). This station continuously measures the WBGT to monitor environmental conditions and anticipate potential heat strain. The system operates using solar power and transmits real-time data wirelessly. These data are accessible via a dedicated web link to all stakeholders involved in the competition, including organisers, medical teams, and athletes. This protocol allows for the collection of hyperlocal environmental data several weeks in advance of the event, enabling the identification of the most thermally strenuous periods and, if necessary, last-minute adjustments to the competition schedule.

The aim of Chapter 1 was to identify the sports and disciplines governed by major IFs that present the greatest risk under hot environmental conditions, and to evaluate both the relevance of the thermal indices currently used and the implementation of associated mitigation strategies.

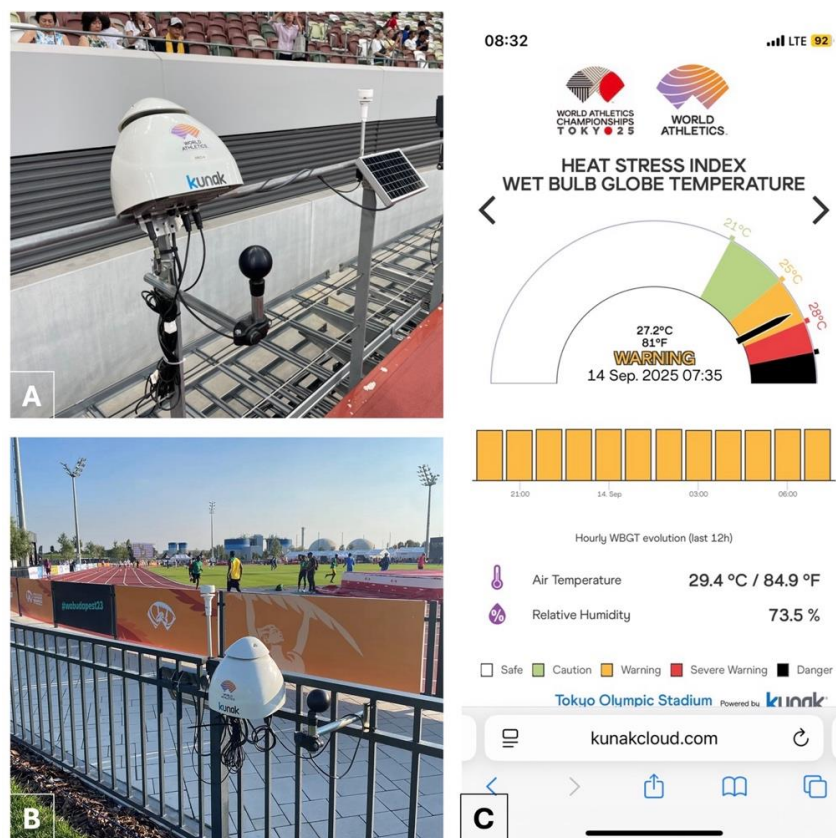


Figure 4: Hyperlocal weather monitoring during World Athletics' major competitions

Panel A: weather station positioned next to the track in the Japan National Stadium for the 2025 World Athletics Championships in Tokyo (Japan). Panel B: weather station positioned at the training venue for the 2023 World Athletics Championships in Budapest (Hungary). Panel C: online dashboard available for stakeholders to access hyperlocal real time weather data including air temperature, relative humidity, wind speed, barometric pressure and outdoor air quality with specific gases concentration.

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Heat-related risk at Paris 2024: a proposal for classification and review of International Federations policies

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ABSTRACT

Several International Federations (IFs) employ specific policies to protect athletes' health from the danger of heat. Most policies rely on the measurement of thermal indices such as the Wet Bulb Globe Temperature (WBGT) to estimate the risk of heat-related illness. This review summarises the policies implemented by the 32 IFs of the 45 sports included in the Paris 2024 Olympic Games. It provides details into the venue type, measured parameters, used thermal indices, measurement procedures, mitigation strategies and specifies whether the policy is a recommendation or a requirement. Additionally, a categorisation of sports' heat stress risk is proposed. Among the 15 sports identified as high, very high or extreme risk, one did not have a heat policy, three did not specify any parameter measurement, one relied on water temperature, two on air temperature and relative humidity, seven on WBGT (six measured on-site and one estimated) and one on the Heat Stress Index. However, indices currently used in sports have been developed for soldiers or workers and may not adequately reflect the thermal strain endured by athletes. Notably, they do not account for the athletes' high metabolic heat production and their level of acclimation. It is, therefore, worthwhile listing the relevance of the thermal indices used by IFs to quantify the risk of heat stress, and in the near future, develop an index adapted to the specific needs of athletes.

INTRODUCTION

Environmental conditions such as high air temperature, high humidity, low air movement or high radiant heat can be strenuous for athletes.¹ This stress emerges from the reduced capacity of the organism to evacuate heat generated by metabolic production to the surrounding environment.^{2,3} Heat can hinder performance from 3% to 20%⁴ and be lethal as it is one of the two main causes of death in athletes⁵ and kills more than any other natural causes.⁶ Exertional heat illnesses (EHI) encompass a spectrum of conditions ranging from muscle cramps and heat exhaustion to life-threatening events referred to as exertional heat stroke (EHS).⁷ EHS is a medical emergency diagnosed by a core temperature exceeding 40.5°C in conjunction with central nervous system dysfunctions (eg, confusion, ataxia, loss of balance, apathy and irritability).⁸

With the climate change and sport globalisation, the risks of EHI will continue to rise during

WHAT IS ALREADY KNOWN?

- ⇒ Exertional heat illness (EHI) is a major concern due to climate change and the globalisation of sports. The most serious form of EHI, exertional heat stroke, is a life-threatening event.
- ⇒ To anticipate the risk of EHI and implement mitigation strategies, international federations employ thermal indices; quantitative indicators for assessing the environmental impact on individuals.

WHAT ARE THE NEW FINDINGS?

- ⇒ 15 sports were identified as high, very high or extreme risk of heat stress. Among them, 1 does not have a dedicated policy, 3 do not specify the measurement of parameters in their policies and 11 mention the use of thermal indices. However, current thermal indices inadequately reflect thermal strain endured by athletes.
- ⇒ It is essential to develop thermal indices reflective of the athletes' thermal strain. More recent indices with an integration of heat budget models could be of interest, but their reliability needs to be tested against the incidence of EHI.
- ⇒ To anticipate the danger of heat before an event, the following three steps are recommended:
Adequately monitor the prevalence of athletes with EHI during competitions.
If the sport is at risk of heat stroke, choose and validate a thermal index that objectively represents the thermal strain athletes endure in this sport.
Define mitigation strategies to reduce the risk of EHI.

the next decades for major sporting events.^{1,9,10} At the Tokyo 2020 Olympics, 50 cases of EHI (14%) occurred at the marathon and race-walking competition venue, and in total 100/567 athletes (18%) and 125/541 non-athletes (23%) were treated at the clinics for heat-related illnesses.¹¹ During the 2019 World Athletics championship at Doha (Qatar), in hot and humid condition, 20 cases of exercise-associated collapse, 16 cases of exercise-associated muscle cramps and 18 cases of heat exhaustion were reported among marathon and race-walk athletes.¹²



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In this context, one of the missions of International Federations (IFs) is to anticipate and mitigate the danger of heat in order to protect athletes' health during competitions.^{1 13} To achieve this, IFs have developed specific heat policies to anticipate the risks of environmental conditions and suggested mitigation strategies to reduce the risks of EHI on the competition venues.¹⁴ To objectively measure the risks of EHI, IFs employ quantitative indicators that aim to represent the impact of the thermal environment on the individuals, known as thermal indices.^{3 15 16} Some environmental thermal indices rely on measuring solely one or more of the four primary environmental parameters (ie, air temperature, humidity, radiant heat and wind velocity) while others incorporate physiological parameters such as people's activity and the resulting metabolic heat production and clothing.^{2 3}

The aim of this review was, therefore, to determine the methods used by IFs participating in the Paris 2024 Olympic Games to assess the risk of heat-related illnesses among athletes, to define the associated procedures and mitigation strategies and to provide future recommendations on evaluating the heat-related illness risk in sports.

METHODS

The Games of the XXXIII Olympiad (Paris 2024) included 45 sports as per International Olympic Committee classification.¹⁷

Categorisation of heat stress risk

To our knowledge, no categorisation of heat stress risk per sport for all summer Olympic sports was previously provided in the literature. Therefore, to discuss the necessity of IFs to have a heat policy, the authors of this review underwent a blinded categorisation of Paris 2024 sports' heat stress risk from 1 to 5: 1-low risk of heat stress, 2-moderate risk of heat stress, 3-high risk of heat stress, 4-very high risk of heat stress and 5-extreme risk of heat stress. The first author suggested a primary categorisation based on five factors: the venue, the duration, the intensity, the exercise type and the clothing. Then, all authors edited this categorisation individually based on their expertise in heat stress. The final categorisation was determined by averaging the notation of each author. This method was conducted for every event in each sport of the 2024 Paris Olympic Games programme (eg, 26 events in athletics). The sport's final categorisation was determined by the event within the sport that had the highest risk level. In this review, the policy of the sports having high, very high or extreme risk of heat stress was considered 'at risk' and was further discussed.

Policy collection and analysis

The policies implemented by the 32 IFs representing the 45 sports engaged in Paris 2024 Olympics were systematically screened for regulations related to the heat. The English documentation on the official website of the IFs was searched to find the books where environmental surveillance was mentioned. The search focused on materials available as of 18 January 2024. When more than one policy was cited, only the major one was reported. In each document, the relevant chapter was identified with a search of the following keywords: 'temperature', 'weather', 'heat', 'hot', 'environment' or 'venue'. If no results emerged, the entire policies were checked, and a search engine search was performed for unofficial documents. If still no conclusive results emerged, the IFs were considered to have no policy for environmental condition surveillance. Finally, the commitment of the policy was categorised as a requirement or a

recommendation, based on the obligation (eg, 'must', 'requires', 'will') or not (eg, 'recommend', 'should', 'may') to apply it. Importantly, the IFs were directly contacted for clarification whenever needed in case of any doubt, uncertainty or missing information. The sources related to the heat policy of IFs can be accessed in online supplemental materials.

Thermal index

The thermal indices used by the IFs to assess environmental conditions were also searched. A thermal index was defined as a quantitative indicator that aims to represent the impact of the thermal environment on the individuals.¹⁵ The type of policy was listed as relying on a 'single' parameter (eg, air temperature), 'multiple' parameters (eg, air temperature and air humidity) or a 'calculation' like the Wet Bulb Globe Temperature (WBGT) which is based on multiple parameters (dry bulb, wet bulb, globe temperatures). When no parameter was mentioned in the heat policy, the policy depended on the judgement of the board organising the competition. The parameter measurement was indicated as 'no or unspecified' (ie, without mentioning any quantitative measurement). Ultimately, the procedure related to the measurement of thermal indices and the mitigation strategies proposed by IFs governing outdoor sports were collected.

Equity, diversity and inclusion statement

The author team comprised seven men, including one junior researcher and six experienced investigators with diverse backgrounds as exercise physiologist, medical doctor and senior lecturer. While three different nationalities are represented within the research team, we acknowledge that all team members are of European nationality. Participant recruitment was not conducted for this research; hence, no specific statement is formulated in this regard.

CATEGORISATION OF HEAT STRESS RISK AND PARAMETER MEASUREMENT

30 sports (67%) were estimated at low or moderate risk of heat stress out of the 45 engaged in the Paris 2024 Olympics (table 1). Among the 21 sports at low risk, 19 sports are indoor and 2 are outdoor with low physical intensity (eg, archery). Thermal strain in indoor activities requires a different approach compared with outdoor activities. The impact of radiant heat is less important indoors as it should be close to none, but the cooling effect of the wind is lacking, possibly hindering heat evacuation.² When an air conditioning system is missing, temperature and humidity can rise throughout the day due to the human activity and the weather outside, contributing to strenuous situations for the athletes.^{18 19} Therefore, current proposed classification of heat stress may differ for amateur events playing in lower quality infrastructures. Only one indoor sport, track cycling, was considered at moderate risk of heat stress as it includes prolonged events (eg, Madison) in traditionally heated velodromes. The eight other sports with moderate risk are outdoors, with either a combination of low intensity and long duration activity (eg, golf) or a short duration (eg, canoe slalom).

15 sports (33%) were estimated at risk of heat stress (ie, high, very high or extreme risk, table 1). Extreme risk of heat stress was highlighted for three sports due to their events combining high intensity and long duration: athletics, cycling road and triathlon. Additionally, six sports were categorised at very high risk: cycling mountain bike, hockey, marathon swimming, rugby sevens, sailing and tennis. Finally, six sports were classified as high risk: basketball 3×3, beach volleyball, cycling

Table 1 Policy employed by the International Federations (IFs) of the 45 sports engaged in Paris 2024 Olympic Games to protect athletes from heat stress in the competitive environment

Sport	International Federation	Venue	Heat stress risk	Heat policy	Parameter measurement	Thermal index	Commitment
Athletics	World Athletics	Outdoor	Extreme	Yes	Calculation	WBGT	Requirement
Cycling Road	International Cycling Union	Outdoor	Extreme	Yes	Calculation*	WBGT	Recommendation
Triathlon	World Triathlon	Outdoor	Extreme	Yes	Calculation	WBGT †	Requirement
Cycling Mountain Bike	International Cycling Union	Outdoor	Very high	Yes	No or unspecified	–	Recommendation
Hockey	International Hockey Federation	Outdoor	Very high	Yes	Multiple	Air T° and rh%	Requirement
Marathon Swimming	World Aquatics	Outdoor	Very high	Yes	Single	Water T°	Requirement
Rugby Sevens	World Rugby	Outdoor	Very high	Yes	Calculation	Heat Stress Index	Recommendation
Sailing	World Sailing	Outdoor	Very high	Yes	No or unspecified	–	Recommendation
Tennis	International Tennis Federation	Outdoor	Very high	Yes	Calculation	WBGT	Requirement
Basketball 3×3	International Basketball Federation	Outdoor	High	No	–	–	–
Beach Volleyball	International Volleyball Federation	Outdoor	High	Yes	Calculation	WBGT	Requirement
Cycling BMX Racing	International Cycling Union	Outdoor	High	Yes	No or unspecified	–	Recommendation
Football	International Federation of Football Association	Outdoor	High	Yes	Calculation	WBGT	Requirement
Modern Pentathlon	World Pentathlon	Outdoor	High	Yes	Multiple	Air T° and rh%	Recommendation
Rowing	World Rowing	Outdoor	High	Yes	Calculation	WBGT	Recommendation
Canoe Flatwater	International Canoe Federation	Outdoor	Moderate	Yes	No or unspecified	–	Requirement
Canoe Slalom	International Canoe Federation	Outdoor	Moderate	Yes	Multiple	Air T° and air movement	Requirement
Cycling BMX Freestyle	International Cycling Union	Outdoor	Moderate	Yes	No or unspecified	–	Recommendation
Cycling Track	International Cycling Union	Indoor	Moderate	No	–	–	–
Equestrian	Fédération Equestre Internationale	Outdoor	Moderate	Yes	Calculation	WBGT	Recommendation
Golf	International Golf Federation	Outdoor	Moderate	Yes	Calculation	WBGT	Recommendation
Skateboarding	World Skate	Outdoor	Moderate	Yes	No or unspecified	–	Recommendation
Sport Climbing	International Federation of Sport Climbing	Outdoor	Moderate	No	–	–	–
Surfing	International Surfing Association	Outdoor	Moderate	Yes	No or unspecified	–	Recommendation
Archery	World Archery Federation	Outdoor	Low	Yes	No or unspecified	–	Recommendation
Artistic Gymnastics	International Gymnastics Association	Indoor	Low	Yes	Calculation	Humidex	Recommendation
Artistic Swimming	World Aquatics	Indoor	Low	Yes	Single	Water T°	Recommendation
Badminton	Badminton World Federation	Indoor	Low	Yes	Multiple	Air T° and air movement	Requirement
Basketball	International Basketball Federation	Indoor	Low	Yes	Single	Air T°	Requirement
Boxing	Athlete 365 Boxing	Indoor	Low	Yes	No or unspecified	–	Requirement
Breaking	World DanceSport Federation	Outdoor	Low	Yes	No or unspecified	–	Recommendation
Diving	World Aquatics	Indoor	Low	Yes	Single	Water T°	Recommendation
Fencing	International Fencing Federation	Indoor	Low	Yes	Single	Air T°	Requirement
Handball	International Handball Federation	Indoor	Low	Yes	Single	Air T°	Requirement
Judo	International Judo Federation	Indoor	Low	Yes	Single	Air T°	Requirement
Rhythmic Gymnastics	International Gymnastics Association	Indoor	Low	Yes	Calculation	Humidex	Recommendation
Shooting	International Shooting Sport Federation	Indoor	Low	No	–	–	–
Swimming	World Aquatics	Indoor	Low	Yes	Single	Water T°	Recommendation
Table Tennis	International Table Tennis Federation	Indoor	Low	No	–	–	–
Taekwondo	World Taekwondo	Indoor	Low	No	–	–	–
Trampoline	International Gymnastics Association	Indoor	Low	Yes	Calculation	Humidex	Recommendation
Volleyball	International Volleyball Federation	Indoor	Low	Yes	Single	Air T°	Recommendation
Water Polo	World Aquatics	Indoor	Low	Yes	Single	Water T°	Recommendation
Weightlifting	International Weightlifting Federation	Indoor	Low	No	–	–	–
Wrestling	United World Wrestling	Indoor	Low	Yes	Single	Air T°	Requirement
The policies collected were indicated in the official documentation of the IFs. A level of heat stress risk was also determined for each sport: low, moderate, high, very high or extreme.							
Sources of policy can be found in online supplemental materials.							
*Estimated WBGT based on: air temperature, relative humidity, estimated radiant temperature, estimated wind speed based on the expected peloton speed.							
†The WBGT is employed for the cycling and running parts of the triathlon while the water temperature is measured for the swimming part.							
rh%, relative humidity; T°, temperature; WBGT, Wet Bulb Globe Temperature.							

BMX racing, football, modern pentathlon and rowing. Among sports at risk, one did not have a heat policy (7%), three did not specify any parameter measurement (20%), one relied on

a single parameter (7%), two on multiple parameters (13%) and eight on a calculation from multiple parameters (53%) (figure 1).

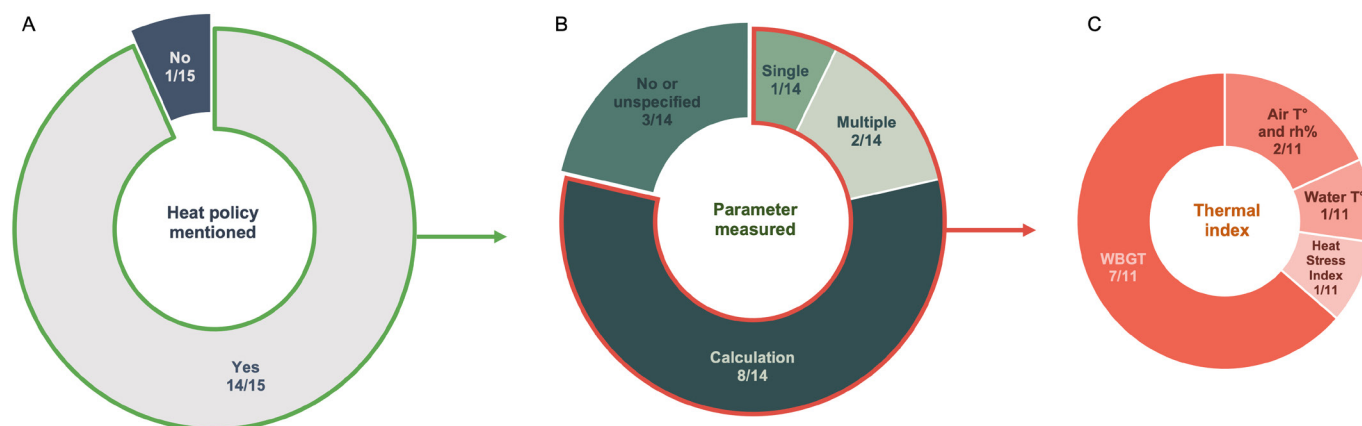


Figure 1 Heat policies for sports with high, very high and extreme risk of heat stress. The presence of a heat policy (A), the measured parameter(s) mentioned in the policy (B) and the thermal indices employed when there is a parameter measured (C). T°: temperature, rh%: relative humidity.

HEAT POLICY BASED ON SINGLE OR MULTIPLE PARAMETERS

Water temperature

A single parameter is employed in marathon swimming and for the swimming part of the triathlon (both in open water): the water temperature (table 1). Despite the conductive and convective cooling effects of water being approximately 2–5 times more effective than air at the same temperature, heat-related illnesses remain a significant risk for swimmers.²⁰ This is particularly crucial, as any loss of consciousness can lead to drowning. A complete review on heat injury in open-water swimming can be found elsewhere.²¹

Air temperature and relative humidity

The IFs of hockey and modern pentathlon are using multiple parameters, the air temperature and the relative humidity, to assess the risk of EHI (table 1). In hockey, the policy applies when the team bench area reaches 35°C, either 10 min before the match or during the third period (table 2). In areas with humidity over 65%, this threshold may be lowered on review. Longer breaks are introduced during the game under these conditions. In modern pentathlon, if the temperature exceeds 21°C and humidity surpasses 50%, a risk assessment matrix is used (table 2). While these are important initial steps, the limitation of this approach is the lack of consideration of other important factors such as wind velocity, radiant heat (eg, cloud covering, shaded area), metabolic heat production and clothing parameters.^{22–23} These parameters are paramount in the heat generation and dissipation mechanisms and influence the occurrence of EHI.^{2,24–25} Whenever feasible, it is also crucial to directly measure environmental parameters at the competition site.²⁶ Indeed, meteorological factors such as wind speed and radiant heat, vary significantly depending on surface type (eg, asphalt, grass) and environmental shading (eg, buildings, trees).^{26–27}

Developing policies to prevent EHI requires collecting various data in a standardised manner, including environmental condition details but also practice session information (eg, duration, intensity, type).^{24–26} Sports injury epidemiologists and clinicians should then analyse the associations between these variables and heat-related injury rates, enabling the establishment of more refined, evidence-driven policies.

HEAT POLICY BASED ON CALCULATION FROM MULTIPLE PARAMETERS

Wet Bulb Globe Temperature

The WBGT is employed in 7/15 (47%) sports at risk (table 1). Six sports directly measure the WBGT on the field of play (ie, athletics, triathlon, tennis, beach volleyball, football, rowing) while it is estimated from meteorological station data in road cycling (table 2). The WBGT²⁸ is a measure of the heat stress in direct sunlight, calculated by merging the wet bulb (T_{wb}), the black globe (T_{bg}) and the dry bulb (T_{db}) temperatures in outdoors as follow: $WBGT (^{\circ}C) = 0.7 * T_{wb} + 0.2 * T_{bg} + 0.1 * T_{db}$. It was developed in the 1950s by the US Army and Marine Corps after several heat-related casualties in training camps.²⁹ Over the years, it has been used in multiple fields going from military, industrial, biometeorology to sports.^{3–30}

The American College of Sport Medicine (ACSM) recommended the use of the WBGT in its special communications of training and competing under the heat in 2007³¹ and has recently renewed this advice in the 2023 edition.³² In this updated consensus, the ACSM aims to account for the individual differences by publishing WBGT guidelines for different locations (ie, northern, middle and southern regions of USA) and different public (ie, acclimatised, fit, low-risk individuals or non-acclimatised, unfit, high-risk individuals). However, despite these individualisations recently proposed, the WBGT remains an environmental index with its limitations.²⁹ Indeed, the WBGT accuracy is impaired in high humidity and/or low air movement,³³ and it does not account for metabolic heat production and clothing, both being different within sports and different between athletes and soldiers.²⁹ Because the athletes' thermal strain relies heavily on the intensity of the activity realised and the evaporation capacity of sweating (ie, clothing, air humidity, air movement), WBGT inadequately reflects the thermal strain endured by athletes.^{2,29–34–36}

Acknowledging those limitations, a strength of the WBGT is that the ACSM recommends thresholds for its implementation in sports, including increasing rest/work ratio, monitoring of fluid intake, decreasing the length of the activity or cancel the exercise.³² To further facilitate WBGT interpretation, the ACSM, World Athletics, World Triathlon and the International Cycling Union are using a coloured flag system (figure 2). For example, the ACSM recommends cancelling any exercise when the WBGT is above 32.3°C, corresponding to a black flag while World Athletics black flag is set at 30.0°C and World Triathlon

Table 2 Procedures and mitigation strategies for outdoor sports using thermal indices

Sport	Heat stress risk	Thermal index	Procedures	Mitigation strategies
Athletics	Extreme	WBGT	For the period of the competition, and on race days, the local organising committee shall arrange to take frequent readings of temperature, humidity, Wet Bulb Globe Temperature (WBGT) and Physiological Equivalent Temperature (PET) at different competition sites. Readings will be performed at various times and the measurements displayed in banners of sufficient size to facilitate information available to athletes, officials and health staff. Warm-up area—one banner indicating the healthcare staff measured every 60 min on-site; road races—one banner at the start line, one at the finish line and another one showing the WBGT/PET measured every 20 min on-site; Race walking—one banner in front of the Team-Refreshments Station showing the WBGT/PET assessed every 20 min on-site. Other thermal stress indices can be used to provide more information as the modified PET (mPET) and Universal Thermal Climate Index (UTCI).	Timetable adjustment, continuous availability of ice supply and sealed cold-drinks, fans, ice packs. Shading areas and air-conditioned team tent. Cold-water immersion treatment available throughout the course and at the finish line. Additional hydration stations can be provided during the race.
Cycling Road	Extreme	WBGT	WBGT values are estimated with the model published by Liljegren <i>et al.</i> ⁴⁰ Temperature and humidity are taken from nearest weather stations observation accessible through reference websites. Three standard values of wind speed are suggested based on the expected peloton velocity. Then, a UCI file is provided to calculate the WBGT based on temperature, humidity and wind value. The radiant temperature is calculated directly in the model.	WBGT <15°C, white zone: no specific countermeasures. WBGT 15°C–17.9°C, green zone: warm-up in the shade with fans, skin protection with non-greasy sun creams, choice of light-coloured clothing, normal hydration plan. WBGT 18°C–22.9°C, yellow zone: warm-up with ice vests, use of fresh towels, application of strict, individualised hydration plans, distribution of 'ice-socks', supply of ice to the teams during the race. WBGT 23°C–27.9°C, orange zone: adaptation of the start area to keep riders in the shade before the start, protect officials, organising staff and volunteers from the sun, increase the number of neutral motorbikes providing riders with drinks and ice packs, adapt the rules limiting hydration and cooling in competition. WBGT >28°C, red zone: modification of start and finish times, possible neutralisation of a section of the race or stage, cancellation of the stage/race.
Triathlon	Extreme	WBGT	The measurement tool should be taken at the finish area every 30 min starting 3 hours before the start of the competition. The device must be placed in direct sunlight 1.5 m above the ground. Provide announcements of its readings at the Sport Information Centre and the Athlete Lounge.	Timetable adjustment, tent with fans and air conditioned, water, sports drink cooled, towels immersed in ice water, ice, inflatable bath with water and ice, Improve the aid/drink stations numbers during the run course. WBGT 30.1–32.2, red flag: if the medical assistance follows all the rules of World Triathlon Event Organiser Manual Medical Services and Exertional Heat Illness Prevention document, standard distance events—change to sprint distance; sprint distance events and below—stay as originally planned. If the medical assistance does not follow all the rules, the competition must be rescheduled for sprint and standard distance events. Meeting conducted between delegates, director and doctor for agreeing the heat countermeasures to be implemented for middle-distance and long-distance events. WBGT >32.2°C, black flag: the competition must be rescheduled or cancelled for sprint and standard distance events. Meeting conducted between delegates, director and doctor for agreeing the heat countermeasures to be implemented for middle-distance and long-distance events.
Hockey	Very high	Air T° and rh%	A measurement device should be stationed at the technical table as this has same conditions with team benches and does not interfere with the teams. The FIH Sport Operations Managers and if available, the FIH Medical Officer will evaluate the measurements at half time/ between quarters.	Rehydration in team changing room or shading area, two fans for each team bench and one for the Technical Table. Temperature in the team bench area ≥35°C, ten minutes before the start of a match or the third period of a match (threshold figure may be reviewed and lowered in locations where relative humidity >65%): breaks at the end of the first and third period will be extended to 4 min. Humidity ≥75% and/or temperatures >42°C as measured on the field of play: break of 1 min to be provided at an appropriate break in play around 7 min and 30 s of the 1st and 2nd quarters. Any decision to apply these break times for 3rd and 4th quarters will be decided based on the weather condition assessed by the FIH Medical Officer, breaks at the end of the first and third period will be extended to 4 min.
Marathon Swimming	Very high	Water T°	Measurement should be checked the day of the race 2 hours before the start and at 1 hour intervals during the race at three points around the course at a depth of 40 cm. The agreed temperature will be the average of the three taken. This control should be done in the presence of a Commission made up of the following persons present: a Referee, a member of the organising committee and one coach from the teams present designated during the Technical Meeting.	Water temperature <16°C or >31°C: the water temperature shall be measured again in 30 min and if that measurement is also <16°C or >31°C, the race must be stopped until such time as the water temperature complies with this rule. Water temperature ≥18°C: swimsuits (men and women) shall not cover the neck, nor extend past the shoulder, nor extend below the ankle.
Rugby Sevens	Very high	Heat Stress Index	Measurement by a Whirling Hygrometer at the site of the game. The hygrometer needs to be whirled for 20 s to obtain readings. Three measurements should be undertaken and averaged. A chart provided by World Rugby allow to convert the measurement in a Heat Stress Index value. ⁶⁴	Heat Stress Index >150: timetable adjustment, provision of dressing room fans if air conditioning not available, provision of sideline shade if game played during the day when radiant heat (direct sunlight) is a contributing factor, strategic positioning of towels immersed in ice water around the ground—behind goal posts and at junction of each quarter line and sideline. 2 min break at the 20 min mark of each half: the focus of this break should be threefold, a medical assessment of each athlete for signs of heat stress, cooling of athletes and rehydration. It is suggested that cooling would be best achieved by immediately removing jersey and shoulder pads, application of ice water to head±body. Using sideline fans and shade (if game during day) would also be ideal. It should be noted that a 2 min break has been recommended (as opposed to a 1 min break) because the focus during this break is primarily medical assessment and cooling.

Continued

Table 2 Continued

Sport	Heat stress risk	Thermal index	Procedures	Mitigation strategies
Tennis	Very high	WBGT	The WBGT recording device should be in direct sunlight, mounted approximately 1 m above the ground and allowed to acclimatise for 2–3 min. Alternatively, Heat Index can be determined from temperature and humidity measured by nearest meteorological station with a chart provided by ITF. ⁶⁵ The WBGT or Heat Index should be measured at least 3 times daily by the ITF Supervisor or his/her designee. Ideally, measurements should be taken every 2 hours, but a minimum 3 readings should be taken at the following times: 30 min before match play begins; middle of the scheduled day's play and just prior to beginning the last match of the day, or just prior to the start of the first evening session match. The WBGT or Heat Index should also be measured following any suspension of play and at the discretion of the ITF Supervisor, in consultation with the tournament doctor and/or sports physiotherapist.	Timetable adjustment, ice supply, cold-wet-towel, ice packs, shaded areas, safe drinking water. WBGT value $\geq 30.1^{\circ}\text{C}$ or Heat Index $\geq 34^{\circ}\text{C}$: Modification of Play criterion—10 min break is allowed between the second and third sets (in a best of 3 tie-break sets match only), only if one or more of the players requests such a break. However, if a match has already resumed following the suspension of play and one set was completed before the suspension of play (in a best of 3 sets match), the 10 min break will no longer be available, unless otherwise decided by the ITF Supervisor. Possible to delay the starting time for matches until such a time as the Modification of Play criterion is no longer met. WBGT value $\geq 32.2^{\circ}\text{C}$ or Heat Index $\geq 40.1^{\circ}\text{C}$: Suspension of Play criterion—the match cannot start or restart. If a game is in progress when the Suspension of Play criterion is met, play should be suspended at the end of that game.
Beach Volleyball	High	WBGT	Measurements are taken on centre court 5 min before the start of each game in front of the scorer's table, approximately 1.5 m above the sand level. If the scorer's table is shaded, the measurement must be made closer to the court or even on court in the sunny area. No measurements are necessary from the outside courts. The measurements are to be taken by a reserve referee (or the referee of the match before). The measurement is conducted using a Heat Stress WBGT Meter (Model HT30, Extech Technology) set for outside mode (OUT) with the protective sliding cover open.	—
Football	High	WBGT	In any location or environmental condition known to be hot and/or humid, a measurement is conducted 90 min before the start of the match and repeated 60 min before the start of the match.	WBGT value $\geq 32^{\circ}\text{C}$: mandatory cooling breaks of 2 min at 30 min and 75 min of play. The match may be either postponed or cancelled, depending on the level of the WBGT and the decision of the match management team. Additional ice supply, cooler boxes on wheels (x2), ice-water-soaked towels and cold bottled water (2 sets of 26 for the 2 cooling breaks, for each player and referees), other individual cooling item allowed, human resources to distribute the ice and the water (3 persons).
Modern Pentathlon	High	Air T° and rh%	—	Timetable adjustment, sport medical risk assessment carried out.
Rowing	High	WBGT	Measurement 1 m above water level from a pontoon.	Timetable adjustment, shaded rest area, crushed ice, extra-water, fans, possible cancellation of the event. Adaptation of the clothing or umpires, officials and volunteers. Temperatures $>32^{\circ}\text{C}$ or WBGT $>28^{\circ}\text{C}$: teams advised to train in the morning and evening hours, cool and/or air-conditioned rooms, free-water should be at least 3 L/day, regular official and umpire rotation. Temperatures $>38^{\circ}\text{C}$ or WBGT $>32^{\circ}\text{C}$: racing course should be closed for training
Canoe Slalom	Moderate	Air T° and air movement	The chief official must use available technology (weather reports, wind metres, etc) to be aware of changes to the competition conditions (eg, weather—wind, lightening, water level) and respond accordingly.	—
Equestrian	Moderate	WBGT	Measurement on course in direct sunlight.	Timetable adjustment, lighter clothing permitted, reduction of the cross-country distance, shaded or air-conditioned area, water/ice supply, fans, misting.
Golf	Moderate	WBGT	Daily measurement on the course and main spectators stands or assembly areas. It is important to coordinate the WBGT measurement with the watering of the pitch by the ground staff as this may artificially decrease the measured WBGT, with possible adverse effects. All WBGT measurements should be recorded on paper and, if possible, photographically.	Timetable and location adjustment, regular breaks, shade and cooling stations around the course, fans/mist and ice slushie drinks. Water, beverages and other fluids, preferably cooled to drink available for players, caddies, staff, media, and spectators. Clothing adaptations and permission of a mid-round change of clothes. Video surveillance to survey the courses and identify athletes in difficulty.

rh%, relative humidity; T°, temperature; WBGT, Wet Bulb Globe Temperature.

32.2°C . The International Tennis Federation, the International Federation of Football Association and World Rowing are also using thresholds to clarify the interpretation of the WBGT, without coloured flag (figure 2). The International Volleyball Federation uses the WBGT without specific thresholds and mitigation strategies (table 2). This decision is informed by the observation that, despite high WBGT levels recorded in Beach Volleyball, the incidence of EHI remains low over 11 years of heat stress monitoring.^{37 38}

In addition to its simplified interpretation, the WBGT is easily measurable in the field using appropriate tools.^{3 29} In cases where on-site measurement is impractical, WBGT can be estimated using meteorological station data as in road cycling event.^{39–41} WBGT can also be computed on dedicated digital platform such as *Climate Chip*⁴², *Fame Lab*⁴³ or *Zunis Foundation*.⁴⁴ The recommendations of the ACSM to use the WBGT, along with the time span of this index and its simplified measurement and interpretation, have likely influenced 7/11 (64%) of the IFs

that employ a thermal index in their heat policies to rely on it (figure 1).

Heat Stress Index

World Rugby has chosen the Heat Stress Index (HSI) to estimate the risks of EHI in rugby sevens (ie, 1/11 sports using thermal indices, figure 1). They studied the risks of EHI associated with the practice of the activity and found that the WBGT would not represent the risks of thermal strain in rugby players, based on its intermittent nature, the length of the halves (40 min), and the facilitated access to water (World Rugby document in online supplemental materials). They observed that the HSI would better represent the thermal strain and recommend measuring it at the site of the game with a whirling hygrometer.⁴⁵ The HSI is a ratio between the evaporative requirement of the player and the maximum evaporative capacity of the environment. The higher the ratio, the more strenuous the conditions because the evaporative capacity of the sweat is reduced.³ Therefore, HSI is

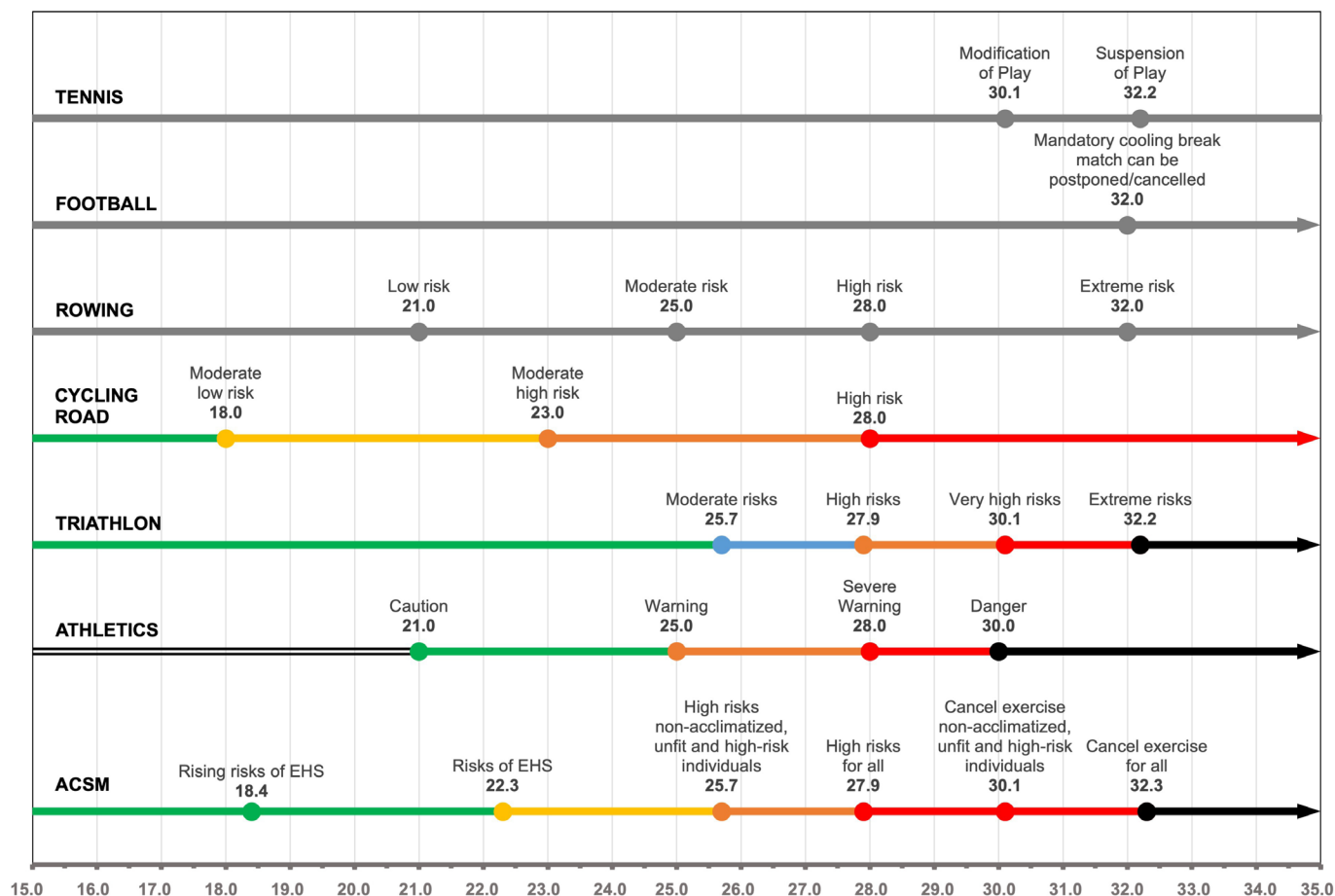


Figure 2 Wet Bulb Globe Temperature (WBGT) thresholds suggested by International Federations and the American College of Sports Medicine (ACSM). World Athletics, World Triathlon, the International Cycling Union and the ACSM are converting the WBGT in a coloured flag system to facilitate the interpretation of the index.

estimating the thermoregulatory response of the human body while the WBGT is characterising the environmental conditions,⁴⁶ probably leading to a better estimation of heat stress for rugby players. However, the limits of this index developed in 1956 have also been demonstrated, as the utilisation of a fixed skin temperature, the simplified heat balance calculation and the lack of consideration of evaporative efficiency of sweat.³ Of note, temperature and humidity can also be used to calculate other thermal indices as the Humidex (table 1). However, this index is only used by the International Gymnastic Association governing sports with low risk of heat stress (ie, rhythmic gymnastics, artistic gymnastics and trampoline).

More than the half of sports at risk of heat stress (8/15 sports, 53%) are currently using thermal indices that are based on the calculation of multiple parameters to assess the environmental condition. In light of the rising concerns about these indices due to their lack of specificity to the world of sport, more recent indices including human thermoregulatory mechanisms and clothing should be tested and developed, to better represent the heat stress endured by athletes.

OTHER HEAT POLICY ASPECTS

No or unspecified parameter measurement

In documentation regarding cycling mountain bike, sailing (ie, both very high risk of heat stress) or cycling BMX racing (ie, high risk of heat stress), no measurements for evaluating the environmental conditions are cited. According to IFs policies, it

is mentioned that in case of extreme weather (ie, freezing rain, snow, strong wind, extreme temperature, poor visibility and air pollution), the organising committee of the competition could meet and decide on modification or cancellation of the event. In this case, the risks' evaluation for EHI lacks quantitative and objective representation, presenting the potential for misinterpretation in strenuous situations.

Absence of heat policy

In basketball 3×3, despite a high level of heat stress (table 1), no official documentation on environmental conditions surveillance was found. It was, therefore, concluded that there is currently no heat policy for this sport (figure 1).

For sports at risk of heat stress, it is crucial to objectively assess environmental conditions to anticipate potentially fatal outcomes. This can be achieved through the use or the development of thermal indices that should be tailored to the world of sport.

HEAT POLICY PROCEDURES AND MITIGATION STRATEGIES

Among the 25 outdoor sports scheduled for Paris 2024, 14 (56%) incorporate the measurement of a thermal index into their heat policy. Table 2 summarises the measurement procedures and mitigation strategies adopted in these sports. For the majority of sports (n=11, 79%), on-site measurement of the thermal index is conducted as recommended to accurately describe the local

thermal stress.^{24–26} For cycling road, the WBGT is estimated using the Liljegren *et al* method⁴⁰ while limited information regarding procedures and mitigation strategies is available for modern pentathlon (high risk of heat stress) and canoe slalom (moderate risk). Mitigation strategies commonly include timetable adjustments to avoid the hottest part of the day and favour cooler morning or evening sessions (eg, athletics, triathlon and rowing). For intermittent activities, sports federations propose modifying work-rest ratios by adding or extending breaks (eg, hockey, football and tennis). In continuous activities, additional hydration stations (eg, athletics, triathlon and cycling road) or significant reduction of the course distance (eg, triathlon and equestrian) are implemented. On-site, the provision of cool areas is recommended by most sports, including air-conditioned rooms or tents for shade, along with the supply of ice, cold drinks, water-soaked towels and fans. In cases where environmental conditions pose critical danger, sports federations reserve the right to cancel competitions and reschedule them under safer conditions (eg, triathlon, marathon swimming and tennis).

PERSPECTIVES

The evolution of thermal indices

From solely meteorological data, thermal indices have integrated physiological parameters in the seventies, considering human thermoregulatory mechanisms and clothing.^{47–48} These 'energy balance' called indices are numerical models able to estimate heat exchanges between the organism and the environment based on human tissue layers (eg, bones, muscles and skin).³ More recently, these indices have become increasingly complex as the Universal Thermal Climate Index (UTCI)^{49–50} or the modified Physiological Equivalent Temperature (mPET).^{51–52}

UTCI has been developed by a working group of 45 scientists from 23 countries,⁵⁰ aiming to create a standard index able to represent the thermal strain of individuals in every region of the globe (computable on *Climate Chip*).⁴² A clothing model is integrated to the index to adapt the seasonal habits of population depending on the climatic conditions.⁵³ However, this model has been developed for light activity (4 km/hour) and has been trained with general population data, therefore, extrapolation for athletes' heat strain warrant further investigations.⁵⁴

To better evaluate existing indices, de Freitas and Grigorieva investigated the validity, usability, transparency, sophistication, completeness and scope of 165 indices.¹⁵ With five points allocated to each category, the indices based on a single parameter or the ones relying only on environmental factors scored the lowest while energy balance thermal indices scored the highest. In details, air temperature scored 14/30, WBGT 20/30, HSI 26/30 and UTCI 27/30.

The mPET is the updated version of the PET suggested by Höppe.⁵⁵ The PET scored 26/30 on the de Freitas and Grigorieva classification.¹⁵ The mPET was developed to estimate the thermal sensation of the population in every climate zone and incorporates a more precise division of the human tissue layers than the PET, along with a clothing model.^{51–52} Like the other energy balance thermal indices, the mPET was designed for the general population and not for athletes, therefore, its reliability in estimating the thermal strain during competition is unknown.

The appearance in the last decades of sophisticated energy balance thermal indices is promising in the representation of athletes' thermal strain and risks of EHI. Studies conducted on the general population have observed a more precise estimation of energy balance than environmental thermal

indices. Further investigations are now warranted to test the responses of these energy balance thermal indices in athletes.

Another challenge for IFs is to effectively communicate the heat stress levels to athletes and staff, once measured.³⁵ The IOC consensus statement by Racinais *et al* recommends using a five-level chart with corresponding colours to represent different levels of stress, along with mitigation strategies for each level.¹ For example, during the Australian Open Grand Slam Tennis tournament, heat stress levels are communicated to spectators and athletes via TV screens with clear and simple recommendations.⁵⁶ Similarly, World Athletics has developed an online platform that allows athletes, staff and visitors to remotely access on-site WBGT readings, displayed with a coloured flag system.⁵⁷

Technological innovation for athletes' health

Recent technological advancements have enabled the live monitoring of physiological, biomechanical, bioenergetic and environmental data during competition.^{58–59} These advancements offer the potential for comprehensive surveillance of athletes and could aid in the early recognition of EHS.^{60–61} This technological advancement is associated with the emergence of new wearables, which must undergo validation to ensure the transmission of reliable data.⁶² Moreover, the introduction of this technology brings ethical dilemmas related to the transmission of live data and the authority of the medical race director to withdraw an athlete from competition due to health considerations.⁶³

CONCLUSION

Considering the life-threatening danger that EHS represents for athletes, the impact of heat on the athletes' performance, the human resources and financial burden associated with a modification of the competition, it is strongly recommended to implement an objective measurement (ie, a thermal index) of heat danger in sports at risk. This index should effectively represent the risk of EHI in the specific activity, be easy to use on the field during competition, and understandable by all (ie, athletes, coach, staff). Among the 15 sports in the Paris 2024 Olympics programme with high, very high or extreme risks of EHI, 14 have a heat policy. For three sports, there is no specification of the measurement of parameters in their heat policy, one is relying on a single parameter, two on multiple parameters and eight on the calculation of several parameters. To anticipate the danger of heat before an event, the three following steps are, therefore, recommended: (1) adequately monitor and diagnose the number of athletes suffering from EHI and/or EHS during competitions, (2) chose and validate thermal indices that objectively represent the thermal strain of athletes in the specific activity and (3) define mitigation strategies to reduce the risks of EHI.

Correction notice This article has been corrected since it published Online First. The ORCID has been added for author Antonio Tessitore.

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Supplementary Materials

"Heat-related risk at Paris 2024: a proposal for classification and review of International Federations policies"

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Table 1: Sources of International Federations policies

Sport	International Federation	Link	Source	Date of consultation
Archery	World Archery Federation	https://rulebook.worldarchery.org/	https://www.worldarchery.org/rulebook	18/01/2024
Artistic Gymnastics	International Gymnastics Association	https://www.gymnastics.org/	FIG website > Rules > Main rules > Technical Regulations 2024	19/01/2024
Artistic Swimming	World Aquatics	https://resources.fina.org/	World Aquatics website > More > Rules > Competition regulations (version 2024)	22/01/2024
Athletics	World Athletics	https://worldathletics.org/	World Athletics website > Library > Health and Sciences > World Athletics Competition Medical Guidelines - October 2020 Second Edition	22/01/2024
Badminton	Badminton World Federation	https://extranet.bwf.org/	https://corporate.bwfbadminton.com/statutes/#1513732591524-c522d2ef-fae8	18/01/2024
Basketball	International Basketball Federation	https://www.venueg.org/	https://www.fiba.basketball/fr/equipment-and-venue	18/01/2024
Basketball 3x3	International Basketball Federation	https://fiba3x3.basketball.org/	https://fiba3x3.basketball.org/	18/01/2024
Beach Volleyball	International Volleyball Federation	https://www.fivb.co	FIVB website > Growing the game > Medical > Health information > FIVB Heat Stress Monitoring Protocol	18/01/2024
Boxing	Athlete 365 Boxing	http://boxing.athlete365.org/	https://boxing.athlete365.org/qualification-system-and-rules/	18/01/2024
Breaking	World DanceSport Federation	https://dancesport.org/	https://www.worlddancesport.org/Rule/Athlete/Competition	22/01/2024
Canoe Flatwater	International Canoe Federation	https://www.canoeicf.com/	https://www.canoeicf.com/rules	19/01/2024
Canoe Slalom	International Canoe Federation	https://www.canoeicf.com/	https://www.canoeicf.com/rules	19/01/2024
Cycling BMX Freestyle	International Cycling Union	https://assets.ctfassets.com/uci/3MyLDDrwJCJJ0BGGOFzOat	https://www.uci.org/regulations/3MyLDDrwJCJJ0BGGOFzOat	19/01/2024
Cycling BMX Racing	International Cycling Union	https://assets.ctfassets.com/uci/3MyLDDrwJCJJ0BGGOFzOat	https://www.uci.org/regulations/3MyLDDrwJCJJ0BGGOFzOat	19/01/2024
Cycling Mountain Bike	International Cycling Union	https://assets.ctfassets.com/uci/3MyLDDrwJCJJ0BGGOFzOat	https://www.uci.org/regulations/3MyLDDrwJCJJ0BGGOFzOat	19/01/2024
Cycling Road	International Cycling Union	https://www.uci.org/	https://www.uci.org/medical/5b1o3UfKP94YXGbFiUvAUa	29/02/2024
Cycling Track	International Cycling Union	https://assets.ctfassets.com/uci/3MyLDDrwJCJJ0BGGOFzOat	https://www.uci.org/regulations/3MyLDDrwJCJJ0BGGOFzOat	19/01/2024
Diving	World Aquatics	https://resources.fina.org/	World Aquatics website > Rules > CURRENT REGULATIONS > Competition regulations (version 2024)	22/01/2024
Equestrian	Fédération Equestre Internationale	https://campus.fei.org/	https://campus.fei.org/course/index.php?categoryid=61	18/01/2024
Fencing	International Fencing Federation	https://static.fie.org/	FIE > FIE Documents > Handbooks of regulation > World Championships > Handbook of regulation. Senior September 2023.	19/01/2024
Football	International Federation of Football Association	https://digitalhub.fifa.org/	FIFA.com > inside fifa > about fifa > more > Official documents > Medical > Football Emergency Medicine Manual 2nd Edition	19/01/2024
Golf	International Golf Federation	https://gsites.brightscore.org/	https://www.igfgolf.org/extreme-heat	19/01/2024
Handball	International Handball Federation	https://www.ihf.info/	IHF website > Statutes and Regulation > Competitions > "list of duties for official IHF competitions"	19/01/2024
Hockey	International Hockey Federation	https://www.fih.hockey/	FIH website > Document > "Competition policies" > FIH Inclement Weather Procedure (1) (264.2 KB)	19/01/2024
Judo	International Judo Federation	https://78884ca608	International Judo Federation website > Documents > Events Management > IJF Olympic Games Judo Requirements for Organisers - 09.10.2020 - ENG tot	19/01/2024

Marathon Swimming	World Aquatics	https://resources.fin	World Aquatics website > More > Rules > Competition regulations (version 2024)	22/01/2024
Modern Pentathlon	World Pentathlon	https://www.uipmwo	https://www.uipmworld.org/uipm-rules-and-regulations	22/01/2024
Rhythmic Gymnastics	International Gymnastics Association	https://www.gymnas	FIG website > Rules > Main rules > Technical Regulations 2024	19/01/2024
Rowing	World Rowing	https://worldrowing	https://worldrowing.com/responsibility/medical/	22/01/2024
Rugby Sevens	World Rugby	https://passport.wor	https://passport.world.rugby/player-welfare-medical/medical-protocols-for-match-day-medical-staff/heat-guidelines/	22/01/2024
Sailing	World Sailing	https://d7qh6ksdplc	https://www.sailing.org/inside-world-sailing/rules-regulations/racing-rules-of-sailing	22/01/2024
Shooting	International Shooting Sport Federation	https://www.issf-	ISSF website > Rules and Regulation > ISSF General Regulations > Annexes > Guidelines for Organizing ISSF Championships	19/01/2024
Skateboarding	World Skate	https://www.worldsk	World skate > Skateboarding > About > Regulation > "Skateboarding street and park competition rules 2022"	22/01/2024
Sport Climbing	International Federation of Sport Climbing	https://www.ifsc-	https://www.ifsc-climbing.org/index.php/world-competition/rules	19/01/2024
Surfing	International Surfing Association	https://mcuserconte	https://isasurf.org/about-isa/isa-rulebook/	19/01/2024
Swimming	World Aquatics	https://resources.fin	World Aquatics website > More > Rules > Competition regulations (version 2024)	22/01/2024
Table Tennis	International Table Tennis Federation	https://documents.it	https://documents.ittf.sport	22/01/2024
Taekwondo	World Taekwondo	http://www.worldtae	World Taekwondo website > Documents > WT Rules	22/01/2024
Tennis	International Tennis Federation	https://www.itftenni	https://www.itftennis.com/en/about-us/governance/rules-and-regulations/?type=tour-regulations#	22/01/2024
Trampoline	International Gymnastics Association	https://www.gymnas	FIG website > Rules > Main rules > Technical Regulations 2024	19/01/2024
Triathlon	World Triathlon	https://www.triathlo	https://triathlon.org/about/downloads/category/medical	22/01/2024
Volleyball	International Volleyball Federation	https://www.fivb.co	FIVB website > Volleyball > The Game > Official Volleyball rules	18/01/2024
Water Polo	World Aquatics	https://resources.fin	World Aquatics website > More > Rules > Competition regulations (version 2024)	22/01/2024
Weightlifting	International Weightlifting Federation	https://iwf.sport/wp-	IWF website > IWF/Weightlifting > Rules	22/01/2024
Wrestling	United World Wrestling	https://d3u2kdyvfax	UWW website > Governance > Regulation > Olympic wrestling > Organisation of competitions > Event preparation guide	22/01/2024

Table 2: Authors' anonymized heat stress classification

Sport	Olympic event (sex)	Venue	Author 1	Author 2	Author 3	Author 4	Author 5	Author 6	Author 7	Mean	Final Class
Archery	Individual (w/m)	Outdoor	2	1	1	2	1	2	1	1,43	1
Archery	Team (w/m/mixed)	Outdoor	2	1	1	2	1	2	1	1,43	1
Artistic Gymnastics	Individual All-Around (w/m)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	Floor exercise (w/m)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	Vault (w/m)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	Pommel horse (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	Still rings (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	Balance beam (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	High bar (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	Uneven bars (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	Parallel bars (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Gymnastics	Team (w/m)	Indoor	2	1	1	1	1	1	1	1,14	1
Artistic Swimming	Free duets (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Swimming	Technical duets (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Swimming	Final duets (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Swimming	Free teams (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Artistic Swimming	Technical teams (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Athletics	10 000m (w/m)	Outdoor	5	5	5	3	5	5	5	4,71	5
Athletics	20km Race Walk (w/m)	Outdoor	5	5	5	3	5	5	5	4,71	5
Athletics	Marathon (w/m)	Outdoor	5	5	5	4	5	5	5	4,86	5
Athletics	Marathon Race Walk mixed relay (mixed)	Outdoor	5	5	5	4	5	4	5	4,71	5
Athletics	5000m (w/m)	Outdoor	4	4	4	3	3	3	4	3,57	4
Athletics	Decathlon (m)	Outdoor	4	2	2	3	2	3	3	2,71	3
Athletics	Heptathlon (w)	Outdoor	4	2	2	3	2	3	3	2,71	3
Athletics	3000m Steeplechase (w/m)	Outdoor	3	2	2	3	3	3	3	2,71	3
Athletics	100m (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	200m (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	400m (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	800m (w/m)	Outdoor	2	1	1	2	2	2	2	1,71	2

Athletics	1,500m (w/m)	Outdoor	2	1	1	2	2	2	3	1,86	2
Athletics	100m Hurdles (w)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	110m Hurdles (m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	400m Hurdles (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	4 x 100m Relay (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	4 x 400m Relay (w/m/mixed)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	High Jump (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	Pole Vault (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	Long Jump (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	Triple Jump (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	Shot Put (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	Discus Throw (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	Hammer throw (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Athletics	Javelin throw (w/m)	Outdoor	2	1	1	2	1	2	2	1,57	2
Badminton	Singles (w/m)	Indoor	1	1	1	1	1	1	1	1,00	1
Badminton	Doubles (w/m/mixed)	Indoor	1	1	1	1	1	1	1	1,00	1
Basketball	Basketball tournament (w/m)	Indoor	1	1	1	1	1	1	2	1,14	1
Basketball 3x3	3x3 Basketball tournament (w/m)	Outdoor	3	3	3	2	1	3	3	2,57	3
Beach Volleyball	Beach volleyball tournament (w/m)	Outdoor	3	3	3	3	3	3	3	3,00	3
Cycling BMX Freestyle	BMX Freestyle (w/m)	Outdoor	3	1	2	3	1	3	3	2,29	2
Cycling BMX Racing	BMX Racing (w/m)	Outdoor	3	2	2	3	2	3	3	2,57	3
Boxing	Weight categories TBD (w/m)	Indoor	1	1	1	1	1	1	1	1,00	1
Breaking	B-girls (w)	Outdoor	1	1	1	1	1	1	1	1,00	1
Breaking	B-boys (m)	Outdoor	1	1	1	1	1	1	1	1,00	1
Canoe Slalom	Kayak single (w/m)	Outdoor	2	1	1	2	2	2	2	1,71	2
Canoe Slalom	Canoe single (w/m)	Outdoor	2	1	1	2	2	2	2	1,71	2
Canoe Slalom	Kayak cross (w/m)	Outdoor	2	1	1	3	2	2	2	1,86	2
Canoe Flatwater	Kayak Single 1000m (m)	Outdoor	2	1	1	3	2	2	3	2,00	2
Canoe Flatwater	Kayak single 500m (w)	Outdoor	2	1	1	3	2	2	2	1,86	2
Canoe Flatwater	Kayak double 500m (w/m)	Outdoor	2	1	1	3	2	2	2	1,86	2
Canoe Flatwater	Kayak four 500m (w/m)	Outdoor	2	1	1	3	2	2	2	1,86	2
Canoe Flatwater	Canoe single 1000m (m)	Outdoor	2	1	1	3	2	2	2	1,86	2
Canoe Flatwater	Canoe double 500m (w/m)	Outdoor	2	1	1	3	2	2	2	1,86	2
Canoe Flatwater	Canoe single 200m (w)	Outdoor	2	1	1	3	2	2	2	1,86	2
Cycling Track	Omnium (w/m)	Indoor	2	2	2	1	3	1	2	1,86	2
Cycling Track	Madison (w/m)	Indoor	2	2	2	1	3	1	2	1,86	2

[illegible]

Rhythmic Gymnastics	Individual all-around (w)	Indoor	1	1	1	1	1	1	1,00	1
Rhythmic Gymnastics	Group event (w)	Indoor	1	1	1	1	1	1	1,00	1
Cycling Road	Time trial (w/m)	Outdoor	5	4	4	4	5	5	4,57	5
Cycling Road	Road race (w/m)	Outdoor	4	3	4	5	4	4	4,00	4
Rowing	Single Sculls (w/m)	Outdoor	3	3	3	4	2	3	3,00	3
Rowing	Coxless Pair (w/m)	Outdoor	3	3	3	4	2	3	3,00	3
Rowing	Double Sculls (w/m)	Outdoor	3	3	3	4	2	3	3,00	3
Rowing	Coxless Four (w/m)	Outdoor	3	3	3	4	2	3	3,00	3
Rowing	Quadruple Sculls (w/m)	Outdoor	3	3	3	4	2	3	3,00	3
Rowing	Eight (w/m)	Outdoor	3	3	3	4	2	3	3,00	3
Rowing	Lightweight Double Sculls (w/m)	Outdoor	3	3	3	4	2	3	3,00	3
Rugby Sevens	Rugby sevens tournament (w/m)	Outdoor	4	4	4	4	3	3	3,71	4
Sailing	One Person Dinghy (w/m)	Outdoor	4	3	3	4	4	3	3,57	4
Sailing	Skiff (w/m)	Outdoor	4	3	3	4	4	3	3,57	4
Sailing	Mixed multihull (mixed)	Outdoor	4	3	3	4	4	3	3,57	4
Sailing	Mixed two person dinghy (mixed)	Outdoor	4	3	3	4	4	3	3,57	4
Sailing	Windsurfing (w/m)	Outdoor	4	2	3	4	3	3	3,29	3
Sailing	Kite (w/m)	Outdoor	4	3	3	4	3	3	3,29	3
Shooting	10m Air Rifle (w/m/mixed)	Indoor	1	1	1	1	1	1	1,00	1
Shooting	50m Rifle 3 Positions (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Shooting	25m Rapid Fire Pistol (m)	Indoor	1	1	1	1	1	1	1,00	1
Shooting	25m Pistol (w)	Indoor	1	1	1	1	1	1	1,00	1
Shooting	Trap (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Shooting	Skeet (w/m/mixed)	Indoor	1	1	1	1	1	1	1,00	1
Shooting	10m Air Pistol (w/m/mixed)	Indoor	1	1	1	1	1	1	1,00	1
Skateboarding	Street (w/m)	Outdoor	2	1	2	1	1	2	1,57	2
Skateboarding	Park (w/m)	Outdoor	2	1	2	2	1	2	1,71	2
Sport Climbing	Boulder & lead combined (w/m)	Outdoor	2	1	1	2	1	2	1,57	2
Sport Climbing	Speed	Outdoor	2	1	1	2	1	2	1,43	1
Surfing	Shortboard (w/m)	Outdoor	3	2	2	2	1	2	2,14	2
Swimming	1500m Freestyle (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	50m Freestyle (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	100m Freestyle (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	200m Freestyle (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	100m backstroke (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	200m backstroke (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	100m breaststroke (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	200m breaststroke (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	100m butterfly (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	200m butterfly (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	200m individual Medley (w/m)	Indoor	1	1	1	1	1	1	1,00	1
Swimming	4x100m Freestyle Relay (w/m)	Indoor	1	1	1	1	1	1	1,00	1

Swimming	4x200m Freestyle Relay (w/m)	Indoor	1	1	1	1	1	1	1,00	1	
Swimming	4x100m medley relay (w/m/mixed)	Indoor	1	1	1	1	1	1	1,00	1	
Swimming	800m Freestyle (w/m)	Indoor	1	1	1	2	1	1	1,14	1	
Swimming	400m Freestyle (w/m)	Indoor	1	1	1	2	1	1	1,14	1	
Swimming	400m individual Medley (w/m)	Indoor	1	1	1	2	1	1	1,14	1	
Table Tennis	Single (w/m)	Indoor	1	1	1	1	1	1	1,00	1	
Table Tennis	Team (w/m)	Indoor	1	1	1	1	1	1	1,00	1	
Table Tennis	Mixed doubles (mixed)	Indoor	1	1	1	1	1	1	1,00	1	
Taekwondo	-58kg (m)	Indoor	1	1	1	2	1	1	1,14	1	
Taekwondo	-68kg (m)	Indoor	1	1	1	2	1	1	1,14	1	
Taekwondo	-80kg (m)	Indoor	1	1	1	2	1	1	1,14	1	
Taekwondo	+80kg (m)	Indoor	1	1	1	2	1	1	1,14	1	
Taekwondo	-49kg (w)	Indoor	1	1	1	2	1	1	1,14	1	
Taekwondo	-57kg (w)	Indoor	1	1	1	2	1	1	1,14	1	
Taekwondo	-67kg (w)	Indoor	1	1	1	2	1	1	1,14	1	
Taekwondo	+67kg (w)	Indoor	1	1	1	2	1	1	1,14	1	
Tennis	Singles (w/m)	Outdoor	4	4	4	3	4	4	5	4,00	4
Tennis	Doubles (w/m/mixed)	Outdoor	4	2	3	3	4	4	5	3,57	4
Trampoline	Individual (w/m)	Indoor	1	1	1	1	1	1	1	1,00	1
Triathlon	Individual (w/m)	Outdoor	5	4	4	5	5	5	5	4,71	5
Triathlon	Mixed relay (mixed)	Outdoor	5	4	4	5	5	5	4	4,57	5
Volleyball	Volleyball tournament (w/m)	Indoor	1	1	1	1	1	1	1	1,00	1
Water Polo	Water polo tournament (w/m)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	49kg (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	59kg (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	71kg (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	81kg (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	+81kg (w)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	61kg (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	73kg (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	89kg (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	102kg (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Weightlifting	+102kg (m)	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Freestyle 50kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Freestyle 53kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Freestyle 57kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Freestyle 62kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Freestyle 68kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Freestyle 76kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Greco-roman 60kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Greco-roman 67kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Greco-roman 77kg	Indoor	1	1	1	1	1	1	1	1,00	1
Wrestling	Greco-roman 87kg	Indoor	1	1	1	1	1	1	1	1,00	1

[illegible]

CHAPTER 2

ASSOCIATION BETWEEN ENVIRONMENTAL,
INDIVIDUAL AND RACE-RELATED VARIABLES
WITH THERMAL STRESS IN ELITE
ENDURANCE ATHLETES

1. Overview

EHS is one of the two leading causes of death in exercising individuals, alongside sudden cardiac arrest (Yankelson et al. 2014). Overall, epidemiological data on EHS remain limited, as the condition is frequently underdiagnosed (Périard, DeGroot, and Jay 2022). This underreporting is largely attributable to the absence of rectal temperature assessment in medical facilities and insufficient training of medical personnel in EHS recognition and management (Hosokawa et al. 2021).

During mass participation running events, the incidence of EHS ranges from 0.4 to 1.3 cases per 1000 participant exposures (Breslow et al. 2021; Divine et al. 2018; Roberts 2000). In higher-risk races such as the Falmouth Road Race, characterized by strenuous environmental conditions, limited heat acclimatization, and highly motivated participants, the incidence increases to approximately 2.1 cases per 1000 exposures (DeMartini et al. 2014; Stearns et al. 2024). In other sports, EHS incidence has been reported to be as high as 4.2 cases per 1000 exposures in American football, exceeding that observed in tennis, football, or field hockey (Gamage, Fortington, and Finch 2020). However, in elite Athletics, the frequency of EHS has never been systematically reported or investigated despite elevated risks and potential severe outcomes.

Moreover, as discussed in Chapter 1, World Athletics like most IFs relies on the WBGT to prevent the risk of EHS (Bandiera et al. 2024). However, the relationship between WBGT and the frequency of EHS has never been examined in the specific context of elite Athletics. Consequently, it remains unknown whether increases in WBGT are associated with a higher incidence of EHS among elite endurance athletes.

Chapter 1 also highlighted several limitations of WBGT (Budd 2008). In particular, its accuracy is reduced under conditions of high humidity and/or low air movement (Vanos and Grundstein 2020), and it does not account for metabolic heat production or clothing of athletes, both of which are critical determinants of individual heat strain in a sporting context (Cramer et al. 2022). In recent years, more advanced “energy-balance” thermal indices such as the UTCI, the PET and the mPET have been developed and may be more suitable for the world of sport. These indices incorporate not only environmental parameters (i.e., ambient air temperature, relative humidity, radiant heat, and air movement) but also individual factors including metabolic heat production and clothing insulation. By applying thermodynamic laws for human heat storage (Cramer and Jay 2019), they estimate both heat production and heat dissipation, and have been shown to provide more reliable estimates of heat strain than indices based solely on environmental variables (De Freitas and Grigorieva 2017).

While EHS represent the most severe form of EHI, elevated thermal strain may also contribute other race-related or medical outcomes. During the 2019 World Athletics Championship in Doha (Qatar), endurance athletes who did-not-finish the race (DNF) and those admitted to the medical station regardless of cause (MED) exhibited a lower rate of skin temperature decline and a reduced core-to-skin temperature gradient (Racinais et al. 2022). These findings suggest that impaired heat dissipation and sustained thermal strain may also be associated with DNF and MED outcomes.

Overall, improving the ability to anticipate the risks of EHS, DNF and MED would facilitate optimized medical coverage during competitions and ultimately contribute to the protection the athlete health.

Accordingly, Chapter 2 examined the frequency of EHS, DNF and MED in endurance elite Athletics, as well as their associations with environmental, individual and race-related variables. In addition, the Chapter evaluated how the WBGT should be used in elite endurance competitions.

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

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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	Heat index	°C	Continuous	Collected
	Sex (female/male)		Nominal	Collected
Race-related	Age		Continuous	Collected
	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 $<21^{\circ}\text{C}$ (white flag), the EHS frequency was 2/1000

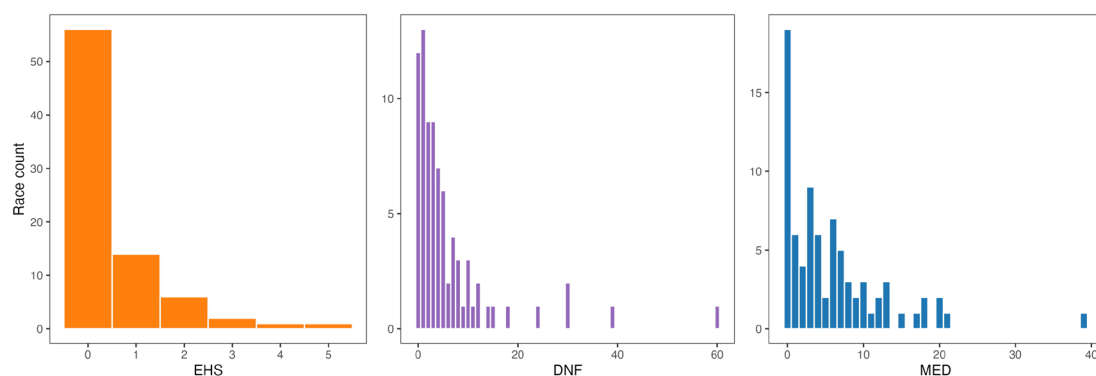


Figure 1 Histograms showing the number of athletes diagnosed with exertional heat stroke (EHS), those who did not finish (DNF) and medical encounters (MED), corresponding to athletes admitted to medical facilities regardless of cause. 80 World Athletics races are depicted, and the data for the three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

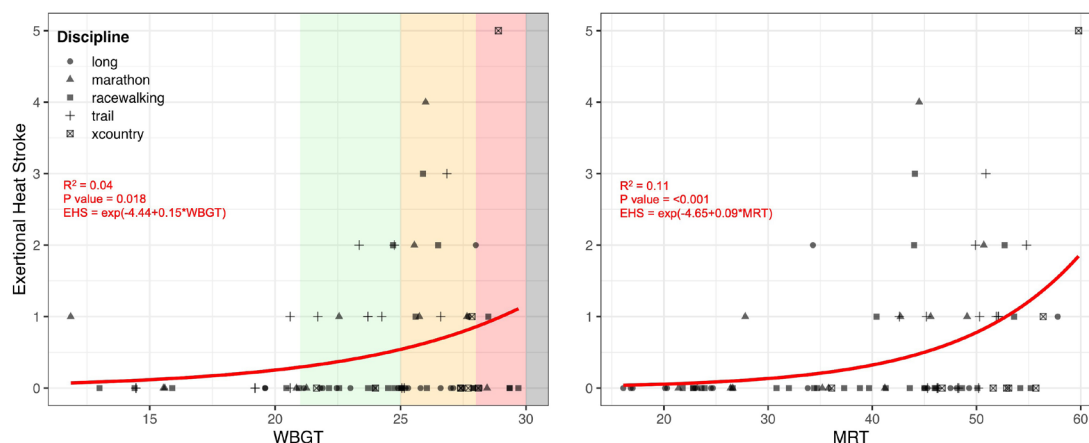


Figure 2 Association between exertional heat stroke (EHS) count and the Wet Bulb Globe Temperature (WBGT, left) or Mean Radiant Temperature (MRT, right). Among the variables retrieved, MRT demonstrates the strongest association, explaining 11% of EHS variability, while WBGT explains 4%. Red line: negative 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 ($R^2=0.41\text{--}0.91$),^{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.

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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.

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Supplementary Materials

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

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	UTCI^a - Thermal stress scale Extreme to Moderate Heat or Cold Stress or Neutral	PET^c - Thermal Comfort Scale Very Cold/Hot to Warm/Hot or Neutral	WBGT - Direct Index	mPET - Thermal Comfort Scale Very Cold/Hot to Warm/Hot or Neutral	Heat Index
Definition & Intended Use	- UTCI equivalent temperature for a given combination of wind, radiation, humidity, & Tair is defined as the air temperature of the reference environment** that produces the same strain index value.¹ - UTCI (Ta, va, pa, MRT) = Ta + Offset (Ta, va, pa, MRT) - One-dimensional; reflects the human physiologic reaction to the environment for average person² - Average population/human	- Tair at which, in a typical indoor setting^^ (without wind & radiation), the human heat balance is balanced with the same Tcore and Tsk as under complex outdoor conditions being assessed^{d5} - Average population/human	- Index creation was part of a campaign to control heat illness outbreaks in military training in South Carolina, USA⁶ - First approximation of the heat stress on a person⁷ - Often used indoors or shaded without Tg, which is not its intended use and results in inaccuracies.	- Tair at which, in a typical indoor setting^^ (without wind & radiation), the human heat balance is balanced with the same Tcore and Tsk as under complex outdoor conditions being assessed^{d5} - Average population/human and single individuals for body parameters	- The Heat Index is an index developed to represent how hot it actually “feels” to the human body when both air temperature and humidity are considered⁹. - An extension of the original Steadman’s human heat balance model was used in the present study allowing its application to a wider range of temperature and humidity¹⁰
Meteorological Inputs Allowed to vary in given models and available programs	- Tair - pa or RH - va at 10m (internally calculates 1.1m height va)² - MRT or Tg	- Tair - pa or RH - va at 1.1m - MRT	- Tair (often called ‘dry bulb’ for WBGT) - Radiation or Tg - RH or pa or Twb - va	- Tair - pa or RH - va at 1.1m - MRT	- Tair - RH
General Metabolic Rate & Activity Speed Assumptions	“Representative activity for average person”: - 2.3 METs (135 W m⁻²) - 1.1 ms⁻¹ (walking), “average” person (74kg, 1.9m²)^{1,2} - These UTCI parameters are non-modifiable **Reference conditions: MRT = Ta; va, 10m = 0.5 ms⁻¹; RH = 50% (Tair < 29 °C); pa = 20 hPa (Tair > 29 °C)	- metabolism of 80 W (light activity), added to basic metabolism equation (bMET)^e - 0 ms⁻¹ (standing still), “average” person (75kg, 1.8m) ^^Reference conditions: MRT = Ta; va, 1.5m = 0.1 ms⁻¹; pa = 12 hPa (or RH of 20% at 20°C)	METs not directly considered in equation	- Activity of 80 W (light activity as default), in addition input of activity in Watt ^^Reference conditions: MRT = Ta; va, 1.1m = 0.1 ms⁻¹; pa = 12 hPa (or RH of 20% at 20°C)	- Activity of 180 W/m² - Represents a person walking at 1.4 ms⁻¹ outdoors - Individual of 1.7 m, 67 kg - Assume wind at 2.6 ms⁻¹

Clothing Assumptions	- Estimated from empirical relationship between intrinsic clothing insulation Icl and Tair, as observed in field observations ^{3,b} (range: 0.40–2.6clo)	- 0.9 clo constant	- Standard work clothing, Icl = 0.60 ^{7,f} - Clothing adjustment values (CAV) for less/more (WBGT _{eff} = WBGT + CAV)	- 0.9 clo constant or specific clothing as input or automatically based on air temperature conditions (similar to UTCI)	- Long trousers and short-sleeved shirt - 84% clothing coverage - Clothing assumed to be 20% fiber, 80% air
Notes on Applicability	- Maximum exposure time of 2hr and constant METs impede its applicability to exercise or rest ⁴ - Input MRT cannot be higher than Tair +70°C	Stationary model	- For ‘warm’ weather ^g - WBGT values should be measured or modeled in sun, otherwise it’s just a temp-humidity metric	Modified PET (mPET) allows for clothing and activity modifications. ⁸ mPET model can be used also for instationary conditions	It is primarily used for public health guidance, weather forecasts, and heat stress warnings.

SM1: Adapted from Grundstein A, Vanos J, Br J Sports Med 2020, doi: 10.1136/bjsports-2020-102920. Commonly used thermal indices across diverse research fields—UTCI, PET, WBGT, mPET and Heat Index. Each has strengths and weaknesses based on development, and thus have strict applications due to their initial purpose/ principles. Table presents overview and intended use and important assumptions specific to human physiologic parameters. Note that the UTCI, PET and mPET are highly sophisticated models yet are purposed for application to simple situations. Because it is impossible to know the METs, clothing, and speed of thousands of individuals in a population, these indices are created for (and applicable to) the general person. Researchers state that for this purpose, it is reasonable to avoid too sophisticated details or equations. These thermal indices have therefore not been developed for athletes.

Tair: air temperature; va,x: windspeed at ‘x’ height (m); Tcore: core temperature; Tsk: skin temperature; pa: water vapor pressure; RH: relative humidity; Tmrt: mean radiant temperature; Tg: globe temperature; Twb: wet bulb temperature; Icl: intrinsic clothing insulation; BSA: body surface area.

^a The UTCI model here differs from the UTCI-Fiala multi-node thermo-physiological model validated under various metabolic rates,¹¹ which is the complex physiological model that the UTCI is derived from, yet not publicly available. Because repeatedly running the Fiala-UTCI thermoregulation model may be too time-consuming for climate simulations or weather forecasts, the publicly available form of calculating the UTCI equivalent temperatures (“fast calculation procedure”) was developed and made available for expansive use and applicability to the general population.^{2,12}

^b $I_{cl} \text{ (clo)} = 1.374 - 0.013485 \cdot T_a - 4.38 \cdot 10^{-4} \cdot T_a^2 - 2.384 \cdot 10^{-5} \cdot T_a$; empirically-derived based on: (1) typical dressing behavior (clothing amount and distribution) as a function of air temperature (from field observations); (2) changes in insulation and vapor resistance due to wind or activity speeds; (3) accounts for height of original wind observation (e.g., 10m versus 1.1m).³

^c Differs from the Munich Energy-balance Model for Individuals (MEMI), which models the thermal conditions of the human body in a physiologically relevant way.

^d Example: if someone were standing outside with moderate temperature, high humidity, high sunlight, their PET or mPET may be 40°C, which is comparable to someone being inside a room of 40°C, which would cause them to reach the same thermal state as the outdoor conditions¹³

^e Male basal metabolic equation used $bMET_{\text{Male}} = 3.45W^{0.75} \cdot (1 + 0.004(30 - \text{age}) + 0.010 \cdot (H \cdot 100 / W^{0.33}) - 43.4)$; in Hoppe (1999), the Munich energy balance model for individuals (MEMI) is applied to change activity and clothing.

^f WBGT thresholds for work:rest are modifiable based on clothing/equipment^{7,14}

^g ISO 7243 states that for accurate WBGT, the Tnwb should measure a range of 5–40 °C and the Tg should measure a range of 20–120 °C

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	Correlation		Negative binomial regression					
	Coefficient	P	Coefficient	P	Pseudo R ²	MAE	LOOCV MAE	LOOCV SDAE
EHS								
MRT	0.37	0.001	0.09	<0.001	0.11	0.58	0.60	0.69
PET	0.39	<0.001	0.09	<0.001	0.10	0.61	0.63	0.65
UTCI	0.35	0.001	0.15	<0.001	0.09	0.63	0.65	0.64
Slope (yes)	-	-	0.86	0.042	0.03	0.65	0.67	0.71
Air temperature	0.24	0.033	0.09	0.024	0.04	0.69	0.70	0.68
WBGT	0.24	0.034	0.15	0.018	0.04	0.69	0.71	0.69
Run (yes)	-	-	0.59	0.225	0.01	0.70	0.71	0.69
mPET	0.23	0.042	0.05	0.013	0.03	0.70	0.72	0.73
Average velocity	-0.11	0.324	-0.22	0.246	0.01	0.70	0.72	0.69
Relative humidity	-0.14	0.210	-0.02	0.213	0.01	0.70	0.72	0.69
Delay spring	0.11	0.347	0.00	0.265	0.01	0.71	0.73	0.69
Dewpoint	0.11	0.348	0.05	0.245	0.01	0.71	0.73	0.68
Wind	-0.05	0.656	-0.18	0.530	0.00	0.72	0.73	0.68
Age	0.02	0.864	0.01	0.893	0.00	0.72	0.74	0.69
Distance	0.03	0.770	0.00	0.744	0.00	0.72	0.74	0.68
Winner race time	-0.03	0.801	0.00	0.752	0.00	0.72	0.74	0.67
Sex (female)	-	-	0.15	0.737	0.00	0.72	0.74	0.68
Last finisher race time	-0.01	0.903	0.00	0.882	0.00	0.72	0.74	0.67
Number of starters	0.07	0.551	0.01	0.426	0.00	0.71	0.74	0.68
Absolute humidity	0.06	0.571	0.03	0.456	0.00	0.72	0.74	0.68
HI	0.15	0.184	0.05	0.049	0.02	0.73	0.77	0.79

SM2: Association between variables retrieved from Athletics races and the number of athletes diagnosed with exertional heat stroke (EHS). Linear (Pearson correlation) and non-linear (negative binomial regression) analysis were performed, and the predictive ability of variables were investigated with a leave-one-out cross-validation (LOOCV). Variables are ranked by lowest mean absolute error from cross validation (LOOCV MAE).

R²: McFadden's R², indicating the proportion of variance in the outcome explained by each variable for count regression models; MAE: Mean Absolute Error, LOOCV MAE: MAE from LOOCV; LOOCV SDAE: standard deviation of absolute error from LOOCV.

	Correlation		Negative binomial regression					
	Coefficient	P	Coefficient	P	Pseudo R ²	MAE	LOOCV MAE	LOOCV SDAE
DNF								
Age	0.48	<0.001	0.15	<0.001	0.08	4.25	4.39	6.70
Distance	0.69	<0.001	0.05	<0.001	0.14	4.08	4.47	9.42
Number of starters	0.51	<0.001	0.02	<0.001	0.07	4.95	5.19	7.30
Average velocity	-0.26	0,02	-0.37	0.001	0.02	5.33	5.51	7.57
Absolute humidity	0.09	0,425	0.02	0.478	0.00	5.50	5.64	7.73
Dewpoint	0.04	0,708	0.01	0.738	0.00	5.54	5.67	7.75
Wind	-0.09	0,437	-0.17	0.300	0.00	5.55	5.68	7.66
Relative humidity	0.17	0,127	0.02	0.013	0.01	5.56	5.70	7.57
Sex (female)	-	-	-0.05	0.857	0.00	5.56	5.70	7.72
UTCI	0.01	0,953	0.00	0.922	0.00	5.57	5.70	7.65
PET	-0.01	0,929	0.00	0.868	0.00	5.57	5.71	7.62
MRT	0.05	0,646	0.01	0.500	0.00	5.58	5.72	7.66
HI	-0.04	0,693	-0.01	0.717	0.00	5.59	5.72	7.73
Slope (yes)	-	-	0.35	0.215	0.00	5.59	5.74	7.68
Run (yes)	-	-	0.44	0.134	0.01	5.64	5.77	7.52
Delay spring	-0.09	0,426	0.00	0.224	0.00	5.64	5.78	7.60
mPET	-0.18	0,101	-0.04	0.005	0.01	5.61	5.79	7.68
Air temperature	-0.14	0,228	-0.03	0.121	0.01	5.63	5.80	7.67
Last finisher race time	0.57	<0.001	0.00	<0.001	0.06	4.90	5.83	13.66
WBGT	-0.21	0.07	-0.05	0.136	0.01	5.67	5.84	7.68
Winner race time	0.68	<0.001	0.01	<0.001	0.08	5.15	6.65	17.39

SM3: Association between variables retrieved from Athletics races and the number of athletes who did not finish the race (DNF). Linear (Pearson correlation) and non-linear (negative binomial regression) analysis were performed, and the predictive ability of variables were investigated with a leave-one-out cross-validation (LOOCV). Variables are ranked by lowest mean absolute error from cross validation (LOOCV MAE).

R²: McFadden's R², indicating the proportion of variance in the outcome explained by each variable for count regression models; MAE: Mean Absolute Error, LOOCV MAE: MAE from LOOCV; LOOCV SDAE: standard deviation of absolute error from LOOCV.

	Correlation		Negative binomial regression					
	Coefficient	P	Coefficient	P	Pseudo R ²	MAE	LOOCV MAE	LOOCV SDAE
MED								
Age	0.47	<0.001	0.01	<0.001	0.03	3.92	4.01	4.25
Average velocity	-0.37	0.001	-0.46	<0.001	0.03	4.03	4.14	4.82
Slope (yes)	-	-	0.46	0.098	0.01	4.52	4.64	4.80
Distance	0.64	<0.001	0.04	<0.001	0.07	4.34	4.70	7.70
MRT	0.13	0.261	0.01	0.245	0.00	4.68	4.81	4.82
Run (yes)	-	-	0.57	0.047	0.01	4.71	4.82	4.57
PET	0.12	0.278	0.02	0.175	0.00	4.77	4.88	4.67
UTCI	0.16	0.160	0.04	0.102	0.01	4.79	4.89	4.61
Wind	-0.12	0.277	-0.19	0.243	0.00	4.80	4.92	4.67
Delay spring	0.05	0.688	0.00	0.650	0.00	4.81	4.93	4.68
Dewpoint	0.22	0.050	0.04	0.142	0.01	4.82	4.94	4.51
Air temperature	0.01	0.939	0.00	0.931	0.00	4.82	4.94	4.69
Absolute humidity	0.26	0.020	0.05	0.087	0.01	4.81	4.94	4.48
Sex (female)	-	-	0.19	0.490	0.00	4.83	4.96	4.66
HI	0.12	0.284	0.02	0.366	0.00	4.86	4.99	4.69
mPET	-0.15	0.188	-0.03	0.045	0.01	4.84	5.01	4.73
Relative humidity	0.18	0.106	0.01	0.077	0.01	4.90	5.02	4.50
WBGT	0.02	0.858	0.01	0.880	0.00	4.90	5.02	4.74
Number of starters	0.49	<0.001	0.02	<0.001	0.05	4.81	5.15	7.19
Last finisher race time	0.51	<0.001	0.00	<0.001	0.04	4.98	5.97	11.12
Winner race time	0.52	<0.001	0.01	<0.001	0.04	5.31	6.90	20.18

SM4: Association between variables retrieved from Athletics races and medical encounters (MED). Linear (Pearson correlation) and non-linear (negative binomial regression) analysis were performed, and the predictive ability of variables were investigated with a leave-one-out cross-validation (LOOCV). Variables are ranked by lowest mean absolute error from cross validation (LOOCV MAE).

R²: McFadden's R², indicating the proportion of variance in the outcome explained by each variable for count regression models; MAE: Mean Absolute Error, LOOCV MAE: MAE from LOOCV; LOOCV SDAE: standard deviation of absolute error from LOOCV.

CHAPTER 3

VALIDATION OF A WEARABLE SENSOR FOR
CONTINUOUS SWEAT SODIUM
CONCENTRATION AND SWEAT LOSS
ESTIMATION DURING EXERCISE

1. Overview

Although elite athletes often have a high capacity to tolerate heat accumulation enabling them to manage intense efforts, high-stakes competitions force them to make compromises, with performance taking precedence over optimal thermoregulation. Indeed, competitive events are situations in which thermoregulatory function is pushed to its physiological limits and where the risk of EHS is particularly high (Périard, DeGroot, and Jay 2022; Racinais et al. 2022). In such conditions, evaporative heat loss through eccrine sweat secretion represents the most effective autonomic thermoregulatory mechanism to dissipate heat (Cramer et al. 2022). Therefore, improving our understanding of whole body sweat loss (WBSL) under real competitive conditions could help appreciate EHS in elite athletes. In this context, wearable sensors offer a major advantage, as they enable continuous physiological monitoring without disrupting athletes' routines before, during, or after competition (Guppy et al. 2023).

As found in Chapter 2, energy-balance thermal indices are only weakly associated with EHS risk in elite athletes, likely because they were originally developed for use in the general population (Bandiera et al. 2026). Specifically, these indices typically assume an activity level equivalent to walking outdoors at approximately 4 km/h, which is substantially lower than the metabolic demands of endurance athletes competing at speeds exceeding 20 km/h (Havenith and Fiala 2015). Consequently, the magnitude and dynamics of heat dissipation differ markedly between the general population and elite athletes. Accurate measurement of sweat rate kinetics in elite athletes during competition would allow these models to be informed by athlete-specific data (Grundstein and Vanos 2021), thereby improving the estimation of heat dissipation capacity. Such data could contribute to the development and validation of energy-balance thermal indices tailored to athletic populations.

Beyond these points, characterising the kinetics of water and sodium losses is important for athlete education and safety due to large interindividual variabilities (Baker 2017, Galan-Lopez et al. 2023; Racinais et al. 2021). Knowledge of individual sweat rate and sweat sodium concentration informs hydration strategies, including when to drink, how much fluid to ingest, and the appropriate sodium content of electrolyte solutions (Shirreffs and Sawka 2011). This is critical to avoid both excessive fluid intake, which may lead to hypervolemic hyponatremia, and insufficient intake, resulting in dehydration (Hoffman and Stuempfle 2015; Montain, Chevront, and Sawka 2006). Accounting for both water and sodium losses is therefore necessary to optimize replacement strategies during competition (McDermott et al. 2017).

Accordingly, Chapter 3 aimed to validate an innovative wearable sensor designed for real-time measurement of WBSL and sweat $[\text{Na}^+]$.

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Sweat sodium composition and sweat loss estimation through wearable sensors and predictive equations in dry and humid hot conditions

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Introduction: Individualized sweat testing is essential for tailoring hydration and nutrition strategies, as water and sodium losses during exercise vary greatly across athletes. The validity of a wearable sweat sensor (S1, Flowbio) and a handheld analyzer (LAQUAtwin, Horiba Advanced Techno) for measuring sweat sodium concentration ($[Na^+]$) was tested against flame photometry (FP). Additionally, whole body sweat loss (WBSL) estimated by the S1 and by a sweat rate calculator (SRC) was compared to the scale-based method.

Methods: Twenty-three recreationally active participants (11 males, 12 females) completed two sessions in hot and dry (40 °C, 36% rh) and hot and humid (30 °C, 81% rh) controlled environmental conditions on a cycling ergometer (74 ± 12 min, 1.9 ± 0.4 W/kg). Participants were instrumented with two S1 sensors and absorbent patches placed on each upper arm. Sweat was extracted from patches to measure $[Na^+]$ with LAQUAtwin and FP. Nude body mass was measured to the nearest 0.005 kg before and after exercise, with fluid intake monitored to determine WBSL. The influence of the method and the condition on the measure of sweat $[Na^+]$ and WBSL was investigated with linear mixed-effects models.

Results: The estimated marginal means of sweat $[Na^+]$ in dry conditions for S1 and LAQUAtwin were equivalent (both 53 mmol/L, $p = 0.952$) and significantly lower than FP (63 mmol, both -10 mmol, $p < 0.001$). No significant interaction effects were observed between methods and conditions. For WBSL, the S1 estimation (1.479 kg) was not different than the scale measure (1.432 kg, 0.047, $p = 0.624$) while the SRC estimation (1.202 kg) was significantly lower than the scale and S1 (both $p < 0.001$), without interactions effects.

Conclusion: S1 offers equivalent and more practical collection of sweat $[Na^+]$ compared to the LAQUAtwin during indoor cycling ergometer exercise. However, measurements from both devices should currently be interpreted

with caution and not considered equivalent to laboratory-grade analyses. Furthermore, S1 is an adequate tool during indoor cycling ergometer exercise to estimate WBSL when scale measurements are impractical, while SRC was found to underestimate fluid loss.

KEYWORDS

electrolytes, flame photometer (FP), fluid loss, hydration, recovery, sweating, thermoregulation, whole body sweat rate

Introduction

During exercise, particularly in hot conditions, sweat production occurs as part of the body's thermoregulatory response to counteract rising core temperature (Périard et al., 2021). Sweating results in the loss of both water and electrolytes, with sodium being of particular importance due to its role as the primary extracellular osmolyte (Baker and Wolfe, 2020; Shirreffs and Sawka, 2011). To maintain homeostasis, it is recommended to replenish water and sodium during and after exercise (Pohl et al., 2013; Sawka et al., 2007). As water and sweat sodium losses exhibit significant variability among athletes and exercise intensity (Baker et al., 2016), individualized sweat testing is valuable in formulating tailored hydration and nutrition plans (Sawka et al., 2007; Belval et al., 2019; McDermott et al., 2017).

The gold standard technique for quantifying whole-body electrolyte loss is the whole-body washdown method (Shirreffs and Maughan, 1997). However, it requires a cumbersome protocol in a controlled laboratory environment, with restricted exercise modalities (Baker, 2017). Thus, regional sweat collection using patches presents a more practical approach for field studies to gather sweat samples during exercise (Baker, 2017). However, the patch method for measuring sweat sodium concentration ($[Na^+]$) has limitations, primarily due to the volume of sweat that needs to be collected. Indeed, sufficient quantities are required for analyses and, depending on the body region, environmental conditions and individual sweat rate, a minimum of ~15 min after the onset of sweating may be required to collect an adequate sample (Baker et al., 2018). Conversely, leaving the patch on for too long can lead to hidromeiosis or patch saturation, making the measurement invalid (Baker, 2017; Kelly et al., 2016). To ensure reliable results, the patch must be removed from the skin at the optimal time, when it contains an adequate amount of sweat but is not saturated (aiming for ~0.5–0.7 g for a 5 × 7 cm Tegaderm patch) (Baker et al., 2020). Managing absorbent patch collection on the field can be challenging and requires training to perform high-quality analyses, making implementation difficult for coaches or athletes.

In addition, estimating sweat $[Na^+]$ typically requires a laboratory analyzer after sweat collection, which provides an average concentration over a set period but does not capture time-related variation. This process requires time and expertise, as it involves transporting sweat samples to the lab, storing samples, performing dilutions, and calibrating the analyzer.

Alternatively, a portable sodium analyzer can be used on-site to measure $[Na^+]$ directly from the sweat collected, making the process more convenient with a measurement bias of $-2 \pm 6\%$ (Brown et al., 2024; Goulet et al., 2017). Another option is the Gx Sweat Patch, a thin-film microfluidic patch applied to the

forearm that channels sweat into enclosed microtubes, with results accessible via a smartphone app (Baker and Wolfe, 2022). However, its sodium estimates are derived from sweat chloride (mean absolute percent error–MAPE, 5%), which itself is predicted with a MAPE of 15%, ultimately limiting accuracy. Moreover, these approaches require consumable materials and do not provide real-time data. Therefore, there is a need for a valid, reusable, and user-friendly sweat sensor capable of continuously measuring sweat $[Na^+]$. Such a device would not only facilitate more responsive hydration strategies during prolonged exercise but also enable the investigation of sweat $[Na^+]$ kinetics throughout exercise, an aspect that current methods cannot capture.

Also, measuring whole body sweat loss (WBSL) is essential to accurately assess sweat sodium and body water loss. It is well-known that maintaining proper hydration during exercise is essential for optimal performance (Sawka et al., 2007; Racinais et al., 2023). Dehydration can elevate core temperature due to reduced sweating and vasoconstriction of skin vessels, increasing the risk of both performance decline and heat-related illnesses (Périard et al., 2021; Bandiera et al., 2024; Casa et al., 2015). Conversely, overhydration without adequate electrolyte intake can lead to hyponatremia (Périard et al., 2021; Hoffman and Stuemfle, 2015; Montain et al., 2006). WBSL measurement is generally based on nude body mass measurements taken both before and after exercise using a digital scale with a precision of at least 0.1 kg (Cheuvront and Kenefick, 2017), along with tracking fluid intake, fluid loss, urine output, food intake, and nonsweat losses. However, this protocol can be cumbersome and impractical in certain scenarios. Consequently, online sweat rate calculator tools have emerged that estimate fluid loss based on standard variables (e.g., power output, body size, mass, environmental conditions) (Jay et al., 2024a; Jay et al., 2024b; Saltivate, 2024). However, the validity of these tools needs to be established to ensure accurate hydration planning.

Hence, the aim of this study was to test the validity of a continuous wearable sweat sensor for regional sweat $[Na^+]$ and whole body sweat loss estimation against reference methods in dry and humid hot conditions. The accuracy of the wearable sensor and a field standard handheld analyzer for sweat $[Na^+]$ was compared to the laboratory gold standard flame photometry analysis (Baker, 2017). Estimations of WBSL from the wearable sensor and from the proposed sweat rate calculator was compared to the gold standard scale method with a 0.005 kg resolution (Cheuvront and Kenefick, 2017). As per previous research, we hypothesized that the LAQUATwin and the sweat rate calculator would lead similar results to FP and the scale-based method, respectively, whereas S1 study was exploratory.

Materials and methods

Participants

Twenty-three participants (11 males and 12 females) volunteered in this study. Participants were recreationally active adults with a mean age of 26.8 ± 7.2 years, a size of 173 ± 9 cm, and a mass of 66.3 ± 9.4 kg. The experimental protocol took place in May and June (i.e., northern hemisphere, end of spring/early summer in Montpellier, France), therefore participants were assumed to be partially heat acclimatized. Of note, the menstrual cycle of the female participants was not controlled, as it was not expected to affect the comparison between devices. All participants gave written informed consent before taking part in the study, which received approval from the University of Montpellier Research Ethics Committee (2023-023) and adhered to the principles of the Declaration of Helsinki.

A power analysis was conducted for the primary comparison (difference in sweat sodium concentration between FP and the S1 device). Assuming a two-sided $\alpha = 0.05$, 80% power, a minimum detectable mean difference of 150 mg/L (6.5 mmol/L) and an expected standard deviation of the differences of 250 mg/L (11 mmol/L), the required sample size was 22 participants. The sample of 23 participants thus provided adequate statistical power.

Experimental design

In a randomized order, participants completed two experimental trials in an environmental chamber at the same time of the day with minimum 24 h of rest in between: one in hot and dry conditions ($39.9^\circ\text{C} \pm 0.3^\circ\text{C}$, $36\% \pm 3\%$ relative humidity, rh) and one in hot and humid conditions ($30.1^\circ\text{C} \pm 0.2^\circ\text{C}$, $81\% \pm 1\%$ rh), both with a simulated front wind at 2 m/s. Participants cycled on an ergometer equipped with a power output sensor (Wattbike Pro, Nottingham, United Kingdom) at an intensity corresponding to 80% of their age-predicted maximal heart rate ($220 - \text{age}$), monitored using a H10 chest strap (Polar, Kempele, Finland). The aim was to induce enough sweat over the session to enable the collection of two consecutive patches from each upper arm, with a maximum duration of 95 min (i.e., inducing variations in intensity and time depending on environmental conditions). Also, to ensure a safe exercise progression in hot conditions, skin temperature was measured via iButton hygrochron sensors (Analog Devices, Wilmington, United States) placed on the left lower arm, chest (under the left part of the chest band) and left anterior thigh (Kavitkar and Mehta, 2022), and intestinal temperature was measured via an ingestible pill (e-Celsius, BodyCap, Caen, France) taken 6 h prior the trial (Mougin et al., 2025). A summary of the experimental protocol is found on Figure 1.

Regional sweat collection

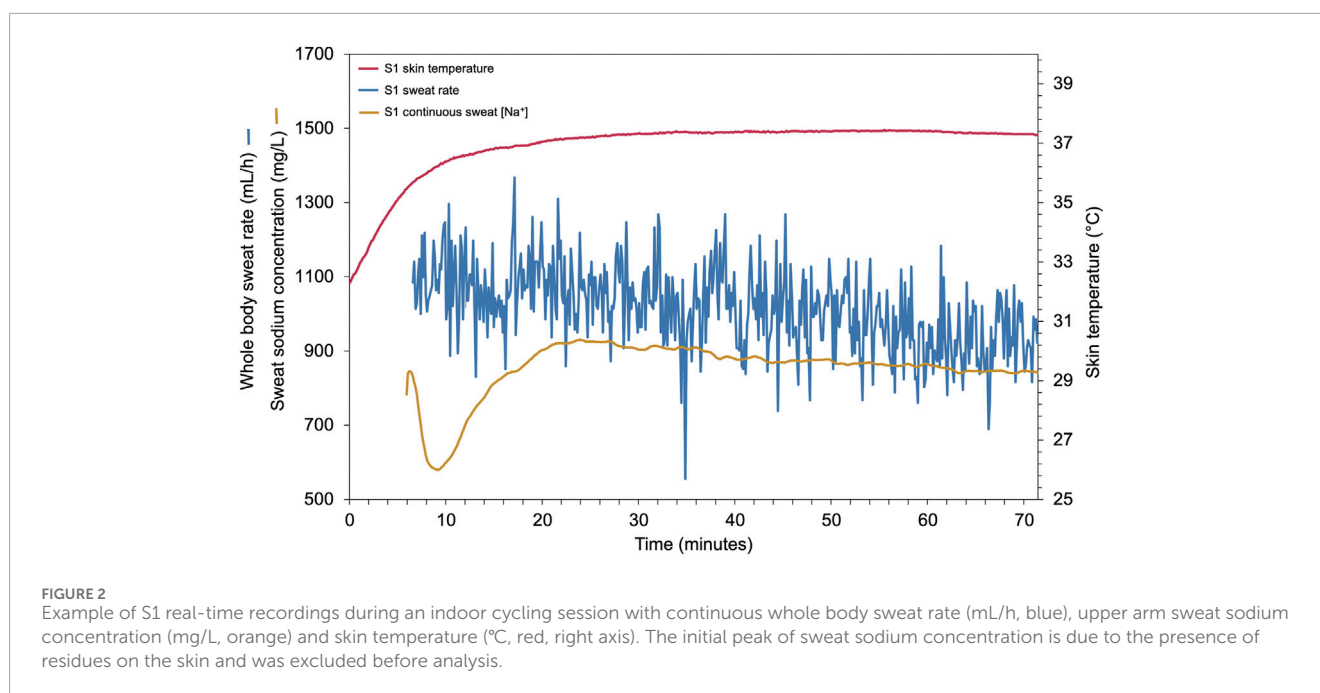
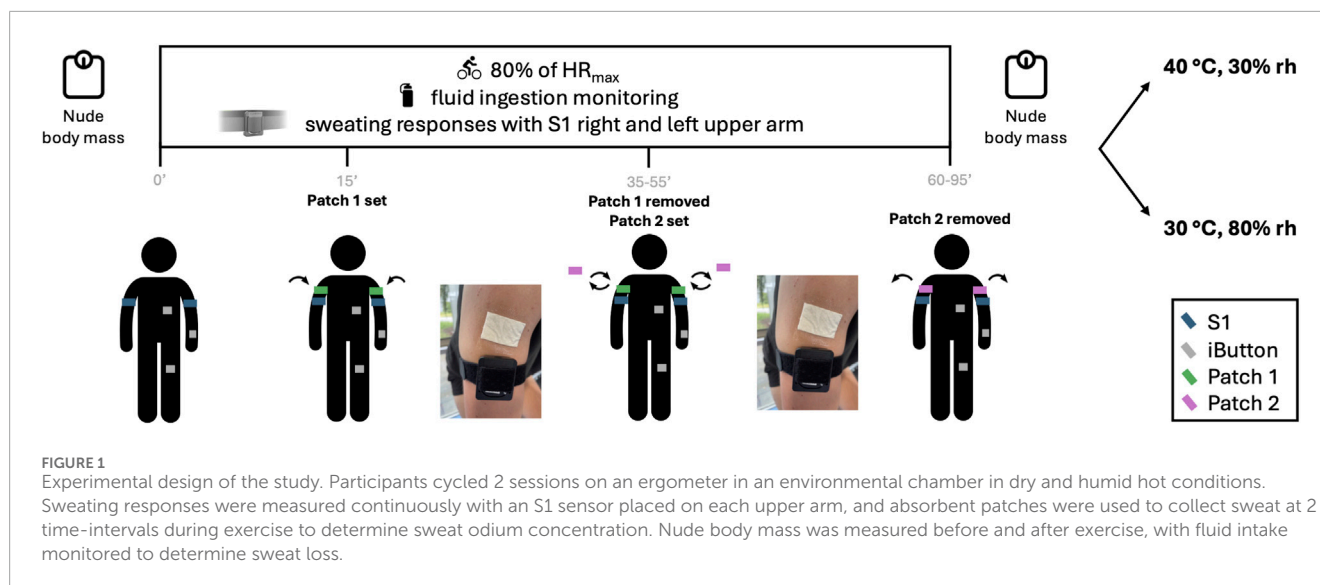
Sweat collection was conducted using the absorbent patch method with 5×7 cm Tegaderm + Pad (3M, St. Paul, United States) (Baker, 2017). The absorbent patches were applied to the lateral

side of both upper arms after 15 min of exercise. This timing was selected to prevent the collection of initial sweat produced during the gradual transition to steady-state sweating (Baker and Wolfe, 2020; Baker et al., 2020), while also ensuring minimal time for the collection of a sufficient sample volume and comparison with the S1 continuous measure. Prior to patch application, the skin was cleaned with deionized water and dried using sterile gauze (Hartmann, Heidenheim an der Brenz, Germany). Patches were removed upon moderate sweat absorption (aiming for $\sim 0.5\text{--}0.7$ g) but before saturation as determined by visual inspection (Baker et al., 2020), with the aim to collect 2 consecutive patches on each arm for each trial. Upon removal of the patch, the absorbent pad was immediately separated from the adhesive dressing using clean forceps and placed in a sterile 10 mL syringe (BD, Franklin Lakes, United States) to extract the sweat from the pad in an air-tight plastic tube (Eppendorf, Hamburg, Germany). The syringe containing the squeezed patch, the plastic tube with the extracted sweat, and the adhesive dressing were weighed on a precision balance to the nearest 0.0001 g (Ohaus corporation, Parsippany, United States) calibrated a week before the experiment (Balco, Saint-Mathieu-de-Tréviers, France) to calculate the mass of the patch prior to extraction (i.e., by subtracting the mass of the syringe and plastic tube). The patch was considered saturated, and the sweat sample deemed unreliable, if its mass exceeded 1.4000 g: 0.7 g of sweat + 0.7 g for the mass of a clean patch.

S1 wearable

The S1 (Flowbio, London, United Kingdom) is a wearable ($42.6 \times 50.6 \times 13.8$ mm, 18 g), reusable electrochemical sensor that uses microfluidics to capture sweat from the skin (Supplementary Material 1). The internal volume is inferior to 2 μL , providing capture times (from sweating to sensor reading) of less than 3 min. The S1 employs a conductometric sensor to measure sodium concentration in sweat. A skin temperature sensor is present on the device, as well as an internal humidity and temperature sensor. WBSL is determined by a proprietary algorithm from a combination of physically acquired metrics (heart rate, skin temperature, intensity, accelerometry) and ambient parameters (temperature, humidity). $[\text{Na}^+]$, WBSL and skin temperature are measured and recorded in real-time with a time interval set to 4 s (Figure 2).

S1 devices were fastened with a strap on both cleaned upper arms below the deltoid tuberosity on a flat surface allowing full contact between the sensor and the skin. The sensors were started few minutes before pedaling and were stopped at the end of the exercise. For comparing $[\text{Na}^+]$ of the S1 (continuous reading) with the FP and LAQUAtwin (2 reading per upper arm corresponding to the 2 patches), the average $[\text{Na}^+]$ measured by the S1 was calculated over the time-interval during which the patches remained on the skin. Two $[\text{Na}^+]$ segments of the S1 corresponding to the two time-intervals were extracted and averaged, resulting in two sweat $[\text{Na}^+]$ values per S1. Before further analysis, each segment was observed individually to check for operating errors: lack of values for several minutes, sudden non-physiological drop of sweat $[\text{Na}^+]$, important noise. These irregularities were often caused by sensor movement on the skin, allowing the introduction



of an air bubble between the skin and the sensor. For WBSL estimation, the S1 was paired with a Garmin Forerunner 255 watch (Garmin, Olathe, United States). WBSL was afterward corrected for nonsweat loss estimated at 0.20 g/kcal (Cheuvront and Kenefick, 2017), with energy expenditure (kcal) estimated from the watch. For subsequent analysis, the WBSL of the entire session was extracted and compared with the reference scale method.

Finally, the comfort of the sensor was assessed at the end of each session. Participants completed a visual analog scale (VAS) ranging from “The sensor did not bother me at all during the exercise” to “The sensor bothered me a lot during the exercise”. The VAS was 10 cm long, with higher values indicating greater discomfort.

LAQUAtwin Na-11 portable device

The portable sodium analyzer LAQUAtwin-Na-11 (Horiba Advanced Techno, Kyoto, Japan) was employed as a “field standard” to assess sweat $[Na^+]$. Sweat samples were analyzed in temperate environments with the LAQUAtwin just after sweat extraction from the patch. Prior to each session, the device was calibrated following the manufacturer’s guidelines. After switching on the device, it was rinsed with deionized water and dried using gauze, and a two-point calibration was conducted using 150 ppm and 2000 ppm standards. Between each sample analysis, the sensor was cleaned with deionized water and dried with a gauze. For each analysis, the plastic tube containing the sweat was shaken to ensure a homogeneous sample. A drop of sweat was then collected with a micropipette (Gilson,

Middleton, United States) and placed on the LAQUAtwin sensor. This process was repeated three times (triplicates), and the average $[\text{Na}^+]$ was recorded in mg/L. The calculation of a coefficient of variation for each sample was performed. Because sodium was present in the collection materials (e.g., patch, syringe, plastic tube), background sodium was quantified by running deionized water through the entire protocol five times (Baker et al., 2018). This procedure yielded a residual sodium concentration of 103 ± 7 mg/L (4.5 ± 0.3 mmol/L), which was subsequently subtracted from all LAQUAtwin measurements.

Flame Photometry

The analytical reference assay method used for sodium quantification was flame atomic emission spectrometry (FP) (Baker, 2017). Errors mainly caused by variations in instrumental parameters and/or matrix effects that may impair accuracy and/or precision were evaluated and considered in the results obtained. The absence of matrix effects was verified, and the external calibration method was adopted. A calibration range was prepared using an appropriate standard solution dilution of 1000 mg/L. The solutions were diluted in a mixture of water for analysis, 1% dilute nitric acid to increase atomization of sodium and cesium to attenuate instrumental interference (buffer ionization) into the flame. The emission intensities from sodium (I^{Na}) were measured 3 consecutive times (triplicates) at 586.9 nm, and the average $[\text{Na}^+]$ was recorded in mg/L. The calculation of a coefficient of variation for each sample was performed. External standard calibration curves were used by plotting I^{Na} versus $[\text{Na}^+]$ for analytical solutions in the 0.25–1.5 mg/L range. When the I^{Na} of the sweat samples was outside of the range of calibration, samples were excluded. Also, several three-level quality control (QC) samples were prepared and analyzed using the calibration line to ensure the accuracy of the assay method. If the mean difference between the I^{Na} of the QC samples and their expected value exceeded 10% of the I^{Na} of the sweat samples, the samples were excluded from the analysis. Finally, to exclude sodium present in the collection materials, the background sodium in the FP protocol was calculated to be 94 ± 5 mg/L (4.1 ± 0.2 mmol/L), this value was therefore subtracted from the FP measurement (Baker et al., 2018).

Scale-based method for WBSL

WBSL was determined by assessing the change in pre-to post-exercise nude body mass, corrected for fluid intake and nonsweat loss, as: mass pre (kg) + fluid ingested (L) - mass post (kg) - nonsweat loss (L), with the reasonable assumption that 1 L of sweat = 1 L of water = 1 kg. Nonsweat sodium loss was estimated at 0.20 g/kcal (Cheuvront and Kenefick, 2017), with energy expenditure derived from the watch, consistent with the S1 method. As a reference method, nude body mass was measured both before and after exercise using a digital scale with a resolution of 0.005 kg and a linearity of ± 0.015 g (Kern & Sohn GmbH, Balingen, Germany), and participants towel dried prior to each measurement (Cheuvront and Kenefick, 2017). During the exercise, participants were not allowed

to go to the toilet, to evacuate saliva, nor eat any food. To minimize the risk of hypohydration, participants were allowed to consume water *ad libitum* during the experimental sessions. Water bottle mass from pre-to post-exercise was measured with a resolution of 0.001 kg using a compact digital scale (Terraillon, Croissy sur Seine, France) to calculate fluid intake.

Sweat rate calculator

WBSL was also estimated with an online sweat rate calculator (SRC) developed by Jay et al., in 2024 (Jay et al., 2024b) (<https://sweatratecalculator.com/hydration-calculator>). This calculator allows to estimate the sweat rate for an indoor cycling exercise from a combination of metrics: body height, body mass, air temperature, air humidity, wind speed, power output and duration of the exercise. It is a tool easily accessible online, with a validity of 0.01 L/h, with 95% confidence interval comprised between -0.22 L/h and 0.25 L/h (Jay et al., 2024b).

Statistics

First, the differences in exercise responses between the dry and humid conditions were investigated, including exercise duration, average heart rate, average power output and average core and skin temperature. Depending on data distribution assessed by a Shapiro-Wilk test, a Student's t-test (t, parametric) or Wilcoxon test (W, non-parametric), was respectively performed to investigate paired differences between conditions. In addition, exploratory Pearson correlation analyses were performed to examine potential associations between the average intestinal temperature, regional sweat $[\text{Na}^+]$ (average of the exercise measured with FP) and WBSL (scale-based method).

The validity of the S1 and the LAQUAtwin were evaluated against the FP, and for WBSL, S1 and SRC were compared to the scale-based method. To detect differences between methods and environmental conditions (dry and humid), a linear mixed-effects model was fitted using method and condition as fixed effects, and participant as a random factor. This structure accounted for repeated measures within participants and unbalanced data. Pairwise comparisons were adjusted using the Tukey method. In addition, Bland-Altman plots were performed for graphical agreement assessment, pooling both environmental conditions together (Bland and Altman, 1986). The mean bias (paired systematic difference) and the 95% limits of agreement (LOA = bias ± 1.96 standard deviation of the differences) were calculated for all comparisons. The concordance correlation coefficient (CCC) was also calculated between compared methods (Lawrence, 1989).

All statistics were conducted in R statistical software (version 4.4.1) (R Core Team, 2024). Values for sweat $[\text{Na}^+]$ were converted from mg/L to mmol/L by dividing by the atomic mass of sodium (22.989769 g/mol). Data were presented in mean $\pm$ standard deviation apart for the results of the linear mixed-effects model reported in estimated marginal means $\pm$ standard error. The level of significance was set at $p < 0.05$.

TABLE 1 Exercise responses comparison in dry (40 °C and 36%) and humid (30 °C and 81%) hot conditions. Statistic refers to the test value obtained from either a paired Student's t-test (t: parametric) or a Wilcoxon signed-rank test (W: non-parametric), depending on data distribution. Values are expressed in mean $\pm$ standard deviation.

Parameter	Dry	Humid	Difference	Statistic	P-value
Duration (min)	75 $\pm$ 13	72 $\pm$ 11	3 $\pm$ 10	t = 0.7	0.467
Heart rate (bpm)	157 $\pm$ 9	158 $\pm$ 9	-1 $\pm$ 6	t = -0.4	0.662
Power output (W)	126 $\pm$ 30	133 $\pm$ 32	-7 $\pm$ 10	t = -0.7	0.510
Average core temp (°C)	38.4 $\pm$ 0.3	38.3 $\pm$ 0.4	0.1 $\pm$ 0.4	W = 117	0.972
Average skin temp (°C)	36.5 $\pm$ 0.5	35.3 $\pm$ 0.6	1.2 $\pm$ 0.7	t = 7.2	<0.001

Results

Exercise responses

Exercise responses in dry and humid hot conditions are presented in **Table 1**. In dry condition, exercise duration (75 $\pm$ 13 min), average heart rate (157 $\pm$ 9 bpm), average power output (126 $\pm$ 30 W), and average core temperature (38.4 °C $\pm$ 0.3 °C) were similar to humid condition (non-significant differences). In contrast, average skin temperature was significantly higher in dry (36.5 °C $\pm$ 0.5 °C) compared to humid condition (35.3 °C $\pm$ 0.6 °C, $p < 0.001$).

Exploratory correlation analyses revealed no significant associations between markers of heat strain and indices of fluid or sodium loss. Specifically, regional sweat [Na⁺] ($r = 0.09$, $p = 0.58$) and WBSL ($r = -0.23$, $p = 0.13$) were not correlated with average intestinal temperature. Similarly, regional sweat [Na⁺] and WBSL were not significantly correlated ($r = 0.11$, $p = 0.51$).

Sample exclusion and sensor operation

In total, 23 participants completed two cycling sessions, during which sweat composition was analyzed twice on each upper arm (23*2*2 = 184), for a target of 184 samples (for LAQUAtwin and FP) and 184 sessions (for S1). Forty-four samples were excluded from FP analysis and 22 for LAQUAtwin, due to not enough sweat being extracted from the patch, the patch being saturated, or the measure being considered not valid (details in **Figure 3**). For S1, 16 sessions were manually repaired after the removal of artefacts, and a total of 42/184 sessions were excluded. These S1 excluded sessions were mainly caused by sensor movement. Out of the 46 exercise sessions performed by participants, 23 included complete sweat [Na⁺] data from all three devices (i.e., FP, LAQUAtwin and S1). For WBSL, all 46 sessions provided valid data for the scale-based method, the S1 and the SRC, and none were excluded. Wearing the S1 did not seem to be associated with discomfort, as VAS scores indicated that participants were not distracted or bothered by the sensor: 0.4 $\pm$ 0.6 cm out of 10 cm. Also, the sensor took an average of 8.3 $\pm$ 3.5 min after the beginning of the exercise to display the first sweat [Na⁺] value.

Sweat [Na⁺] measures

The coefficient of variation of the triplicates for FP was 0.8% $\pm$ 0.7%, and the mean difference between the QC samples I^{Na} and their expected value represented 2.1% $\pm$ 4.0% of the sweat samples I^{Na}. For LAQUAtwin, the coefficient of variation of the triplicates was 0.6% $\pm$ 1.3%.

The linear mixed-effects model with participant as a random intercept revealed significant main effects of device and environmental condition on sweat [Na⁺] ($p < 0.001$). The estimated marginal mean of sweat [Na⁺] in dry conditions was 63 mmol/L for the FP device. S1 and LAQUAtwin significantly underestimated sweat [Na⁺] compared with FP (both 53 mmol/L), each by 10 mmol/L ($p < 0.001$, **Table 2**). As expected, the difference between S1 and LAQUAtwin was not significant (0 mmol/L, $p = 0.952$).

Sweat [Na⁺] measured by FP was slightly lower in the humid condition (60 mmol/L, $p = 0.034$) compared to the dry one, and no significant interactions between device and condition were detected ($p = 0.44$ for S1*humid and $p = 0.27$ for LAQUAtwin*humid).

In addition, when both dry and humid conditions were pooled and only paired data were compared, the bias was 7 $\pm$ 12 mmol/L for S1 (55 $\pm$ 19 mmol/L) compared to FP (62 $\pm$ 18 mmol/L), with LOA comprised between -17 and 30 mmol/L (**Figure 4A**) and a CCC of 0.74. For LAQUAtwin (54 $\pm$ 16 mmol/L) compared to FP (62 $\pm$ 17 mmol/L), the bias was 8 $\pm$ 11 mmol/L with LOA comprised between -13 and 30 mmol/L (**Figure 4B**) and a CCC of 0.69. For S1 (53 $\pm$ 21 mmol/L) compared to LAQUAtwin (54 $\pm$ 20 mmol/L) the bias was 0 $\pm$ 11 mmol/L with LOA comprised between -22 and 23 mmol/L (**Figure 4C**) and a CCC of 0.84.

Side-to-side variability

FP sweat [Na⁺] measured on the right (61 $\pm$ 16 mmol/L) and left (64 $\pm$ 18 mmol/L) upper arms showed a bias of -3 $\pm$ 8 mmol/L. S1 right (55 $\pm$ 21 mmol/L) and left (51 $\pm$ 21 mmol/L) measures presented a bias of 4 $\pm$ 8 mmol/L while for LAQUAtwin the right (55 $\pm$ 18 mmol/L) and left (55 $\pm$ 19 mmol/L) side had a bias of 0 $\pm$ 4 mmol/L. Also, the temperature measured with the S1 on the right (37.3 °C $\pm$ 1.5 °C) and on the left (37.3 °C $\pm$ 1.5 °C) upper arms revealed a bias of 0.0 °C $\pm$ 0.3 °C.

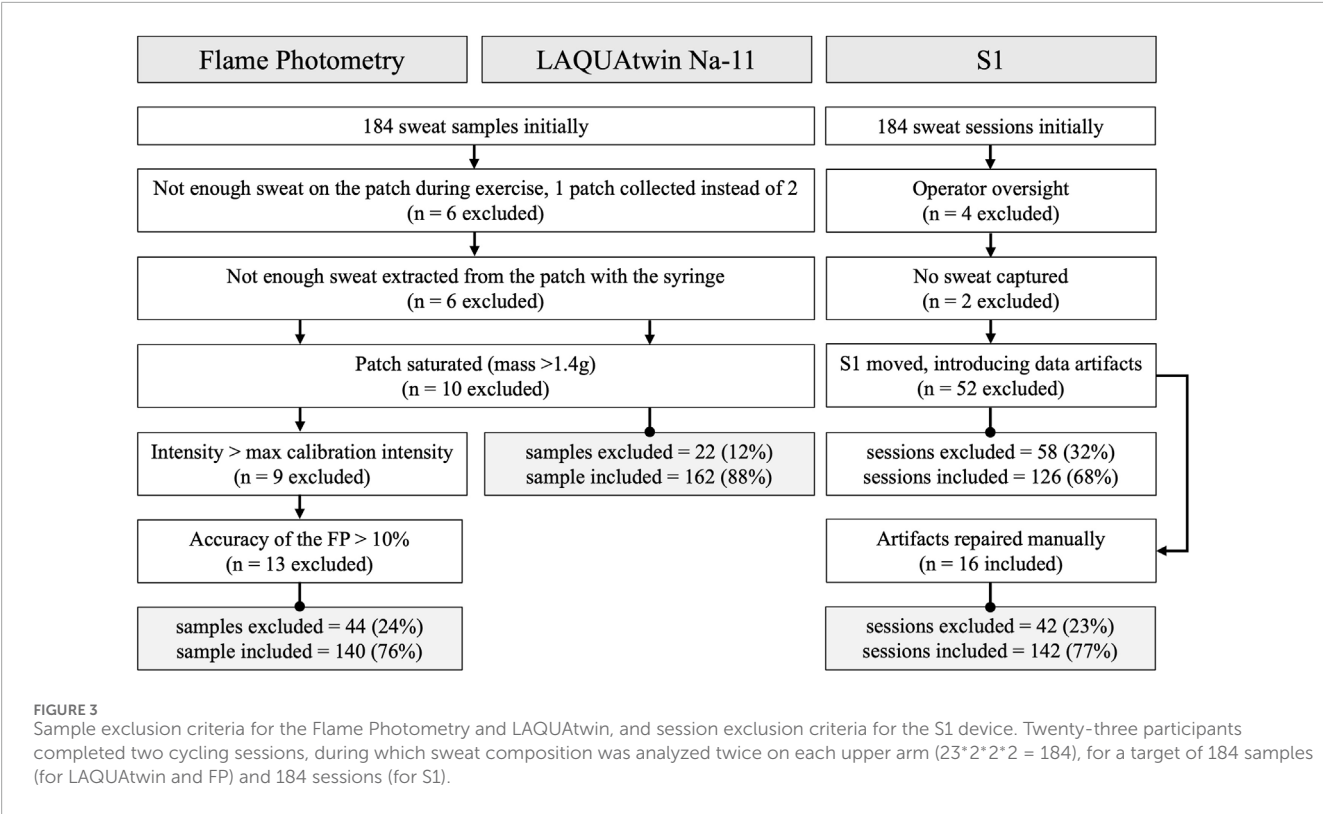
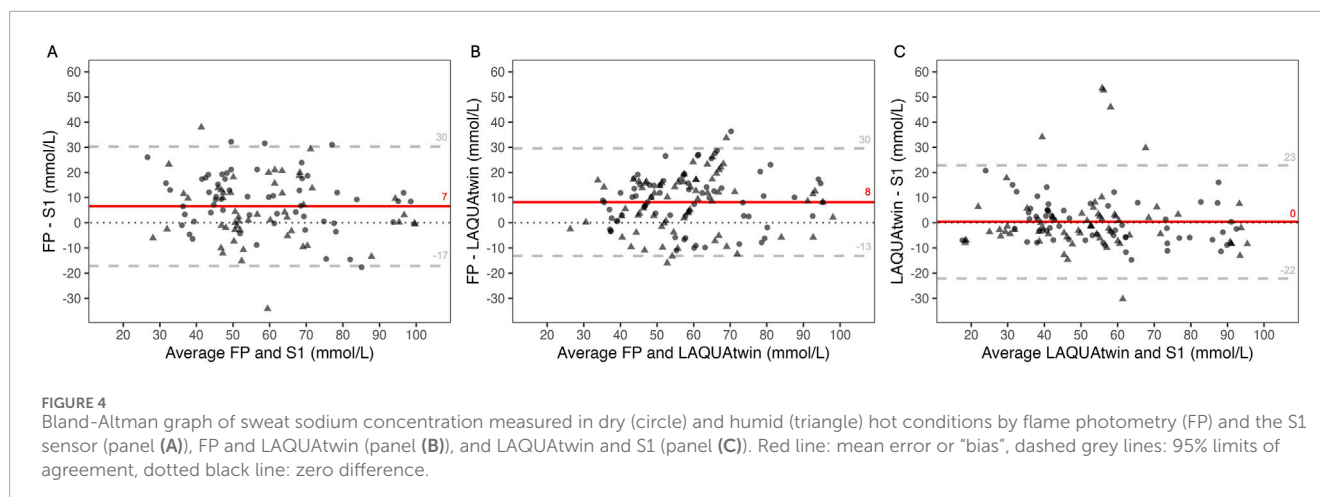


TABLE 2 Sweat sodium concentration comparison between flame photometry (FP), the S1 sensor, and LAQUAtwin in dry and humid hot conditions. A linear mixed-effects models was fitted using method and condition as fixed effects, and participant as a random factor. Results are presented in estimated marginal means $\pm$ standard error.

Comparison	Condition	Method	n	Estimated sweat [Na ⁺]	Estimated error	P-value
				(mmol/L)	(mmol/L)	
FP - S1	dry	FP	71	63 $\pm$ 4	10 $\pm$ 2	<0.001
		S1	70	53 $\pm$ 4		
	humid	FP	69	60 $\pm$ 4	9 $\pm$ 2	<0.001
		S1	72	51 $\pm$ 4		
FP - LAQUAtwin	dry	FP	71	63 $\pm$ 4	10 $\pm$ 1	<0.001
		LAQUAtwin	80	53 $\pm$ 4		
	humid	FP	69	60 $\pm$ 4	8 $\pm$ 1	<0.001
		LAQUAtwin	82	52 $\pm$ 4		
LAQUAtwin - S1	dry	LAQUAtwin	80	53 $\pm$ 4	0 $\pm$ 2	0.952
		S1	70	53 $\pm$ 4		
	humid	LAQUAtwin	82	52 $\pm$ 4	-1 $\pm$ 1	0.737
		S1	72	51 $\pm$ 4		



Whole body sweat loss measures

In average, participants drank 1.002 ± 0.403 L of water, and nonsweat loss represented 0.132 ± 0.023 L. Participants lost $0.64\% \pm 0.57\%$ of their body mass during exercise (overconsumption of water and mass gain in 5/46 trials), with individual changes ranging from a 1.88% loss to a 0.68% gain.

The linear mixed-effects model revealed significant main effects of device and environmental condition on WBSL ($p < 0.001$). The estimated marginal mean of WBSL in dry conditions was 1.432 kg for the scale-based method. The estimation for the S1 (1.479 kg) was not different (-0.047 , $p = 0.624$) while the estimation for the SRC (1.202 kg) was significantly lower than the scale and S1 (0.230 and 0.277 kg respectively, both $p < 0.001$, [Table 3](#)).

Across all devices, WBSL was lower in the humid condition by 0.229 kg ($p < 0.001$). No significant interactions between device and condition were detected ($p = 0.077$ for S1*humid and $p = 0.068$ for SRC*humid), indicating that S1 and SRC deviation to the scale was consistent across environmental conditions.

In addition, when both environmental conditions were pooled and only paired data were compared, the bias for WBSL was 0.017 ± 0.288 kg (0.038 ± 0.260 L/h, results expressed in sweat rate in [Supplementary Material 2](#)) for S1 (1.300 ± 0.299 kg) compared to the scale (1.317 ± 0.357 kg) with LOA comprised between -0.548 and 0.582 kg ([Figure 5A](#)), and a CCC of 0.62. For SRC (1.021 ± 0.259 kg) compared to the scale (1.317 ± 0.357 kg), the bias was 0.296 ± 0.271 kg (0.268 ± 0.272 L/h, SM2) with LOA comprised between -0.236 and 0.828 kg ([Figure 5B](#)), and a CCC of 0.43. For SRC (1.021 ± 0.259 kg) compared to S1 (1.300 ± 0.299 kg), the bias was 0.279 ± 0.081 kg (0.229 ± 0.064 L/h, SM3) with LOA comprised between 0.120 and 0.437 kg ([Figure 5C](#)), and a CCC of 0.64.

Discussion

The validity of the S1 sensor and portable analyzer LAQUAtwin to measure sweat $[\text{Na}^+]$ was tested against the gold standard FP. Although the S1 and LAQUAtwin devices produced equivalent results, both significantly underestimated sweat $[\text{Na}^+]$ relative to FP. Therefore, while the S1 may offer practical advantages for field data

collection compared to the LAQUAtwin, its measurements should currently be interpreted with caution and not considered equivalent to laboratory-grade analyses. However, for WBSL estimation, the errors of the S1 compared to the gold standard scale method were not significant and considered acceptable for fluid intake recommendation in indoor cycling, whereas WBSL obtained from the sweat rate calculator was significantly different from the gold standard and should be used with caution in the environmental conditions tested.

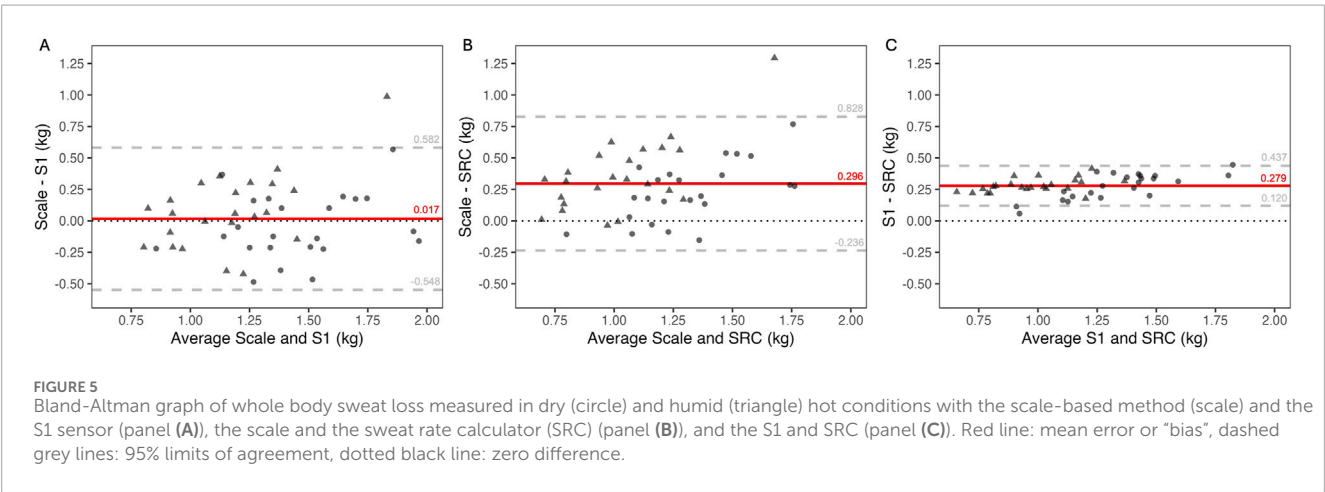
Exercise responses

The exercise duration and intensity were similar in dry (40°C and 36%) and humid (30°C and 81%) conditions ([Table 1](#)), suggesting comparable metabolic heat production ([Périard et al., 2021](#)). However, despite similar core temperature, skin temperature was lower in the humid compared to the dry condition, indicating a lower heat stress in the humid condition ([Table 1](#)) ([Cramer and Jay, 2019](#)). Indeed, the 2 m/s airflow likely reduced heat strain in the humid environment by enhancing sweat evaporation and heat dissipation, whereas in the dry condition it may have increased convective heat gain because air temperature (40°C) exceeded skin temperature (36.5°C) ([Foster et al., 2022](#)). This reduced heat stress in the humid condition likely resulted in a lower WBSL.

Furthermore, the significant lower sweat $[\text{Na}^+]$ observed in the humid condition likely reflects the reduced WBSL, as these two parameters are closely related ([Buono et al., 2008](#)). Indeed, previous work has shown that higher sweat rates are generally associated with higher sweat $[\text{Na}^+]$ within individuals. This relationship is thought to result from reduced sodium reabsorption by eccrine sweat glands when secretion rate increases. However, this phenomenon is mainly observable at the intra-individual level. This may explain why, in the present study, when data from both conditions were pooled, the correlation between sweat $[\text{Na}^+]$ and WBSL was not significant. In addition, the reduced WBSL could also be related to effects of hydrominosis in the humid condition. Indeed, high skin wettability due to a reduced sweat evaporation can lead to lower sweat eccrine secretion and lower sweat $[\text{Na}^+]$ ([Baker, 2017](#)).

TABLE 3 Whole body sweat loss (WBSL) comparison between the scale-based method (Scale), the S1 sensor, and the sweat rate calculator (SRC) in dry and humid hot conditions. A linear mixed-effects models was fitted using method and condition as fixed effects, and participant as a random factor. Results are presented in estimated marginal means $\pm$ standard error.

Comparison	Condition	Method	Estimated WBSL	Estimated error	P-value
			(kg)	(kg)	
Scale - S1	dry	Scale	1.432 $\pm$ 0.055	−0.047 $\pm$ 0.051	0.624
		S1	1.479 $\pm$ 0.055		
	humid	Scale	1.202 $\pm$ 0.055	0.081 $\pm$ 0.051	0.251
		S1	1.121 $\pm$ 0.055		
Scale - SRC	dry	Scale	1.432 $\pm$ 0.055	0.230 $\pm$ 0.051	<0.001
		SRC	1.202 $\pm$ 0.055		
	humid	Scale	1.202 $\pm$ 0.055	0.362 $\pm$ 0.051	<0.001
		SRC	0.840 $\pm$ 0.055		
S1 - SRC	dry	S1	1.479 $\pm$ 0.055	0.277 $\pm$ 0.051	<0.001
		SRC	1.202 $\pm$ 0.055		
	humid	S1	1.121 $\pm$ 0.055	0.281 $\pm$ 0.051	<0.001
		SRC	0.840 $\pm$ 0.055		



Sweat [Na⁺] measures

The linear mixed-effect model analysis revealed no significant interaction between the method used to measure sweat [Na⁺] (FP, S1, LAQUAtwin) and the environmental conditions (dry and humid hot conditions). These results indicate that S1 and LAQUAtwin errors relative to FP were consistent across both climates. When both conditions were considered, the differences between S1 and LAQUAtwin over the gold standard FP revealed biases of 10% $\pm$ 22% and 12% $\pm$ 17%, respectively (Figures 4A,B). The magnitude and the variability of these differences do not support the use of these methods for precise measures of sweat [Na⁺] (Barnes et al., 2019).

However, there was no significant difference between S1 and LAQUAtwin (0 and −1 mmol/L in dry and humid conditions respectively, Table 2). Therefore, S1 provides in average an equivalent ability to LAQUAtwin for determining sweat [Na⁺] in athletes during indoor cycling exercise.

To assess the potential impact of S1 and LAQUAtwin errors on sodium replacement strategies, regional sweat [Na⁺] values obtained from each device were converted into whole-body sodium losses using a scaling (Baker et al., 2020), together with the fluid losses of the present study measured via the scale-based method (details of the calculations in Supplementary Material 3). This approach allowed to estimate how inaccuracies

from S1 and LAQUAtwin in sweat $[\text{Na}^+]$ measurement may translate into practical recommendations deviations for sodium intake after exercise. In our study, 95% of the S1 errors relative to FP fell between an overestimation of 685 mg and an underestimation of 909 mg of whole-body sodium loss. For the LAQUAtwin, errors ranged from an overestimation of 616 mg to an underestimation of 897 mg. To our knowledge, no clear consensus exists regarding the exact amount of sodium that should be replaced following exercise (Barnes et al., 2019), making it difficult to define a universally acceptable error margin. Nevertheless, assuming that total sodium losses should be replaced, these error ranges correspond to less than half a teaspoon of table salt (one teaspoon contains approximately 2300 mg of sodium). From a practical standpoint, for the type of exercise duration (75 min), intensity (1.9 W/kg), and environmental conditions tested in this study, such deviations are unlikely to lead to meaningfully incorrect sodium replacement strategies. Consequently, both the S1 and LAQUAtwin appear acceptable for estimation of sodium intake after exercise.

Beyond the accuracy of the measure itself, the practical aspects associated with the use of FP, LAQUAtwin, and S1 should be considered by practitioners. The FP method involves a labor-intensive analytical process, including optimal sweat collection in patches, extraction, sample transport to the laboratory, storage, dilution, instrument calibration, and manual analysis (Baker, 2017). The LAQUAtwin, although portable, still requires patch handling, a precision balance, syringe use, and pipetting. In contrast, the S1 offers a simple “plug-and-play” approach, providing immediate readings of sweat $[\text{Na}^+]$ without additional sample processing. As the S1 and LAQUAtwin demonstrated equivalent performance (Figure 4C) and was not impacted by hot and humid conditions, the S1 appears particularly suitable for field use due to its practicality, whereas the FP should be prioritized when the highest analytical accuracy of sweat $[\text{Na}^+]$ is required.

The measurement reliability of the S1 and LAQUAtwin was estimated by the comparison of sweat $[\text{Na}^+]$ between the left and right upper arms. Indeed, side-to-side variation in sweat $[\text{Na}^+]$ is typically low (0–3 mmol/L) (Baker et al., 2018). For S1 and LAQUAtwin, biases of $5\% \pm 28\%$ and $0\% \pm 8\%$ were respectively found. Hence, side-to-side reliability of both methods are considered adequate for tracking intra-individual adaptations during heat acclimation, as sweat $[\text{Na}^+]$ typically decreases by 30%–50% in acclimated individuals (Allan and Wilson, 1971; Chinevere et al., 2008; Tyler et al., 2016). Also, given that the day-to-day variability in sweat $[\text{Na}^+]$ is approximately 15%, the S1 and LAQUAtwin are considered suitable for monitoring substantial fluctuations due to factors such as exercise intensity, environmental conditions, and clothing (Baker, 2017).

A previous version of the LAQUAtwin (B-722) demonstrated a bias of 1 mmol/L and a standard error of the estimate of 3.8 mmol/L when validated against ion chromatography (IChr) (Goulet et al., 2017), hence our former hypothesis on the validity of the LAQUAtwin. However, it was not supported in our study, where a bias of 8 mmol/L was observed. One possible explanation is the different reference method used (i.e., IChr compared to FP), which can affect sweat $[\text{Na}^+]$ measurements (Goulet et al., 2017; Dziedzic et al., 2014). In comparison, the LAQUAtwin utilizes a direct ion-selective electrode (DISE), which tends to be 11% lower than those obtained from frozen sweat

samples analyzed by FP (Dziedzic et al., 2014), which aligns well with the 12% bias observed in our study.

The limitation of our sweat $[\text{Na}^+]$ analysis is the absence of crossover measurements to directly assess the magnitude of differences between the analytical methods used (Dziedzic et al., 2014) (i.e., direct ion-selective electrode for LAQUAtwin, atomic emission spectroscopy for FP, and electrochemical sensing for S1). Furthermore, each device presents its own inherent bias, and the conditions under which the measurements were performed likely influenced the sweat $[\text{Na}^+]$ values. Indeed, the analyses were conducted inside the chamber for S1, immediately after patch removal in a temperate environment for LAQUAtwin, and several days later following sample freezing for FP (Baker, 2017). These limitations are inherent to the protocols used and may partly explain the differences observed between methods.

Whole body sweat loss measures

S1 estimation of WBSL in hot and dry conditions was not significantly different than the sweat loss measured with the scale-based method (-0.047 kg, $p = 0.624$, Table 3), and no significant interaction was observed with humid conditions. When dry and humid conditions were considered together, 95% of the differences ranged between an underestimation of 0.582 kg and an overestimation of 0.548 kg, corresponding to -0.9% – 0.8% of body mass difference in our participants (Figure 5A). Hence, excluding nonsweat losses, the maximum errors of the sensor remained within the recommended 2% threshold to avoid deleterious effects of dehydration (Cheuvront et al., 2003). Therefore, the S1 is considered as a valuable tool for estimating WBSL on an indoor cycling ergometer. It offers an effective solution for optimizing hydration during training when precise scale measurements are not applicable.

In contrast, the SRC in dry and humid hot conditions estimated a significantly lower WBSL than the scaled-based method and the S1 (-0.230 and -0.277 kg respectively, both $p < 0.001$, Table 3), conversely to our hypothesis. This finding contrasts with the original validity study, where the bias from the scale-based method during an indoor cycling exercise was 0.01 L/h (Jay et al., 2024b) (0.268 ± 0.272 L/h, SM3). This discrepancy could be attributed to the particularly strenuous environmental conditions in our study, either very hot (40°C) or highly humid (80%), while the SRC has been validated in temperatures ranging from 23°C to 40°C and humidity levels between 14% and 60%. Our conditions were therefore at the upper limits or outside these ranges, and it may have led to reduced heat dissipation and higher sweat rate (Périard et al., 2021) than what was predicted by the SRC. Of note, an underestimation of sweat loss may be less problematic than overestimation, as the latter could encourage excessive fluid intake and increase the risk of exercise-associated hyponatremia (Montain et al., 2006). Ninety-five percent of the differences ranged between an underestimation of 0.828 kg and an overestimation of 0.236 kg, corresponding to -1.2% – 0.4% of body mass difference in our participants. The errors of the SRC therefore remained within the recommended 2% threshold (Cheuvront et al., 2003).

Limitations

The present study was conducted in under specific experimental conditions, with a moderate intensity indoor cycling exercise performed in controlled environmental settings and *ad libitum* fluid intake. The accuracy and practical implications reported here should therefore be interpreted within the context of these conditions only. Of note, the hydration status of the participants was not controlled prior to the trials. In addition, this study focused on validating the S1 sensor when placed on the upper arm, therefore, its accuracy at other body sites cannot be inferred. Future studies testing the S1 in outdoor field-conditions are now warranted.

Conclusion

The S1 wearable is a sweat sensor allowing continuous sweat sodium concentration ($[Na^+]$) and whole body sweat loss (WBSL) estimation. Our study demonstrated a significant difference for sweat $[Na^+]$ measure of the S1 and the LAQUAtwin when compared to the gold standard flame photometry. However, S1 and LAQUAtwin measurements yielded comparable results. S1 appears to offer a more practical alternative to the LAQUAtwin since it does not necessitate absorbent patch application. Additionally, our study showed that the S1 is adequate to estimate WBSL during cycling ergometer exercise when the gold standard scale-based method is not feasible, while the sweat rate calculator measures were significantly lower than the scale and should therefore be used with caution in very dry or humid conditions. In summary, the S1 is a promising tool when tested in laboratory setting, with additional studies warranted to assess its validity and reliability in field conditions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by University of Montpellier Research Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

DB: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review and editing. JB: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – original draft, Writing – review and editing. DM-J: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review and

editing. LD: Conceptualization, Data curation, Methodology, Writing – review and editing. NE: Conceptualization, Data curation, Methodology, Writing – review and editing. JR: Conceptualization, Investigation, Methodology, Writing – review and editing. J-CA: Funding acquisition, Project administration, Resources, Validation, Writing – review and editing. SR: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review and editing. AT: Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review and editing. YP: Project administration, Resources, Supervision, Writing – review and editing, Conceptualization, Funding acquisition, Investigation, Methodology.

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Conflict of interest

Author YP is the founder of company Human Telemetrics Ltd (UK).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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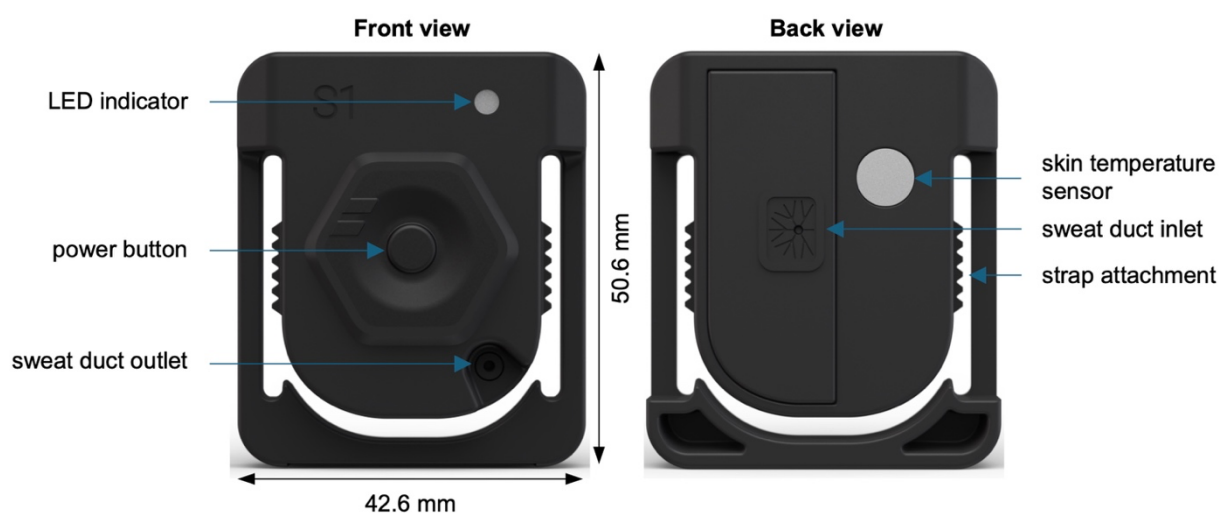
Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fphys.2025.1717275/full#supplementary-material>

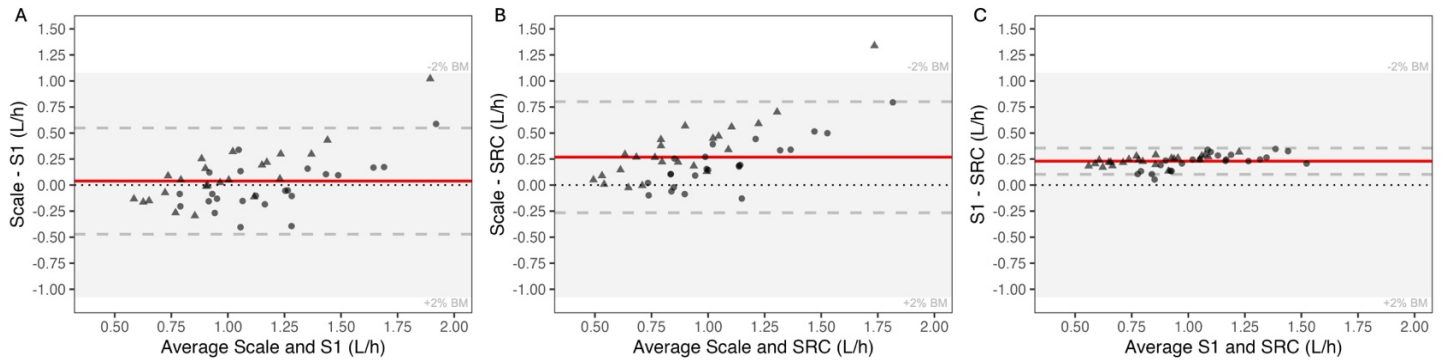
Supplementary materials

“Sweat sodium composition and sweat loss estimation through wearable sensors and predictive equations in dry and humid hot conditions”

SM1: Features of the S1 sensor. The sensor is positioned with its back against the skin, the biochemical sensors are located inside the sweat duct.



SM2: Bland-Altman graph of sweat rate (L/h) measured in dry (circle) and humid (triangle) hot conditions with the scale-based method (scale) and the S1 sensor (panel A), the scale and the sweat rate calculator (SRC) (panel B), and the S1 and SRC (panel C). The shaded area represents $\pm 2\%$ of body mass (BM) loss. Red line: mean error or “bias”, dashed grey lines: 95% limits of agreement, dotted black line: zero difference.



	Mean (L/h)	n	Mean Error	LOA upper	LOA lower
Scale	1.112 ± 0.404	46	0.038 ± 0.260	0.548	-0.472
S1	1.074 ± 0.256				
Scale	1.112 ± 0.404	46	0.268 ± 0.272	0.801	-0.266
SRC	0.845 ± 0.225				
S1	1.074 ± 0.256	46	0.229 ± 0.064	0.356	0.103
SRC	0.845 ± 0.225				

SM3: Potential impact of S1 and LAQUAtwin errors on sodium replacement strategies.

Regional sweat $[Na^+]$ values obtained from S1 and LAQUAtwin devices were converted into whole-body sodium losses (in mg) using a scaling equation and fluid losses of the present study measured via the scale-based method.

1. Regional sweat $[Na^+]$ 95% error (mmol/L):

	LOA -	BIAS	LOA +
FP-S1	-17	7	30
FP-LAQUATWIN	-13	8	30
LAQUATWIN-S1	-22	0	23

2. Whole-body sweat $[Na^+]$ - 95% error (mmol/L):

	LOA -	BIAS	LOA +
FP-S1	-23	17	30
FP-LAQUATWIN	-20	18	30
LAQUATWIN-S1	-25	0	26

Based on the scale up equation from upper arm sweat $[Na^+]$ to whole-body sweat $[Na^+]$ cross validated in Baker et al. 2020:

$$\text{Whole-body sweat } [Na^+] = 0.565 * (\text{upper arm sweat } [Na^+]) + 12.927$$

Baker LB, Nuccio RP, Reimel AJ, Brown SD, Ungaro CT, De Chavez PJD, et al. Cross-validation of equations to predict whole-body sweat sodium concentration from regional measures during exercise. *Physiol Rep.* 2020;8(15). Available from: <https://onlinelibrary.wiley.com/doi/abs/10.14814/phy2.14524>

3. Whole-body sweat $[Na^+]$ - 95% error (mg/L):

	LOA -	BIAS	LOA +
FP-S1	-520	383	690
FP-LAQUATWIN	-468	403	681
LAQUATWIN-S1	-584	0	594

$$[Na^+] \text{ in mg/L} = ([Na^+] \text{ in mmol/L}) * 22.989769$$

4. Whole-body sweat sodium losses - 95% error (mg):

	LOA -	BIAS	LOA +
FP-S1	-685	504	909
FP-LAQUATWIN	-616	531	897
LAQUATWIN-S1	-769	0	783

The value of whole-body sweat $[\text{Na}^+]$ (mg/L) was multiplied by the mean WBSL: 1.317 L.

CHAPTER 4

VALIDATION OF A WEARABLE SENSOR FOR CONTINUOUS SKIN TEMPERATURE MEASUREMENTS DURING EXERCISE

1. Overview

Accurately estimating an athlete's ability to dissipate heat is an important consideration for EHS prevention (Périard, Eijssvogels, and Daanen 2021). Indeed, heat strain results from an imbalance between internal heat production and heat dissipation. Among the physiological variables that inform this balance, skin temperature provides a particularly relevant insight into the status of thermoregulatory processes during exercise (Cramer et al. 2022).

Skin temperature reflects the net result of thermal exchanges occurring at the interface between the body and the environment. According to the thermodynamics of heat transfers, skin temperature is influenced by multiple pathways (Cramer and Jay 2019). First, conductive heat exchange may contribute to skin temperature; however, in endurance athletics, its role is marginal due to limited contact with solid surfaces. Radiative heat exchange also affects skin temperature, through both emitted body heat and absorbed environmental radiation, particularly solar radiation and its reflections (Honjo et al. 2018).

More importantly, skin temperature is strongly influenced by evaporative heat loss resulting from eccrine sweat secretion, a mechanism for which the feasibility of reliable measurement was examined in Chapter 3 through the validation of an innovative wearable sensor (Bandiera et al. 2026). In addition, convective heat exchange, mediated by blood flow to the skin and air movement around the body, plays a major role in determining skin temperature, especially during outdoor endurance events (Aylwin et al. 2023; Racinais et al. 2022).

In general, the gradient between core and skin temperature provides critical information regarding the body's capacity to transfer heat from the core to the periphery (Cramer et al. 2022). A cooler skin temperature facilitates heat dissipation via the blood, thereby limiting core temperature rise and reducing the risk of EHS. Conversely, elevated skin temperatures may impair this heat transfer (Rowell 1986). Improving our understanding of these interactions would support the development and validation of energy-balance thermal indices tailored to elite athletes.

Therefore, Chapter 4 aimed to validate a wearable sensor designed for real-time measurement and to describe best practice for skin temperature measures.

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3. Publication

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Validation of the iButton and Flex sensors for measuring skin temperature

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Abstract

Purpose Skin temperature is a critical component of athletes' heat strain during exercise in the heat. This study evaluated the innovative Flex sensor (BodyCap, Caen, France), allowing real-time measurements, against a data logger (iButton hygrochron DS1923, Analog Devices, Wilmington, USA), commonly used in sports science.

Methods In a first study, the accuracies of iButton faces as well as the Flex sensor were tested on a constant-temperature Peltier module affixed to a brass plate. In a second study, concurrent skin temperature measurements were conducted with both sensors on eight participants cycling in hot conditions.

Results Both faces of the iButton underestimated plate temperature, with the base (ME = mean error: 0.59 ± 0.25 °C at 30 °C, 1.62 ± 0.48 °C at 40 °C) being significantly more accurate than the top (ME: 1.14 ± 0.26 °C at 30 °C, 3.02 ± 0.71 °C at 40 °C, $p < 0.001$). The rate of temperature increase of the base was also higher than the top at 30 °C (1.97 ± 0.16 °C/min vs 1.49 ± 0.15 °C/min) and 40 °C (4.41 ± 0.46 °C/min vs 3.14 ± 0.16 °C/min, both $p < 0.001$). The Flex sensor underestimated plate temperature (ME: 1.31 ± 0.32 °C at 30 °C, 3.00 ± 0.84 °C at 40 °C), showing larger errors than the iButton base ($p < 0.001$). During exercise, the Flex sensor (36.91 ± 1.19 °C) measured higher skin temperature compared to the iButton (36.50 ± 1.15 °C), with an ME of -0.41 ± 0.55 °C.

Conclusion In the absence of a gold standard, for scenarios where real-time monitoring is not required, using the iButton with its base applied to the skin is therefore recommended. To enhance the Flex sensor's accuracy, implementing a calibration protocol before use is strongly suggested, enabling its full potential for real-time monitoring.

Keywords Thermoregulation · Monitoring · Heat · Hot environment · Exercise · Wireless · Contact thermometry

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Introduction

During exercise in hot conditions, both metabolic heat production and challenging environmental factors drive an increase in core temperature, with the skin playing a central role in its regulation (Cramer et al. 2022; Périard et al. 2021). Vasodilation of skin vessels redirects blood from the heated core to the cooler skin, facilitating heat dissipation at the level of the skin (Cramer et al. 2022). Indeed, rising core temperature triggers sweating, and the evaporation of sweat cools both the skin and circulating blood (Cheuvront and Haymes 2001). Similarly, airflow reduces athletes' thermal strain by improving convective and evaporative heat loss at skin level (Ganse and Degens 2020; Saunders et al. 2005). Interestingly, during the World Championships of road races in Doha (i.e., marathon and racewalking), skin temperature (T_{skin}) was higher in "Did Not Finish" athletes (DNF) compared to finishers (32.0 vs 30.6 °C, $p < 0.001$) (Racinais et al. 2022). Also, the decrease of T_{skin} during the race (-0.1 vs -1.5 °C, $p < 0.001$) and the core-to-skin temperature gradient (6.7 vs 9.4 °C, $p < 0.001$) were lower in DNF compared to finishers, while core temperature alone was not discriminant. Indeed, the skin is the primary site for heat exchange between the body and the environment. A lower skin temperature maintains a larger core-to-skin gradient, facilitating heat transfer from the core to the periphery. Conversely, a higher skin temperature, together with a reduced decrease during exercise, limits this gradient and thereby impairs heat dissipation, which contributes to greater thermal and cardiovascular strain and, ultimately, reduced performance (Rowell 1986). Therefore, measuring skin temperature allows to better understand the impact of heat on the human body (Aylwin et al. 2023).

Various methods exist for measuring T_{skin} , though no clear gold standard has been established (Bach et al. 2015; MacRae et al. 2018). Contact thermometry, despite inherent temperature deviation caused by sensor contact and coverage that alter the skin environment, remains a standard technique for measuring T_{skin} during exercise due to its good accuracy, ease of use, and portability (Bach et al. 2015; James et al. 2014; MacRae et al. 2018). In sport sciences, the iButton sensor (Analog Devices, Wilmington, USA) is commonly used for its lightweight design and embedded data logger, offering an accuracy of ± 0.5 °C (Maxim Integrated 2025). The latest models can store up to 2560 readings with intervals of 1 s or longer with a resolution of 0.0625 °C. However, questions remain regarding the thermal inertia of the iButton once attached to the skin. To reach thermal equilibrium, it is recommended to attach the sensor "well before" recording begins, which is not always achievable in field conditions (MacRae et al. 2018).

Additionally, the iButton has two faces, yet the manufacturer documentation does not specify which face to apply for surface temperature measurement (Maxim Integrated 2025). Consequently, it is uncertain whether temperature differences may occur between the two faces. Finally, iButton sensors are no longer upgraded, and do not allow T_{skin} readings in real time.

The Flex sensor (BodyCap, Caen, France) has recently emerged as a promising tool for real-time T_{skin} assessment, with its use reported in several research protocols (Esh et al. 2025; Guppy et al. 2023; C. James et al. 2025). This sensor is a flattened adaptation of the e-Celsius ingestible capsule (BodyCap, Caen, France), designed to ensure optimal contact with the skin. The e-Celsius capsule is widely used in research (Singh et al. 2023). It has demonstrated excellent validity and reliability compared with a wired temperature probe in a water bath gradually heated from 33 to 44 °C, showing a mean difference of -0.081 ± 0.055 °C (Bongers et al. 2018; Koumar et al. 2023). With the introduction of this new Flex sensor, validation is essential to confirm its accuracy for T_{skin} measurement (Düking et al. 2018; Muniz-Pardos et al. 2021).

This study aimed to assess the validity of the recently developed Flex sensor and to examine the responses of both faces of the iButton. The first study evaluated the Flex sensor as well as both faces of the iButton on a Peltier plate for temperature measurement. The second study compared the Flex sensor to the iButton for T_{skin} measurements accuracy during exercise in hot condition.

Materials and methods

This research involved two studies, following different protocols but both using the same sensors.

Sensors

iButton data logger

The iButton hygrochron DS1923 (Analog Devices, Wilmington, USA) is a temperature and humidity data logger designed for environmental monitoring (Maxim Integrated 2025). To our knowledge, it is the most common sensor used in sport science to measure T_{skin} during exercise. It features a compact, coin-sized design (diameter 17.35mm, width 5.89mm, 5g) with a durable stainless-steel casing. The iButton utilizes an oscillator-based digital system for temperature measurements (accuracy ± 0.5 °C) and a capacitive sensor for humidity (accuracy $\pm 5\%$ rh), offering an operational temperature range of -20 °C to $+85$ °C with a resolution of 0.0625 °C. Humidity readings are provided within a range of 0–100% rh, with a resolution of 0.04% rh. Powered

by a non-rechargeable lithium battery, the sensor supports extended deployment without the need for maintenance. It can record data at user-defined intervals, from 1 s to 273 h, and can store up to 2560 temperature and humidity readings without rollover. iButton activation, interruption, and data retrieval can be performed using either the 1-Wire software (Analog Devices, Wilmington, USA) or ExactLog (Serious Sensor, Whitewater, USA). While ExactLog remains supported, 1-Wire is no longer updated.

Flex temperature sensor

The Flex sensor (BodyCap, Caen, France) is a wireless device designed for continuous T_{skin} monitoring. Compact and flexible (5.5×2.0 cm, 6.38 g) with silicone casing, the sensor allows close skin contact. It measures temperatures within a range of 0–45 °C with a resolution of 0.1 °C and transmits data at user-defined intervals of 15 s, 30 s, 1 min, 2 min, or 5 min. The device can store up to 2000 measurements without rollover and is powered by a non-rechargeable zinc–silver battery, providing ~20 days of operation once activated (i.e., the sensor can be activated and deactivated several times to save battery). Sensor configuration is conducted via an app or external receiver, and it can be activated or deactivated as needed. Data is transmitted via telemetry up to ~1 m to the receiver or to a proprietary gateway embedded in a wristband (BodyCap, Caen, France). The gateway enables further data transmission via Bluetooth Low Energy to multiple wearable devices (e.g., smartphone, watch). This setup supports integration with remote data collection systems, allowing non-invasive, real-time temperature tracking (Guppy et al. 2023).

Study 1: Peltier module experiment

Peltier module description

The Flex and iButton sensors were tested on a device consisting of a temperature regulator connected to a Peltier module affixed to a brass plate. This setup was fully controlled by a computer. A Peltier module includes two ceramic plates separated by semiconductor materials through which an electric current flows. One plate absorbs heat while the other dissipates it, creating distinct hot and cold sides. The temperature of each side varies based on the intensity of the current. To maintain the desired temperature, the regulator adjusts the current intensity accordingly. A K-type thermometer (Fluke t3000 FC, Everett, USA) was inserted into the brass plate and secured using a thermally conductive adhesive, providing a reference temperature with an accuracy of ± 0.2 °C (illustration of the setup in supplementary information).

Experimental setup

Twenty iButton and 20 Flex sensors were positioned in full contact on the Peltier plate for a duration of 10 min. To simulate T_{skin} range in hot conditions, this experiment was conducted twice, with a Peltier module temperature set at 30 °C and 40 °C. Temperature readings were recorded every 15 s by each sensor. The rate of temperature increase (°C/min), time to plateau (min), and the accuracy of stabilized temperature measurements were analyzed. A stable temperature was defined as a variation inferior to 0.0625 °C, corresponding to the iButton's resolution. The mean temperature during the stable period was then calculated and compared to the reference temperature measured by the K-type thermometer. Each iButton was tested on both faces in a random order. Face A of the iButton was defined as the face with the hole for humidity measurement, while face B was the larger and flat face with device number (Fig. 1).

Study 2: skin temperature experiment

Participants

A total of eight participants (6 females, 2 males) took part in the study with an average age of 29.4 ± 10.5 years old, mass of 63.9 ± 10.2 kg, and size of 169.6 ± 7.1 cm. They were recreationally active adults and gave informed consent before taking part in the experiment, which received approval from

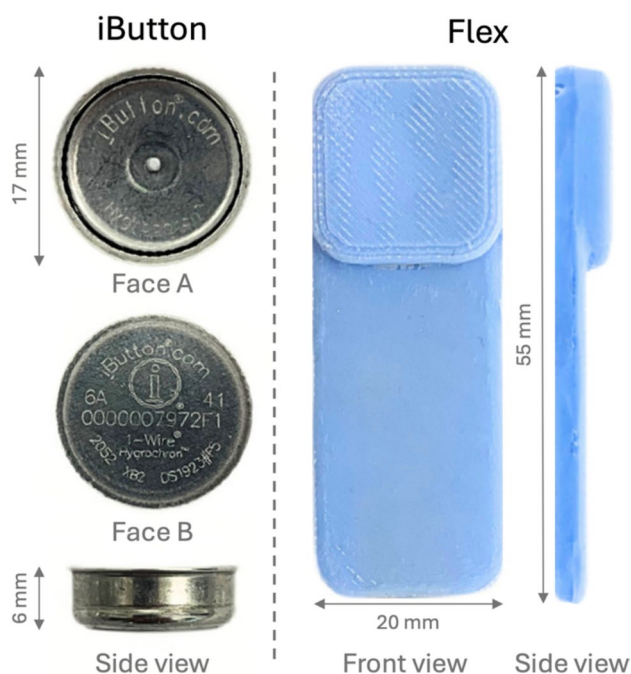


Fig. 1 Picture of both faces of the iButton (left) and the Flex sensor (right)

the University of Montpellier Research Ethics Committee (2023–023) and adhered to the principles of the Declaration of Helsinki.

Experimental procedures

Exercise was performed in a controlled environmental chamber in hot conditions (37.6 ± 4.5 °C, $46.3 \pm 20.8\%$ rh). An air-flow at 2m/s was simulated with a wind tower including two industrial fans of 50 cm of diameter vertically aligned facing the chest and head of the participants. Participants cycled on an ergometer (Wattbike, Nottingham, UK) for 60–90 min, targeting 80% of theoretical maximal heart rate (Polar, Kempele, Finland) calculated as $220 - \text{age}$, with a minimum power output of 2W/kg. T_{skin} was measured every 15 s with iButton hygrochrons DS1923 (Analog Devices, Wilmington, USA) and Flex sensors (BodyCap, Caen, France). Both devices were placed side by side and attached to the skin with Leukotape (BSN medical GmbH, Hamburg, Germany) at three body sites: left forearm, chest (under the left part of the chest band), and left anterior thigh. The T_{skin} on each site was averaged every minute, and Flex measurements were compared to the iButton ones, the latter being considered as the reference. *Whole-body* T_{skin} from the three sites was calculated as follows: $0.14 * \text{forearm} + 0.5 * \text{chest} + 0.36 * \text{thigh}$ (Kavitar and Mehta 2022).

Statistical analysis

Statistics were performed in R statistical software (version 4.4.1) (R Core Team 2024). Different calculations were computed to assess the validity: the mean error (ME, average of the differences), the mean absolute error (MAE, average of the absolute differences), the mean percent error (average

of the relative differences), and the concordance correlation coefficient (CCC) (Lawrence I-Kuei Lin 1989). The concordance correlation coefficient (CCC) was interpreted as follows: poor (< 0.90), moderate ($0.90 - 0.95$), substantial ($0.95 - 0.99$), and almost perfect (> 0.99) (McBride 2005). Each average was expressed with its standard deviation. Also, Bland–Altman graph was plotted with the ME and the 95% limit of agreements (LoA) (Bland and Altman 1986). For the Peltier module experiment, the performances of both iButton faces were compared, as well as those of the Flex sensor and the iButton faces. Following a data distribution check using a Shapiro–Wilk test, the Student's *t*-test for parametric data was performed. To estimate the magnitude and practical relevance of the differences, Cohen's effect size (ES) was calculated and interpreted as follows: < 0.2 negligible effect, < 0.5 small, < 0.8 medium, and ≥ 0.8 large effect (Cohen 1988).

Results

Peltier module experiment

The mean temperature measured by face A of the iButton was 28.84 ± 0.27 °C at 30 °C, with an ME of 1.14 ± 0.26 °C, while it measured 37.05 ± 0.69 °C at 40 °C with an ME of 3.02 ± 0.71 °C (Table 1). The rate of temperature increase of face A was 1.49 ± 0.15 °C/min at 30 °C and 3.14 ± 0.16 °C/min at 40 °C. Finally, time to plateau was 2.43 ± 0.25 min at 30 °C and 3.63 ± 0.39 min at 40 °C.

The mean temperature recorded by face B of the iButton was 29.39 ± 0.22 °C at 30 °C with an ME of 0.59 ± 0.25 °C and 38.46 ± 0.49 °C at 40 °C with an ME of 1.62 ± 0.48 °C (Table 1). Also, the rate of temperature increase of face B

Table 1 Validation result of the iButton and the Flex sensors against the Peltier plate (considered as the reference) heated at two different temperatures: 30 and 40 °C

Sensor	Condition	Comparison	Mean (°C)	<i>n</i>	Mean error (°C)	Mean percent error (%)	Mean absolute error (°C)
iButton	Side A	30 °C	Reference	20	1.14 ± 0.26	3.8 ± 0.9	1.14 ± 0.26
		iButton	28.84 ± 0.27				
		40 °C	Reference	20	3.02 ± 0.71	7.5 ± 1.8	3.02 ± 0.71
		iButton	37.05 ± 0.69				
	Side B	30 °C	Reference	20	0.59 ± 0.25	2.0 ± 0.8	0.59 ± 0.25
		iButton	29.39 ± 0.22				
Flex		40 °C	Reference	20	1.62 ± 0.48	4.0 ± 1.2	1.62 ± 0.48
		iButton	38.46 ± 0.49				
	30 °C	Reference	30.00 ± 0	20	1.31 ± 0.32	4.4 ± 1.1	1.31 ± 0.32
		Flex	28.69 ± 0.32				
	40 °C	Reference	40.05 ± 0.05	20	3.00 ± 0.84	7.5 ± 2.1	3.00 ± 0.84
		Flex	37.05 ± 0.84				

was 1.97 ± 0.16 °C/min at 30 °C and 4.41 ± 0.46 °C/min at 40 °C. Finally, time to plateau was 2.13 ± 0.21 min at 30 °C and at 2.92 ± 0.33 min 40 °C.

For the Flex sensor, the temperature measured was 28.69 ± 0.32 °C at 30 °C with an ME of 1.31 ± 0.32 °C and 37.05 ± 0.84 °C at 40 °C with an ME of 3.00 ± 0.84 (Table 1). The rate of temperature increase of the Flex was 1.83 ± 0.32 °C/min at 30 °C and 4.15 ± 0.52 °C/min at 40 °C. Finally, time to plateau was 2.41 ± 0.25 min at 30 °C and 3.39 ± 0.30 min at 40 °C.

For the iButton faces, the errors were lower for face B compared to face A at both 30 and 40 °C (respectively, $t = 15.4$ and $t = 17.1$, both $p < 0.001$ and large ES, Fig. 2). The ME of face B of the iButton was also significantly lower than that of the Flex at 30 °C ($t = 7.96$, $p < 0.001$, ES = 2.52, large) and 40 °C ($t = 6.42$, $p < 0.001$, ES = 2.03, large). However, errors from Flex and face A of the iButton were not significantly different at 30 °C ($t = 1.85$, $p = 0.07$, ES = 0.58, moderate) and 40 °C ($t = -0.08$, $p = 0.94$, ES = -0.03, negligible).

The rate of temperature increase of the iButton face B was higher than the face A at 30 °C ($t = -8.1$, $p < 0.001$, ES = -1.8, large) and 40 °C ($t = -12.9$, $p < 0.001$, ES = -2.89, large), and not different from the Flex at 30 °C ($t = -1.8$, $p = 0.08$, ES = -0.57, moderate) and 40 °C ($t = -1.72$, $p = 0.09$, ES = -0.55, moderate). Also, the rate of temperature increase of the Flex was higher than the iButton face A at 30 °C ($t = 4.4$, $p < 0.001$, ES = 1.38, large) and 40 °C ($t = 8.3$, $p < 0.001$, ES = 2.64, large).

Skin temperature experiment

The participants cycled for 80 ± 11 min, representing 626 min of T_{skin} recording at three body sites ($626 \times 3 = 1878$ data points). The mean heart rate was 159 ± 7 bpm, $83 \pm 5\%$ of estimated maximum heart rate. The mean power output was 124 ± 27 W, corresponding to a relative intensity of 2.0 ± 0.4 W/kg.

Since the Peltier module experiment revealed a better accuracy of the iButton for its face B, this is the face that was applied to the skin for T_{skin} measurement in the second study. *Whole-body* T_{skin} was 36.28 ± 0.79 °C [min 34.60; max 37.11 °C], with peak *Whole-body* T_{skin} varying from 34.85 to 38.01 °C.

When all three sites were pooled, the Flex sensor (36.91 ± 1.19 °C) measured higher T_{skin} compared to the iButton (36.50 ± 1.15 °C), with an ME of -0.41 ± 0.55 °C (Table 2). This represents an MAE of 0.56 ± 0.40 °C with 95% of the difference between -1.49 and 0.68 °C (Fig. 3).

For a visual representation of the individual differences between iButton and Flex sensor, the skin temperature per site in each participant is shown in Fig. 4.

Discussion

This study is the first to evaluate the validity of the innovative Flex sensor and of both faces of the iButton Hygrochron DS1923. Results showed that iButton face B was significantly more accurate than face A and the Flex sensor for surface temperature measurement. Also, during skin

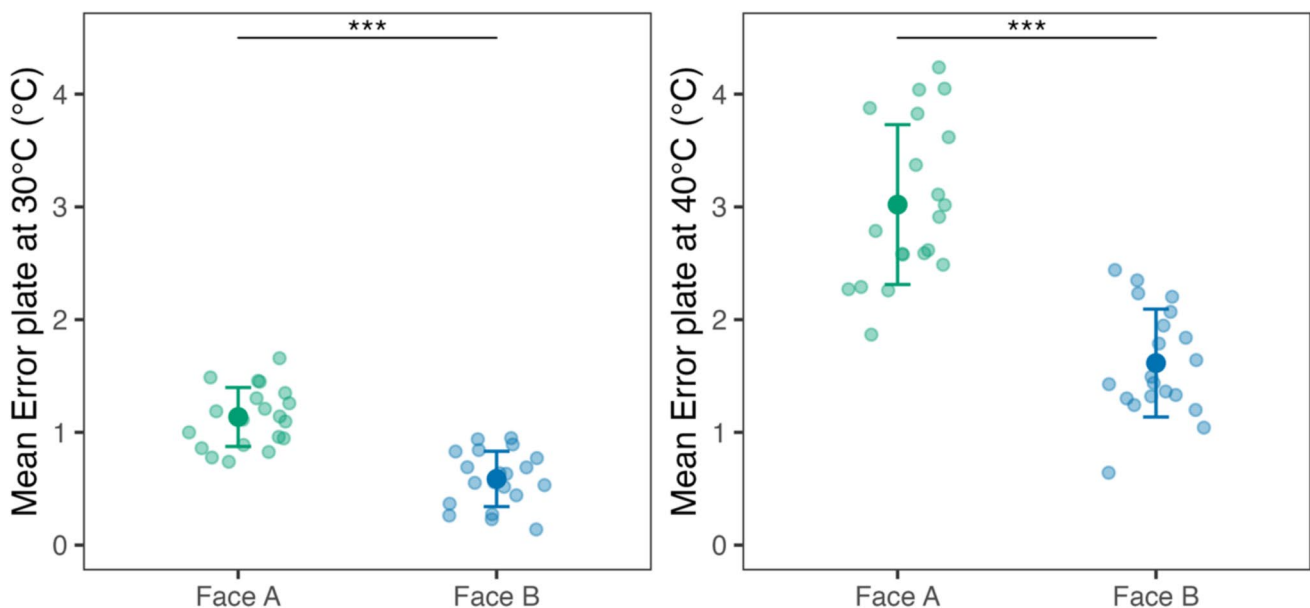
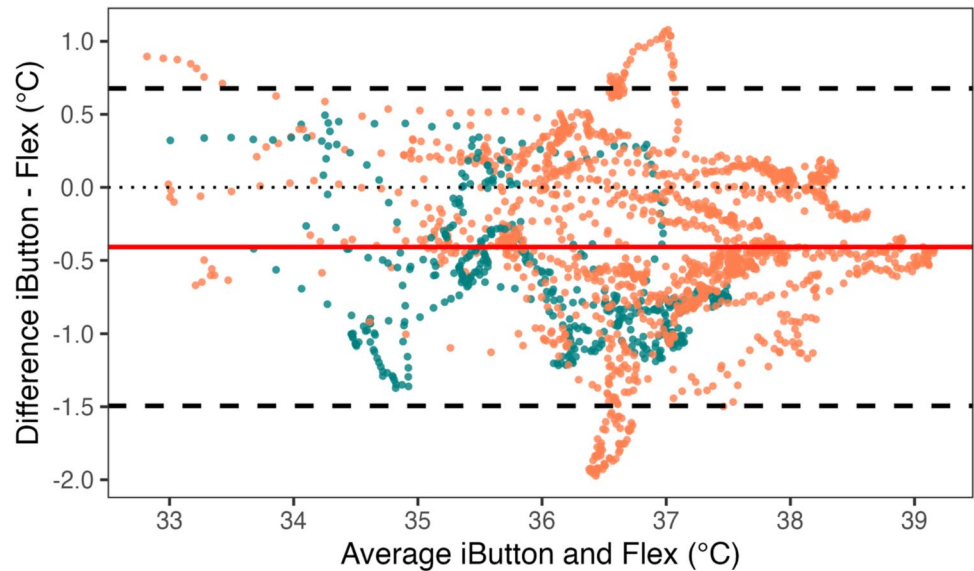
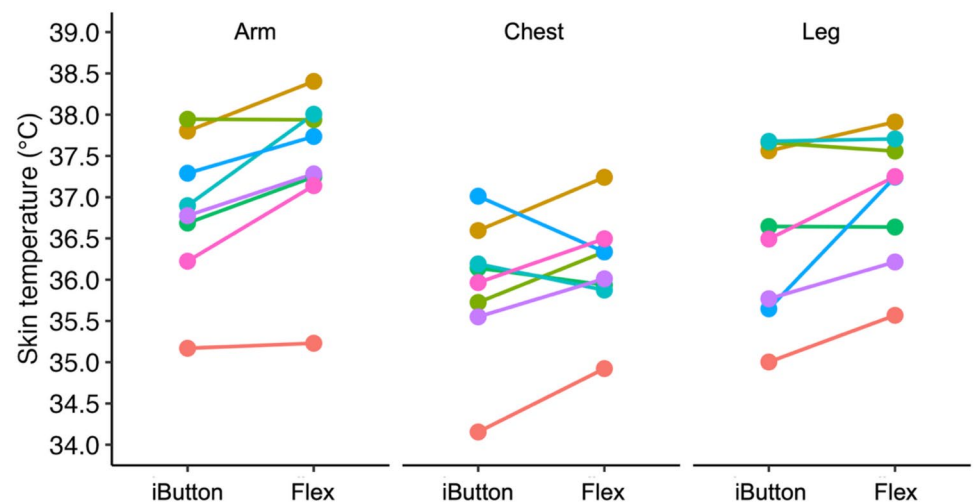


Fig. 2 Comparison of face A and face B of the iButton, on a plate at 30 °C (left) and 40 °C (right). *** $p < 0.001$

Table 2 Validation result of the Flex compared to the iButton face B for skin temperature measurement

Sensor	Mean (°C)	<i>n</i>	Mean error (°C)	Mean percent error (%)	Mean absolute error (°C)	LOA upper (°C)	LOA lower (°C)	CCC
iButton	36.50 ± 1.15	1878	-0.41 ± 0.55	-1.1 ± 1.5	0.56 ± 0.40	0.68	-1.49	0.838
Flex	36.91 ± 1.19							

Fig. 3 Bland–Altman graph of skin temperature measured by iButton face B and Flex devices. The red line is the mean error or “bias” and the dashed lines are the 95% limits of agreement, while the dotted line represents zero difference. Orange: female, green: male**Fig. 4** Individual skin temperature at each site measured across the entire exercise with iButton and Flex sensors

temperature assessment in exercising individuals, the difference between the Flex and the iButton remained below 0.5 °C. Therefore, the iButton face B provides greater accuracy under controlled conditions, while the Flex offers the advantage of practicality and demonstrated acceptable accuracy when real-time feedback is required.

Our results showed that face B of the iButton provided better accuracy than face A (Fig. 2), contrary to findings from earlier studies (Hasselberg et al. 2013; van Marken Lichtenbelt et al. 2006). This discrepancy stems probably

from differences in device models: we used the iButton hydrochron DS1923 (temperature and humidity sensors), whereas earlier studies studied the iButton thermochron DS1921H (temperature sensor only). The design of the thermochron places the battery on face B and the temperature sensor on face A, resulting in faster response times for face A (van Marken Lichtenbelt et al. 2006). In contrast, the hydrochron integrates a hygrometer on face A, suggesting that the battery may be repositioned, potentially to the device's center and the temperature sensor on face B, which

could explain the superior responsiveness and accuracy for face B.

In our study, iButton face B showed a lower error at the 30 °C plate temperature (0.59 ± 0.25 °C) compared with the 40 °C plate temperature (1.62 ± 0.48 °C, Table 1), despite similar ambient conditions (23 °C). This increase in error when the difference between the measured surface and the ambient condition increases can be attributed to the fact that both face of the sensor affect the measurement (the one on the skin and the one exposed to environmental conditions). Therefore, when the gap between ambient and surface temperatures increases, iButton users should anticipate larger measurement errors (van Marken Lichtenbelt et al. 2006).

The Flex sensor demonstrated larger errors at both 30 °C and 40 °C compared to iButton face B when tested on the Peltier plate ($p < 0.001$, large ES, Table 1), indicating that the iButton is more accurate under these conditions. Similarly to the iButton, the Flex underestimated the plate temperature. One possible explanation is the thickness of the silicone casing, which, while facilitating optimal contact with the skin, introduces an insulative layer between the sensor and the surface being measured (Papailiou and Schmuck 2013). This additional layer may dampen the heat transfer and impact the temperature readings. Interestingly, the e-Celsius capsules, which use the same temperature sensor as the Flex (i.e., BodyCap company), also underestimated temperatures in its earlier version (0.19 °C in water bath at 35 °C) (Travers et al. 2016). A calibration procedure improved their accuracy, and these adjustments were integrated into later capsule generations, resulting in an excellent precision of 0.08 °C for bath temperature ranging from 33 to 44 °C (Bongers et al. 2018). In line with these observations, a calibration procedure would also be recommended before using a Flex sensor to improve their accuracy.

Similarly to the iButton, the accuracy of the Flex sensor may also be compromised by the surrounding air temperature. Notably, the error on the Peltier plate was higher at 40 °C compared to 30 °C (1.62 vs 0.59 °C, respectively), suggesting that larger temperature differences between the surface and the surrounding environment (23 °C) may amplify measurement errors. This observation is further supported by the Flex's overestimation of skin temperature relative to the iButton under hot conditions (0.41 ± 0.55 °C, Fig. 3). During the cycling trials, participants were in an environmental chamber with a mean air temperature of 37.6 °C, exceeding the iButton-measured skin temperature of 36.5 °C. Therefore, the Flex sensors may have been influenced by heat from the surrounding air, leading to overestimated skin temperature readings.

The difference between the Flex compared to iButton for skin temperature measurement may lie at the threshold of what is considered practically meaningful, based on criteria established in previous studies (C. A. James et al. 2014;

MacRae et al. 2018; Smith et al. 2010). While the ME of 0.41 °C observed in our study falls within the recommended threshold of ± 0.5 °C for in vivo experimentation, the limits of agreement (± 1.09 °C) slightly exceed the ± 1.0 °C margin typically regarded as the boundary for practical significance. In this context, calibrating the Flex in a water bath before use is strongly recommended, as it would likely reduce measurement discrepancies to within the range of practically meaningful differences.

Of note, Flex and iButton must be activated before use. However, the number of activation and deactivation is limited by battery life. In the current study, the Flex sensors had a lifespan of 19.7 ± 7.5 days [min 7.0; max 33.0]. Each sensor underwent an average of 8 ± 3 activation/deactivation cycles [min 4; max 16], resulting in a total recording time of 17.6 ± 9.0 h [min 5.4; max 37.9]. Conversely, the iButtons used for the current study were also used for other projects without battery failure.

Limitations

The Peltier module was used to simulate skin temperature, but plate temperature does not fully replicate the complex thermoregulatory environment of human skin (e.g., sweating), and no core temperature or other thermoregulatory responses have been reported here. Also, two temperatures were tested to mimic hot skin conditions (30 and 40 °C), but the accuracy of the iButton and Flex sensors at other temperatures remains uncertain. Finally, no calibration of the iButton and Flex sensors was performed prior to the study (van Marken Lichtenbelt et al. 2006; Smith et al. 2010), which could have influenced measurement accuracy.

Conclusion

This study highlighted significant differences between the two faces of the hygrochron iButton for surface temperature measurement. Based on our findings, researchers and sports scientists using the iButton DS1923 are advised to apply face B (i.e., the larger side or base) to the skin for improved accuracy. Additionally, the recently developed Flex sensor was evaluated and compared to the iButton. While both sensors underestimated the surface temperature of a Peltier plate, the Flex demonstrated larger errors. For skin temperature measurement, the Flex appeared to be influenced by elevated air temperature, leading to an overestimation compared to the iButton. Implementing a proper calibration protocol for the Flex prior to use would likely improve its accuracy, enabling users to fully benefit from its real-time monitoring capabilities, which represent a key advantage over the iButton.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00421-025-06020-9>.

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Author contributions DB, PJ, SCE, JCA, SR, AT, and YP contributed to the study conception and design. Material preparation, data collection, and analysis were performed by DB and JDB. The first draft of the manuscript was written by DB and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Data are available upon reasonable request.

Declarations

Conflict of interest This study was supported by funding from Human Telemetrics Ltd, of which YP is a co-founder. The other authors have no competing interest to declare.

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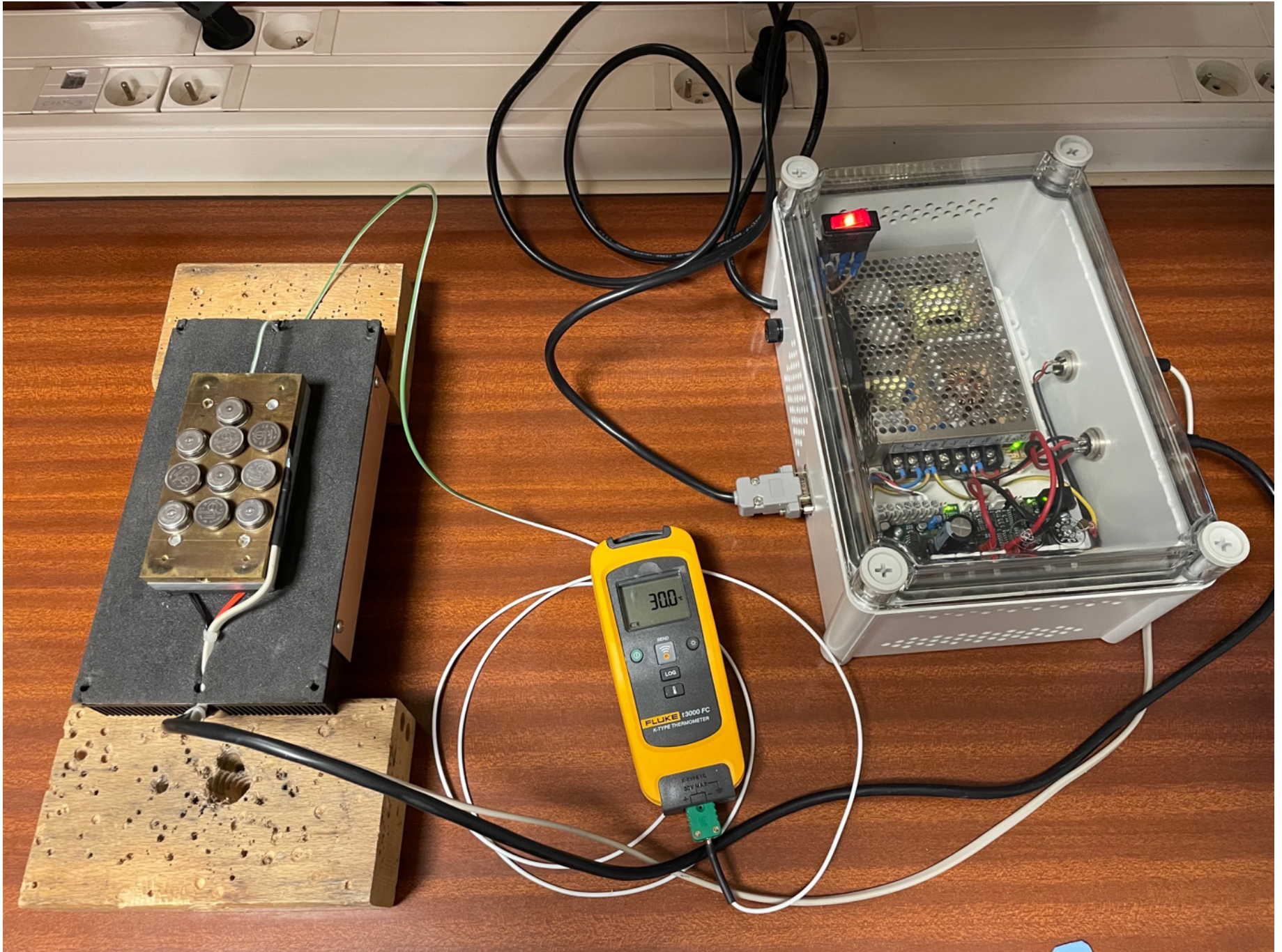
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SUPPLEMENTARY INFORMATION

« Validation of the iButton and Flex sensors for measuring skin temperature »

David Bandiera, Jean de Bardonnèche, Philippe Janry, Sylvie Calas-Étienne, Jean-Christophe Aubin,

Antonio Tessitore, Yannis Pitsiladis, Sébastien Racinais



SI 1: installation used in study 1 to test the validity of iButton and Flex sensors against a plate at constant temperature. The temperature regulator (grey box on the right) was connected to a Peltier module affixed to a brass plate (black module on the left). iButton and Flex (iButton on the picture) were then placed on the plate. The temperature of the plate was controlled with a thermometer, inserted into the brass plate and secured using a thermally conductive adhesive (in yellow at the centre).

DISCUSSION AND PERSPECTIVES

1. Main findings and implications

1.1. Heat stress risk in sports

EHS represents the most severe form of heat-related illnesses and can be fatal if not promptly and appropriately treated (Casa et al. 2015). High-level athletes are increasingly exposed to the risk of EHS as a result of rising global surface temperatures and the growing frequency and intensity of heatwaves associated with climate change (IPCC 2023). In parallel, many major international sporting events (e.g., the Olympic Games, World Athletics Championships) are traditionally held during the summer months, when environmental conditions are often the most thermally challenging (Bermon and Adami 2019). In this context, IFs have the responsibility to ensure that competitions are conducted under safe conditions and must therefore anticipate and mitigate heat-related risks before and during events.

The first aim of this thesis was to identify sports at elevated risk of heat-related illness. In elite athletes, the risk of EHI is primarily associated with prolonged outdoor exposure, strong performance-driven motivation, and high metabolic heat production (Julien D. Périard, Eijssvogels, and Daanen 2021; Roberts et al. 2023). These characteristics are not shared by all Summer Olympic sports and, consequently, do not warrant the same level of preventive attention from all IFs.

In Chapter 1, we identified 15 sports from the Paris Summer Olympic programme (33%) as presenting a high, very high, or extreme risk of heat stress (Bandiera et al. 2024). Athletics, road cycling, and triathlon were particularly exposed, with activities classified as presenting an extreme risk (i.e., the most elevated classification). Based on these findings, World Athletics, alongside the International Cycling Union (UCI) and World Triathlon, should implement robust and evidence-based heat policies to protect athletes from heat-related dangers.

At present, these IFs rely on the WBGT to estimate the risk of heat-related illness. However, WBGT has been shown to inadequately reflect the thermal strain experienced by athletes, particularly during high-intensity exercise (Budd 2008). International federations should therefore evaluate the relationship between WBGT and the actual occurrence of exertional heat illness within their sport. If this relationship proves weak, the selection of thermal indices should instead consider sport-specific factors such as exercise intensity, environmental conditions, and clothing (e.g., large contribution of the wind in cycling, water contact in triathlon).

It is unlikely that a single thermal index is suitable for all sports (Grundstein and Vanos 2021). Each discipline may require tailored approaches, including the development or adaptation of indices that better reflect its specific physiological and environmental demands. Ultimately, any

proposed solution should be validated against real-world data on exertional heat illness incidence to ensure its relevance and effectiveness.

1.2. Preventing EHS in Athletics

In elite endurance events in Athletics, Chapter 2 demonstrated that the frequency of EHS is particularly high, averaging 8 cases per 1000 athlete exposures and increasing to 16 cases per 1000 exposures under hot environmental conditions (WBGT 28-29.9 °C) (Bandiera et al. 2026). In such contexts, the level of EHS risk must be anticipated in order to ensure adequate on-site medical and pre-hospital care and, when necessary, to justify event delays or cancellations if the risk becomes excessive.

In addition, the ability of thermal indices to predict EHS was assessed in Chapter 2 using leave-one-out cross-validation. Briefly, each race was removed from the dataset one at a time, the model was trained on the remaining races, and the number of EHS cases was predicted for the omitted race. Prediction error was calculated as the absolute difference between predicted and observed EHS cases, expressed as EHS cases per race. MRT, PET and UTCI showed slightly lower prediction errors than WBGT. The mean absolute error was 0.6 ± 0.7 EHS/race for MRT and PET, and 0.7 ± 0.6 EHS/race for UTCI, compared with 0.7 ± 0.7 EHS/race for WBGT. The absolute improvement over WBGT was minimal, with an average difference of 0.1 EHS/race. Thus, although these indices marginally outperformed WBGT statistically, they were not meaningfully superior from an operational perspective. Given that WBGT is actively used by World Athletics (and by most IFs exposed to heat stress risk, Bandiera et al. 2024), replacing it with MRT, PET or UTCI would require substantial administrative changes, educational material, and stakeholder training, without clear evidence of improved EHS risk prediction. The present findings therefore support a pragmatic approach: WBGT should continue to be used in elite Athletics with clear awareness of its limitations, while future research should aim to develop athlete-specific indices that substantially improve the prediction of EHS risk.

Importantly, World Athletics WBGT flag categories were found to be informative for predicting EHS risk in elite Athletics events, as increasing flag severity was associated with progressively higher EHS risk (i.e., white, green, orange, red, black colours; $P = 0.003$). Based on these observations, we recommend that local organising committees for elite competitions with a limited number of participants (fewer than 100) plan medical resources according to the worst-case WBGT flag expected:

	WBGT white flag (<21°C): preparation for 2 EHS cases
	WBGT green flag (21-24.9°C): preparation for 3 EHS cases
	WBGT orange flag (25-27.9°C): preparation for 5 EHS cases
	WBGT red flag (28-29.9°C): preparation for 6 EHS cases
	WBGT black flag (≥30°C): consider event schedule changes or postponement

All together, these findings indicate that WBGT should not be considered a predictive tool of elite athletes' thermal strain, but rather a preparation guide for EHS risk.

1.3. Future research directions and perspectives

To anticipate EHS risk more accurately, these results indicate that a thermal index specifically tailored to elite endurance athletes should be developed. Such index should estimate heat production, heat dissipation, and net heat storage during exercise, in line with the conceptual framework of existing energy balance thermal indices (Havenith and Fiala 2015). However, current energy balance indices were established using physiological characteristics representative of the general population (Błażejczyk et al. 2010; Chen and Matzarakis 2018). Consequently, the physiological responses generated by these models are unlikely to reflect those of elite endurance athletes during high-intensity competition, which may partly explain the weak associations observed between these indices and EHS frequency in this population (UTCI: $R^2 = 0.09$, mPET: $R^2 = 0.03$) (Bandiera et al. 2026). An athlete-specific thermal index should therefore be constructed using thermoregulatory data directly measured in elite athletes. Moreover, these data should be collected during competition, when thermoregulatory strain is maximal and when EHS events are most likely to occur (Julien D. Périard, DeGroot, and Jay 2022).

We propose that three primary physiological responses involved in thermoregulation should be prioritised for monitoring: fluctuations in core temperature, eccrine sweat secretion, and changes in skin temperature. Core temperature reflects internal heat storage and the potential risk of vital organ dysfunction. Eccrine sweat secretion represents evaporative heat loss capacity, the primary mechanism for heat dissipation in exercising athletes. Skin temperature reflects peripheral heat exchange with the environment and therefore provides insight into the organism's overall cooling capacity (Cramer et al. 2022). Together, these variables allow quantification of the dynamic balance between heat production, heat dissipation, and net heat storage (Cramer and Jay 2019). Monitoring these responses would enable a more precise distinction between compensable and uncompensable heat strain in athletes (Bernard, Wolf, and Kenney 2024). Importantly, periods of uncompensable heat strain and marked elevations in core temperature are expected during elite endurance performance (Racinais et al. 2019; Singh et al. 2023). However, more advanced modelling approaches could allow estimation of the magnitude and duration of these uncompensable phases and determine their potential association with EHS occurrence. Traditional laboratory instruments used to assess core temperature, eccrine sweat secretion and skin temperature are not suitable for field deployment during official events and often require invasive or bulky equipment that athletes are reluctant to wear (Baker 2017; Notley, Mitchell, and Taylor 2023). However, recent technological advances have enabled real-time physiological monitoring during competition (Guppy et al. 2023). The emergence of wearable sensors offers new opportunities, although these devices must undergo rigorous validation to ensure the accuracy and reliability of

transmitted data (Düking et al. 2018). Several core temperature monitoring systems have been validated, most commonly ingestible or rectal telemetry pills (Koumar et al. 2023). These systems provide reliable measurements without interfering with performance, although their cost remains a limitation. In Chapter 3, we demonstrated that eccrine sweat secretion can be estimated with acceptable precision in a controlled hot environment using an innovative continuous wearable sensor (Bandiera, De Bardonèche, et al. 2026). A recently developed sweat rate calculator (SRC) (Jay et al. 2024) was also tested in this chapter, and the results showed a lower precision for WBSL estimation compared to the S1 sensor. The SRC should be interpreted as an accessible estimation tool rather than a substitute for direct individualised sweat testing. Although Jay et al. validated the calculator using anthropometric, exercise, and environmental inputs, sweat rate remains highly variable between athletes, even under comparable exercise and environmental conditions. This variability is influenced by several factors including metabolic heat production, body composition, aerobic fitness, heat acclimation status, and individual sweat gland function (Baker 2017). Therefore, the underestimation of WBSL observed in the Chapter 3 may reflect both the hot and humid conditions being at the upper limits or outside the original validation range of the SRC and residual interindividual variability not fully captured by the model. For individualised hydration planning, scale-based assessment under representative exercise and environmental conditions remains the reference.

Chapter 4 further identified methodological considerations and best practices for measuring skin temperature in applied settings (Bandiera et al. 2025). Further research is needed to develop lighter, less intrusive, and more accessible sensors that athletes are willing to wear during competition while still providing key physiological outputs. Nevertheless, existing technologies already offer substantial opportunities. The next step is not only technological refinement but also increased adoption of validated tools in elite competition settings to accurately measure thermal strain in endurance athletes.

The development and validation of a model capable of estimating the magnitude and duration of uncompensable heat strain phases in elite endurance athletes should constitute a primary step. In addition, it is likely that two major parameters may modify the relationship between uncompensable heat strain and the occurrence of EHS and should therefore be explicitly incorporated into such a model.

First, the level of heat acclimation should be considered. During the 2019 World Athletics Championships in Doha, acclimated athletes exhibited lower peak core and skin temperatures compared with their non-acclimated counterparts (Racinais et al. 2022). Similarly, EHI outcomes was reported among players who were not seasonally acclimated during the Beach

Volleyball World Tour (Racinais, Alhammoud, et al. 2021). These observations may be explained by thermoregulatory adaptations associated with heat acclimation, including neuroplastic adjustments leading to an earlier activation of heat-dissipating effectors and an increased eccrine sweat response (J. D. Périard, Racinais, and Sawka 2015). Compared with non-acclimated athletes, these adaptations likely promote earlier onset and greater rates of heat dissipation. In addition, heat acclimation induces cytoprotective mechanisms, notably the upregulation of heat shock proteins such as HSP70, which may contribute to delaying cellular thermal injury (Horowitz 2014). Consequently, acclimated athletes may present a lower risk of EHS at a given heat strain or tolerate higher heat strain for an equivalent level of risk, compared with non-acclimated athletes. In the 2023 American College of Sports Medicine consensus statement on EHI, different WBGT thresholds were proposed for “acclimatized, fit, low-risk individuals” and “nonacclimatized, unfit, high-risk individuals” (Roberts et al. 2023). However, this classification may have limited applicability to elite endurance athletes, who would always be categorised as fit because of their high aerobic capacity. As a result, the current framework does not adequately distinguish between acclimatized and nonacclimatized elite athletes. A more relevant comparison for elite endurance sport may therefore be between “acclimatized, high aerobic fitness” and “nonacclimatized, high aerobic fitness” athletes. Consequently, further research is warranted to determine the extent to which heat acclimation modifies the environmental thresholds associated with EHS risk in elite endurance athletes, as this remains poorly documented.

Second, the health status of the athlete should be incorporated in the development of this athlete-specific thermal index. Evidence indicates that the frequency of EHI may be associated with the occurrence of diarrhoea or gastroenteritis in the days preceding competition (Racinais, Alhammoud, et al. 2021; Racinais et al. 2022). Exercise in the heat is known to induce alterations in gut microbiota and gastrointestinal function, which may impair thermoregulatory capacity (Bennett et al. 2020). Initiating competition in a thermally stressful environment with compromised gastrointestinal health could therefore increase physiological strain. The negative impact of diarrhoeal illness on heat tolerance is likely multifactorial, involving disturbances in hydration status and electrolyte balance (Casa et al. 2015). As with acclimation status, the extent to which pre-competition health status modifies the risk of EHS in elite endurance athletes remains unknown, and this interaction should be specifically investigated in future research. We therefore recommend that future research in elite endurance athletes examine both the association between heat acclimation and pre-competition health status with EHS frequency. Given that EHS cases are systematically recorded during major international Athletics competitions, these events provide an appropriate framework for data collection. Two

standardized questions could be implemented prior to competition to inform on the level of acclimation and health status:

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

Responses to these closed-ended questions would allow rapid data collection and straightforward analysis. Ideally, completion should be mandatory for endurance athletes and integrated into the accreditation process upon arrival at the competition venue. This approach would ensure high response rates, as accreditation is compulsory, and would avoid the limitations associated with email-based surveys (i.e., erroneous email addresses, lack of responses). To ensure clarity and quality of responses, the questionnaire should be translated into multiple languages, as was done in similar designs in the past (Racinais et al. 2022; Racinais, Ihsan, et al. 2021).

2. Elite versus recreational competitions settings

It is important to note that the present findings cannot be directly transferred to mass-participation sporting events. In elite Athletics endurance competitions, EHS incidence was approximately 8 cases per 1000 athlete exposures on average, while reported EHS incidence in recreational endurance running events is generally lower, around 0.4-1.3 cases per 1000 athlete exposures (Breslow et al. 2021, Divine et al. 2018, Roberts 2000). This gap likely reflects distinct participant fitness level, metabolic heat production, exposure duration, acclimation status, motivation for performance, health status and medical surveillance systems between elite and recreational settings.

Elite endurance athletes present high aerobic fitness and may be more prone to properly heat acclimatise (Esh et al. 2024). In contrast, recreational participants are more heterogeneous in terms of fitness level and acclimation status (Heatherly et al. 2023). Lower aerobic fitness and reduced heat adaptation may impair heat dissipation and increase susceptibility to thermal strain during prolonged exercise in the heat (Julien D. Périard, Eijsvogels, and Daanen 2021). In addition, elite athletes compete at higher intensities and generate greater metabolic heat production, but their shorter event duration reduces overall exposure time to environmental heat stress compared to mass-participation events. Recreational participants usually exercise at lower intensities but remain exposed to strenuous conditions for longer periods, potentially increasing cumulative thermal strain and the likelihood of dehydration, fatigue, gastrointestinal dysfunction, and progressive impairment of thermoregulatory function.

The two populations also differ in motivation and pacing behaviour. Elite athletes may be more inclined to continue exercise despite symptoms of heat strain because of competitive pressure, sponsorship obligations, ranking objectives, or financial incentives (Périard, DeGroot, and Jay 2022). Recreational participants may be more likely to reduce pace or stop exercise when symptoms develop, although this is probably variable between individuals.

Health status may further contribute to differences in EHI risk (Racinais et al. 2022). Elite athletes are typically younger and less likely to present chronic comorbidities. However, frequent international travel may increase exposure to gastrointestinal illness, sleep disruption, or transient infections before competition. In contrast, mass-participation events include broader age ranges and individuals with more heterogeneous medical profiles, including cardiovascular disease, metabolic disorders, medication use, or limited previous exposure to exercise in the heat.

Post-finish-line management also differs markedly. Elite Athletics competitions usually provide immediate access to trained medical teams and cooling strategies, including ice towels, cold-

water dousing, or rapid cold-water immersion when necessary (Racinais et al. 2023). Recreational events often have more limited medical resources relative to participant numbers, and cooling interventions may be delayed after exercise cessation. This may be particularly important because hyperthermia can continue to rise transiently after exercise due to the abrupt reduction in convective cooling once running stops (Saunders et al. 2005). In addition, elite endurance events generally involve relatively small participant numbers, often between 20 and 150 athletes, allowing close medical monitoring and rapid identification of EHS cases (Hosokawa et al. 2021). In contrast, mass-participation races may involve thousands to tens of thousands of runners, substantially increasing logistical complexity and reducing the availability of medical resources per participant (Breslow et al. 2021).

Therefore, the operational recommendations proposed in this thesis, including the interpretation of WBGT flag categories and heat-deck capacity, should be considered specific to elite World Athletics endurance competitions and should not be directly extrapolated to mass-participation events without further validation.

3. Strength and limitations

A primary strength of this thesis lies in the use of real-world data collected during elite international competitions. Analyses were conducted using hyperlocal environmental measurements and official race results. Another major strength is that EHS cases were clinically diagnosed by trained medical doctors using established criteria such as rectal temperature measurement, ensuring accuracy of case identification. This reduces misclassification bias and reinforces the validity of the associations explored. Given that EHS remains incompletely understood and cannot be fully replicated or simulated computationally, reliance on real events strengthens the ecological validity of the findings.

In addition, the wearable sensors investigated in Chapters 3 and 4 were validated under standardized laboratory conditions in both sexes, providing reliable baseline evidence regarding their measurement accuracy. This methodological rigor supports their potential use in similar conditions.

Several limitations should be acknowledged. First, this thesis focused specifically on EHS and did not investigate other forms of exertional heat illness or milder heat strain. The broader spectrum of heat-related risks was therefore not addressed.

Second, the number of races included in the analyses remains limited. Although 80 events were examined, the dataset does not capture the full diversity of possible climatic conditions. Consequently, observed associations may partly reflect the environmental characteristics of the included competitions. Additional data across a wider range of climates would strengthen the robustness and generalisability of the findings.

Second, the number of races included in the analyses remains limited. Although 80 events were examined, the dataset does not capture the full diversity of possible climatic conditions. In addition, the ecological design of the study prevents inference at the individual athlete level, and the relatively low number of EHS cases may limit statistical power and contribute to weak associations between environmental variables and outcomes. Consequently, observed associations may partly reflect the environmental characteristics and structure of the included competitions. Additional data across a wider range of climates and competitions would strengthen the robustness and generalisability of the findings.

Third, as discussed above, it is important to emphasize that the findings and associations regarding EHS frequency are specific to elite endurance competitions and cannot be directly extrapolated to mass-participation events, where athlete characteristics, thermal exposure, and medical infrastructures differ substantially, and where EHS incidence may follow different patterns.

Finally, the wearable validation studies included in this thesis were conducted under controlled laboratory conditions, primarily in recreationally active participants. Therefore, the findings may not fully translate to elite endurance athletes competing in ecological settings. In addition, the primary objective of these studies was to evaluate the validity and practical applicability of different wearable technologies for monitoring thermophysiological variables, rather than to predict EHS risk during competition. Consequently, although athlete monitoring may contribute to a better understanding of thermoregulatory responses in athletes and potentially support heat-stress management strategies, the present findings should not be interpreted as evidence that these devices can directly predict EHS occurrence in elite competition. Further field-based investigations in elite endurance athletes are required to determine the ecological validity of such technologies during real-world competitions and their link with EHS outcome.

4. Conclusions

This thesis aimed to evaluate heat stress risk in elite endurance athletes. Chapter 1 identified the Wet Bulb Globe Temperature (WBGT) as the principal thermal index used by most International summer Federations, including World Athletics, to assess environmental heat risk in elite sports. In elite Athletics endurance events, Chapter 2 demonstrated that the frequency of exertional heat stroke (EHS) is particularly high, averaging 8 cases per 1000 athlete exposures and increasing to 16 cases per 1000 exposures under hot environmental conditions (WBGT 28-29.9°C). To our knowledge, this represents the highest reported incidences of EHS in elite sport. EHS is the most severe form of exertional heat illness and may be fatal without rapid recognition and treatment. Anticipation of heat stress risk in elite Athletics is therefore essential to ensure adequate on-site medical coverage, appropriate pre-hospital management, and, when necessary, evidence-based decisions regarding event delay or cancellation.

Chapter 2 further showed that WBGT should not be considered a predictive tool of elite athletes' thermal strain, but rather a preparation guide for EHS risk. Although the association between WBGT and EHS frequency was weak, increasing WBGT flag severity was consistently associated with progressively higher EHS incidence. Accordingly, local organising committees should plan medical resources according to the worst-case WBGT flag level anticipated for competition.

To improve EHS risk anticipation, the findings of this thesis support the development of a thermal index specifically tailored to elite endurance athletes. Such an index requires a more precise characterisation of athletes' thermoregulatory responses under competition conditions, where physiological strain reaches its maximum. This necessitates the use of valid wearable technologies capable of monitoring key thermoregulatory variables. Chapter 3 demonstrated that eccrine sweat secretion can be estimated with acceptable precision in controlled hot environments using an innovative continuous wearable sensor, while Chapter 4 identified methodological considerations and best practices for measuring skin temperature in applied settings.

Future research should focus on quantifying the thermal burden experienced by athletes during competition. This includes quantifying the magnitude and duration of uncompensable heat strain, the rate of core temperature increase, and the efficiency of peripheral heat dissipation, reflected by the core-to-skin temperature gradient and sweating dynamics. Integrating these physiological responses with individual modifiers such as acclimation status and pre-competition illnesses may enable more accurate estimation of EHS probability than current thermal indices. This athlete-specific framework would provide a more mechanistically grounded basis for pre-competition thermal risk evaluation in elite Athletics events.

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APPENDIX

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Appendix 1: Cross-over design – Consent agreement



RECUEIL DU CONSENTEMENT ECLAIRÉ

Titre du projet

Étude de validation d'un capteur innovant permettant d'estimer la quantité et le contenu de la sueur

Responsables scientifique du projet

- David Bandiera, doctorant Université de Rome « Foro Italico » en partenariat avec World Athletics. Thèse sur le développement d'un index visant à réduire le risque de coup de chaud chez les athlètes.
- Jonathan Rubio, doctorant thèse CIFRE au Creps de Montpellier et avec la Fédération Française de Triathlon, UMR DMeM. Thèse sur la synergie entre hypoxie, chaleur, humidité et réponses à l'entraînement.
- Sébastien Racinais, professeur en physiologie de l'exercice, coordonnateur de la cellule stress environnemental du Creps de Montpellier.
- Jean de Bardonèche, ingénieur de recherche en charge de la présente étude

Objectifs du projet

Mesurer la validité de la mesure de sudation d'un nouveau capteur : la quantité totale d'eau perdue par sudation ainsi que son taux en sodium.

Ce que l'on attend de vous :

La préparation

- À votre arrivée au laboratoire, vous serez invité à vous peser, nu(e) dans une cabine individuelle.
- Vous serez équipé(e) de 2 capteurs de sueur innovants. 1 capteur sera positionné sur chaque bras. Ces capteurs estiment la quantité de sueur produite (la quantité d'eau perdue), ainsi que la concentration en sodium de cette sueur. Aujourd'hui, l'exactitude de cette estimation est inconnue. Le but de cette étude est donc de mesurer la précision de ce capteur. Votre rythme cardiaque sera suivi grâce à une ceinture de fréquence cardiaque.
- Des compresses seront placées aux mêmes endroits que les capteurs. Ces compresses permettront d'absorber la sueur que vous produirez durant l'effort physique. Nous analyserons ensuite leur composition en sodium en laboratoire, et nous comparerons cette concentration avec celle estimée par les capteurs de sueur.
- Lors de cette étude, nous suivrons en direct votre température centrale et votre température cutanée. Vous serez équipés de 2 types de capteurs cutané (2 marques différentes). Nous installerons donc 6 capteurs au total, 2 sur les 3 sites suivants : avant-bras, torse, cuisse. Pour le suivi de la température centrale, nous vous inviterons à avaler une gélule thermomètre 6h avant le début de l'étude. Cette gélule est un dispositif médical (taille : 17,7 mm x 8,9 mm, masse : 1,7 g), elle est équipée d'un capteur de température. Après quelques heures, elle est naturellement évacuée par le tube digestif. Elle est régulièrement utilisée dans les études de thermorégulation et par les athlètes qui s'exercent en milieu chaud et ne présente aucun risque pour la santé.
- Des photos des différents capteurs utilisés sont à retrouver en Annexe 1 de ce document.

Le protocole d'effort

- L'étude se déroule ensuite dans une chambre environnementale où des conditions chaudes et humides seront simulées. Vous pédalerez entre 60 et 95 min (suivant votre débit de sudation) à 80% de votre fréquence cardiaque maximale théorique ($220 - \text{âge}$) et une puissance minimum de 2 W/kg. Cet effort représente une intensité soutenue. Pendant l'effort

nous collecterons les compresses et les remplacerons par de nouvelles. L'objectif est de collecter 2 compresses pleines de sueur par bras durant chaque session. À la fin de l'effort, vous vous pèserez à nouveau, nu(e), afin de connaître la quantité d'eau que vous avez perdue durant l'effort. Cette information sera comparée avec celle donnée par le capteur.

- Pendant la session de pédalage vous pourrez boire de l'eau à volonté et des ventilateurs seront placés face à vous pour simuler le vent créé par votre vitesse sur un vélo.
- Ce protocole sera réalisé 2 fois avec minimum 24h de repos entre les deux sessions. Les sessions seront réalisées en chambre environnementale à 40°C et 30% d'humidité relative (hr) et 30°C et 80% hr (climat similaire à celui du sud de la France durant l'été), dans un ordre aléatoire.
- Enfin, à la fin de l'exercice, vous noterez le confort du capteur de sueur à l'aide d'une échelle visuelle analogique.

Vos droits de quitter l'étude

La contribution à cette recherche est volontaire. Vous pouvez vous retirer de cette étude à tout moment, et demander que vos données soient détruites, sans conséquences. Si vous êtes étudiant(e), votre décision de participer ou non à l'étude n'aura aucun impact sur vos notes universitaires, votre statut ou vos relations avec l'Université de Montpellier.

Vos droits de poser des questions

Vous pouvez poser toutes les questions que vous souhaitez à l'adresse électronique suivante : debardonneche.jean@gmail.com. Vous aurez rapidement une réponse, nous pouvons également parler au téléphone si vous le préférez.

Vos droits à la confidentialité et au respect de votre vie privée

Les données mesurées seront anonymisées. À votre arrivée au laboratoire un code vous sera attribué, qui vous suivra tout au long de l'étude et lors de l'analyse des résultats. La correspondance entre ce code et vos coordonnées sera présente uniquement sur l'ordinateur de l'investigateur principal de l'étude, protégé par un mot de passe.

Afin de calculer votre taux de sudation et la composition de votre sueur, il sera nécessaire d'envoyer les données de sudation récoltées durant l'étude sur le serveur de la société qui vend le capteur. Durant ce procédé, votre code d'anonymisation sera utilisé, les données seront donc anonymisées et la société ne pourra pas relier ces données à vous.

Vos coordonnées ne seront pas partagées avec le reste de l'équipe de recherche, ni la société qui vend le capteur, et resteront confidentielles. L'accès aux données anonymisées sera réservé à l'équipe de recherche seulement, et stocké sur des ordinateurs protégés par un mot de passe ou une empreinte digitale, ainsi que sur un cloud.

Risques possibles de l'étude

Cette recherche implique les mêmes risques et inconforts qu'un entraînement de sport à intensité soutenue durant l'été. Pédaler 95 min (maximum) à 80% de la fréquence cardiaque maximale et minimum 2 W/kg peut engendrer de la fatigue et des courbatures dans les jours suivant l'étude. Pédaler en environnement chaud et sec ou chaud et humide comme proposé dans cette étude peut provoquer un inconfort respiratoire, ainsi qu'une certaine difficulté à évacuer la chaleur. Votre température centrale et cutanée augmentera mais seront en permanence contrôlées grâce aux capteurs mentionnés plus haut, permettant une pratique encadrée et en toute sécurité. En cas d'augmentation inattendue de la température centrale, vous serez immédiatement sorti(e)s de la chambre environnementale, et refroidi(e)s. Les chercheurs impliqués dans ce projet réalisent régulièrement ce type de protocole et ont l'habitude des méthodes réalisées.

Bénéfices attendus de l'étude



- Un bon d'achat de 50 € vous sera remis après la participation à l'intégralité du protocole de l'étude, afin de vous remercier.
- En termes de données physiologiques, vous connaîtrez la quantité d'eau et la quantité de sodium que vous avez perdu durant les efforts en environnement chaud. Cela donne des indications sur les apports que vous devez suivre pour ne pas vous déshydrater ou être en manque d'électrolytes (hyponatrémie) dans des conditions similaires.
- La détermination de la validité de ce capteur est primordiale pour permettre aux athlètes de contrôler en direct leur hydratation et leurs apports en électrolytes. Ainsi, il est possible de réduire les risques de déshydratation ou d'hyponatrémie dont les conséquences peuvent être importantes pour la santé et le niveau de performance. Si le capteur propose des données fiables, il pourrait être utilisé par plusieurs athlètes lors des Jeux Olympiques de Paris 2024.

Consentement

En signant le formulaire de consentement, vous certifiez que vous avez lu et compris les renseignements ci-dessus, qu'on a répondu à vos questions de façon satisfaisante et qu'on vous a avisé que vous étiez libre d'annuler votre consentement ou de vous retirer de cette recherche en tout temps, sans préjudice.

A remplir par le participant :

Consentement

- ☐ J'ai lu et je comprends les informations figurant dans ce document.
- ☐ J'accepte de manière libre et éclairée de participer à ce projet de recherche.

Date, Nom, Prénom, Signature :

.....
.....

A remplir par l'expérimentateur :

Date, Nom, Prénom, Signature :

.....
.....

ANNEXE 1

Capteur de sueur Flowbio

Marque : Flowbio, Londres (Royaume-Uni)

Site internet : <https://www.flowbio.com>

Linkedin :

<https://www.linkedin.com/company/flowbio/about/>

Photos :



Capteurs température cutané BodyCap

Marque : BodyCap, Caen, France

Site internet : <https://www.bodycap.fr>

Photos :



Capteurs température cutané IButton

Marque : Maxim Integrated, San Jose, États-Unis

Site internet :

<https://www.analog.com/en/product-category/ibutton-products.html>

Photos :



Capteur température centrale Bodycap

Marque : BodyCap, Caen, France

Site internet : <https://www.bodycap.fr>

Photos :



Échelle Visuelle Analogique concernant le confort du capteur

Le participant placera un curseur entre ces deux points. Plus le curseur est proche du point droit, plus le capteur a gêné le participant, et vice-versa.

Le capteur ne m'a pas du tout gêné(e) durant l'exercice



Le capteur m'a beaucoup gêné(e) durant l'exercice

Appendix 2: Cross-over design – Ethical approval



UNIVERSITÉ DE
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Comité d'Éthique de la Recherche de l'Université de Montpellier

Avis consultatif n° UM 2023-023bis-bis

Vu Règlement (UE) 2016/679 du Parlement européen et du Conseil du 27 avril 2016 relatif à la protection des personnes physiques à l'égard du traitement des données à caractère personnel et à la libre circulation de ces données, et abrogeant la directive 95/46/CE,

Vu le Règlement Intérieur du Comité d'Éthique de la Recherche de l'Université de Montpellier,

Les membres du Comité d'Éthique de la Recherche de l'UM entendus en sa séance du 20 juin 2023,

Les membres du Comité d'Éthique de la Recherche de l'UM entendus en sa séance du 03 octobre 2023,

Le Bureau du Comité d'Éthique de la Recherche de l'UM entendu en sa séance du 12 décembre 2023.

Le Comité d'Éthique de la Recherche de l'Université de Montpellier donne un avis favorable au projet « Étude de validation d'un capteur permettant d'estimer la quantité et le contenu de la sueur » soumis par Jonathan Rubio.

Fait à Montpellier

Le 19/12/2023

Le Président du Comité d'Éthique de la Recherche
de l'Université de Montpellier

Thierry Lavabre-Bertrand



Appel à participants - Étude scientifique

Objectif

Tester la précision d'un capteur innovant permettant la mesure de la quantité de sueur et de sa concentration en sodium, dans la chambre environnementale du CREPS de Montpellier.

Participants

10 femmes et 10 hommes pratiquant une activité physique régulière (≥ 1 fois par semaine).

Dates et lieu

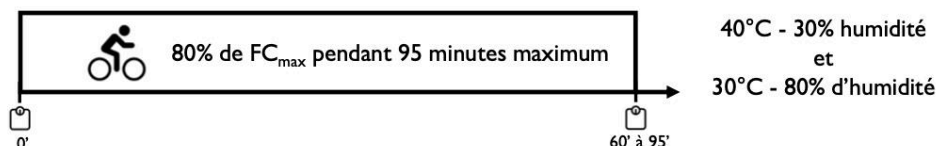
- Du 5 au 28 juin, 2 sessions de 3h par participant(e)
- CREPS de Montpellier, 2 Avenue Charles Flahaut

Intérêt

- Un bon d'achat de 50€
- Connaître son taux de sudation dans un environnement chaud pour mieux adapter son hydratation
- Participer à une étude scientifique innovante

Protocole de l'étude

95 minutes de vélo à intensité soutenue. Réalisé 2 fois, en chambre environnementale, avec minimum 24h de repos entre chaque session.



Si vous êtes intéressé.e, écrivez à cette adresse :

debardonneche.jean@gmail.com



Appendix 4: Custom R script - Pearson's correlation

```
library(ggplot2)

correlation_function = function(variable_x, variable_y, label_x, label_y, x
_name, y_name, path){

  # Create data frame and keep complete rows only
  data_frame <- data.frame(variable_x, variable_y)
  data_frame <- data_frame[complete.cases(data_frame),]

  # Calculate Pearson correlation coefficient and perform Bravais-Pearson t
  est
  correlation <- cor(data_frame$variable_x, data_frame$variable_y)
  cor_test <- cor.test(data_frame$variable_x, data_frame$variable_y)

  # Perform linear regression
  linear_model <- lm(variable_x ~ variable_y, data = data_frame)
  r_squared <- summary(linear_model)$r.squared
  formula <- paste(
    "y = ",
    round(summary(linear_model)$coefficients[2], 3),
    "x + ",
    round(summary(linear_model)$coefficients[1], 2),
    sep = ""
  )

  # Generate correlation plot
  plot_cor = ggplot(data_frame, aes(x = variable_x, y = variable_y)) +
    geom_point(alpha = 1, size = 1, stroke = FALSE) +
    geom_smooth(method = "lm", formula = y ~ x, se = FALSE, color = "red",
linewidth = 0.5) +
    annotate(
      "text",
      x = min(data_frame$variable_x, na.rm = TRUE),
      y = max(data_frame$variable_y, na.rm = TRUE),
      label = paste(
        "r:", round(correlation, 3), "\n",
        "p-value:", ifelse(cor_test$p.value < 0.001, "<0.001", format(cor_t
est$p.value, digits = 2)), "\n",
        "R²:", round(r_squared, 3)
      ),
      hjust = 0, vjust = 1, size = 3,
      color = "darkblue", family = "Arial", alpha = 0.7
    ) +
    labs(x = label_x, y = label_y) +
    theme_bw() +
    theme(
      panel.grid = element_blank(),
      legend.position = "none"
    )

  # Save figure
  setwd(path)
```

```
ggsave(  
  paste("corplot-", x_name, "-", y_name, ".png", sep = ""),  
  plot_cor,  
  width = 4, height = 3, dpi = 800  
)  
return(plot_cor)  
}
```

Appendix 5: Custom R script - Pearson's Chi-squared test for count data

```
chi_function_2by2 = function(row1_name, row2_name, col1_name, col2_name, top_left, top_right, down_left, down_right, path, id){
  chi_table <- matrix(c(top_left, top_right, down_left, down_right), nrow = 2, byrow = TRUE,
                      dimnames = list(c(row1_name, row2_name), c(col1_name, col2_name))) # create the matrix
  chi_result_1 <- chisq.test(chi_table, correct=FALSE)

  expected_frequencies <- chi_result_1$expected
  min_expected_frequency <- min(expected_frequencies)

  chi_result <- chisq.test(chi_table)

  res = data.table("Variable" = c(rownames(chi_result$observed)), chi_result$observed,
                  "Incidence/1000" = c(round(top_left/(top_right+top_left)*1000, 1), round(down_left/(down_right+down_left)*1000, 1)), # calculate the incidence /1000
                  "RR" = c(round((top_left/(top_right+top_left)*1000)/(down_left/(down_right+down_left)*1000), 2), NA), # calculate the risk ratio incidence female / incidence male if male is the reference
                  "Df" = c(chi_result$parameter, NA), # Degree of freedom
                  "X2" = c(round(chi_result$statistic, 2), NA), # X2 coeff
                  "P" = c(round(chi_result$p.value, 3), NA)) # P value

  write_xlsx(res, paste0(path, id, "_chi_results.xlsx"))
}
```

Appendix 6: Custom R script - Negative binomial regression with leave-one-out cross-validation

```
library(tidyr)
library(dplyr)
library(pscl)
library(Metrics)
library(MASS)
library(parallel)
library(writexl)

# Configuration
set.seed(123)
df1 <- read.csv("path.csv")
df1 <- df1 %>% drop_na() # clean NAs
response_var <- "ehs" # or med or dnf
predictors <- setdiff(colnames(df1), response_var)

# LOOCV function
get_loocv_metrics <- function(data, formula_str) {
  n <- nrow(data)
  actual <- numeric(n)
  predicted <- numeric(n)

  for (i in 1:n) {
    train <- data[-i, ]
    test <- data[i, , drop = FALSE]

    model <- try(glm.nb(as.formula(formula_str), data = train), silent = TRUE) # "try" allow the code to run even if there is no solution found.

    if (!inherits(model, "try-error")) { # if not solution, return NA, if solution, run normal stats. inherits() catch the errors formulated by try().
      pred <- predict(model, newdata = test, type = "response")
      actual[i] <- test[[response_var]]
      predicted[i] <- pred
    } else {
      return(c(RMSE = NA, MAE = NA, SDAE = NA))
    }
  }
  errors <- abs(actual - predicted)
  return(c(RMSE = rmse(actual, predicted), MAE = mae(actual, predicted), SDAE = sd(errors)))
}

results <- data.frame()

# List all models
all_models <- list()
for (k in 1:length(predictors)) {
  combos <- combn(predictors, k, simplify = FALSE)
  all_models <- c(all_models, combos)
}
```

```

# Evaluate models
evaluate_model <- function(vars) {
  formula_str <- paste(response_var, "~", paste(vars, collapse = " + "))

  model <- try(glm.nb(as.formula(formula_str), data = df1), silent = TRUE)

  if (!inherits(model, "try-error")) {
    preds_train <- predict(model, type = "response")

    # For unilateral LOOCV
    coef_value <- coef(model)[2] # Get coefficient for the independent variable
    p_value <- summary(model)$coefficients[2, 4] # Get p-value

    # Key variables
    AIC_val <- AIC(model)
    logLik_val <- logLik(model)
    pseudoR2 <- capture.output(r2 <- pR2(model))
    pseudoR2 <- r2["McFadden"]
    RMSE_train <- rmse(df1[[response_var]], preds_train)
    MAE_train <- mae(df1[[response_var]], preds_train)
    loocv <- get_loocv_metrics(df1, formula_str)

    return(data.frame(
      Model = paste(names(coef(model))[-1], collapse = "+"),
      Predictors = length(vars),
      Coefficient = round(coef_value, 3), # For unilateral LOOCV
      P_Value = round(p_value, 4), # For unilateral LOOCV
      AIC = round(AIC_val, 1),
      LogLik = round(logLik_val, 1),
      PseudoR2 = as.numeric(round(pseudoR2, 3)),
      RMSE = round(RMSE_train, 3),
      MAE = round(MAE_train, 3),
      RMSE_LOOCV = as.numeric(round(loocv["RMSE"], 3)),
      MAE_LOOCV = as.numeric(round(loocv["MAE"], 3)),
      SDAE_LOOCV = as.numeric(round(loocv["SDAE"], 3))
    ))
  } else {
    return(NULL)
  }
}

# Start Parallelism
start_time <- Sys.time()
results_list <- mclapply(all_models, evaluate_model, mc.cores = detectCores() - 1) # run the function "evaluate_model" with each element of the list "all_models"
results <- do.call(rbind, results_list)
end_time <- Sys.time()
execution_time <- end_time - start_time
print(execution_time)

# Export results
write_xlsx(results, "path.xlsx")

```

Appendix 7: Custom R script - Bias and Bland-Altman analysis

```
library(DescTools)
library(ggplot2)
library(openxlsx)

validation_function = function(method1, method2, sex, condition, method1_label_Reg, method2_label_Reg, scale_reg, method1_label_BA, method2_label_BA, unit_BA, scale_y_BA, number_resolution, filename, working_directory){
  # Creation of the data frame
  df_general = data.frame("method1" = method1, "method2" = method2, "sex" = sex, "condition" = condition)
  df_general = df_general[complete.cases(df_general),] # keep only complete rows

  # labels
  bland_x = paste("Average", method1_label_BA, "and", method2_label_BA, unit_BA)
  bland_y = paste(method1_label_BA, "-", method2_label_BA, unit_BA)

  # Descriptives
  mean_method1 = mean(df_general$method1, na.rm = TRUE)
  mean_method2 = mean(df_general$method2, na.rm = TRUE)
  sd_method1 = sd(df_general$method1, na.rm = TRUE)
  sd_method2 = sd(df_general$method2, na.rm = TRUE)

  df_general$diff = df_general$method1 - df_general$method2
  df_general$diff_abs = abs(df_general$diff)
  df_general$diff_rel = df_general$diff / df_general$method1 * 100
  df_general$diff_abs_rel = abs(df_general$diff_rel)

  bias_method2 = mean(df_general$diff, na.rm = TRUE) # Mean Error, bias
  bias_method2_abs = mean(df_general$diff_abs, na.rm = TRUE) # Mean Absolute Error
  bias_method2_rel = mean(df_general$diff_rel, na.rm = TRUE) # Mean Percent Error, relative bias
  bias_method2_abs_rel = mean(df_general$diff_abs_rel, na.rm = TRUE) # Mean Absolute Percent Error

  sd_bias_method2 = sd(df_general$diff, na.rm = TRUE) # SD of the differences, random error
  sd_bias_method2_abs = sd(df_general$diff_abs, na.rm = TRUE) # SD of the absolute differences
  sd_bias_method2_rel = sd(df_general$diff_rel, na.rm = TRUE) # SD of the relative differences
  sd_bias_method2_abs_rel = sd(df_general$diff_abs_rel, na.rm = TRUE) # SD of the relative absolute differences

  # Concordance Correlation Coefficient (Lin)
  ccc = CCC(df_general$method1, df_general$method2)

  # Graph regression
  plot_regression <- ggplot(df_general, aes(x = method1, y = method2, color = sex, shape = condition)) +
```

```

    geom_point(size = 1.5) +
    geom_abline(slope = 1, intercept = 0, color = "black", linetype = "dashed") + # Identity line y = x
    labs(x = method1_label_Reg,
         y = method2_label_Reg) +
    scale_x_continuous(breaks = function(x) seq(floor(min(x)/scale_reg) * scale_reg, ceiling(max(x)/scale_reg) * scale_reg, by = scale_reg)) +
    scale_y_continuous(breaks = function(x) seq(floor(min(x)/scale_reg) * scale_reg, ceiling(max(x)/scale_reg) * scale_reg, by = scale_reg)) +
    scale_color_manual(values = c("H" = "#008080", "F" = "#FF7F50")) +
    scale_shape_manual(values = c("D" = 16, "H" = 17)) +
    theme_bw() +
    theme(panel.grid.major = element_blank(), panel.grid.minor = element_blank(), legend.position = "none")

# Graph Bland-Altman
df_general$mean <- (df_general$method1 + df_general$method2) / 2
loa_upper <- bias_method2 + 1.96 * sd_bias_method2 # Upper limit of agreement
loa_lower <- bias_method2 - 1.96 * sd_bias_method2 # Lower limit of agreement

plot_ba <- ggplot(df_general, aes(x = mean, y = diff, shape = condition)) +
  geom_hline(yintercept = bias_method2, color = "red", linetype = "solid", linewidth = 0.8) + # Mean difference
  geom_hline(yintercept = loa_upper, color = "grey", linetype = "dashed", linewidth = 0.8) + # Upper LOA
  geom_hline(yintercept = loa_lower, color = "grey", linetype = "dashed", linewidth = 0.8) + # Lower LOA
  geom_abline(slope = 0, intercept = 0, linetype = "dotted", color = "black", alpha = 0.8) + # Identity line (y=0)
  geom_point(size = 1.5, alpha = 0.6) +
  labs(x = bland_x, y = bland_y) +
  scale_x_continuous(breaks = function(x) seq(floor(min(x)/scale_reg) * scale_reg, ceiling(max(x)/scale_reg) * scale_reg, by = scale_reg),
                    limits = c(15, 105)) + # x-axis limits
  scale_y_continuous(breaks = function(x) seq(floor(min(x)/scale_y_BA) * scale_y_BA, ceiling(max(x)/scale_y_BA) * scale_y_BA, by = scale_y_BA),
                    limits = c(-35, 60)) + # y-axis limits
  scale_shape_manual(values = c("D" = 16, "H" = 17)) +
  theme_bw() +
  theme(panel.grid.major = element_blank(), panel.grid.minor = element_blank(), legend.position = "none")

# Export results
# Create the first data frame for the first sheet
result_df = data.frame("DESCRIPTIVES" = c(paste(method1_label_Reg, ": ", round(mean_method1, number_resolution), " SD ", round(sd_method1, number_resolution), sep = ""),
                                           paste(method2_label_Reg, ": ", round(mean_method2, number_resolution), " SD ", round(sd_method2, number_resolution), sep = ""),
                                           paste("n:", nrow(df_general)),
                                           paste("")),

```

```

        paste("VALIDATION", " (", method1_label_Reg, "-", method2_label_Reg, ")", sep = ""),
        paste("Mean Error:", round(bias_method2, number_resolution),
            "+", round(sd_bias_method2, number_resolution)),
        paste("Mean Percent Error (%):", round(bias_method2_rel, 1),
            "+", round(sd_bias_method2_rel, 1)),
        paste("Mean Absolute Error:", round(bias_method2_abs, number_resolution),
            "+", round(sd_bias_method2_abs, number_resolution)),
        paste("Mean Absolute Percent Error (%):", round(bias_method2_abs_rel, 1),
            "+", round(sd_bias_method2_abs_rel, 1)),
        paste("LOA upper:", round(loa_upper, number_resolution)),
        paste("LOA lower:", round(loa_lower, number_resolution)),
        paste("Correlation (r):", round(cor_method1_method2, 3)),
        paste("Regression (R2):", round(cor_method1_method2*cor_method1_method2, 3)),
        paste("Concordance correlation coefficient:", round(as.numeric(ccc$rho.c[1]), 3)))

# Create the workbook
wb <- createWorkbook()
addWorksheet(wb, "Descriptives") # Add the first sheet with result_df
writeData(wb, sheet = "Descriptives", result_df)

# Save
setwd(working_directory)
saveWorkbook(wb, file = paste(filename, "_results.xlsx", sep = ""), overwrite = TRUE)
ggsave(paste(filename, "_reg_graph", ".png", sep = ""), plot_regression, width = 5, height = 3, dpi = 400)
ggsave(paste(filename, "_ba_graph", ".png", sep = ""), plot_ba, width = 4, height = 3, dpi = 400)
}

```

Appendix 8: Custom R script - Linear mixed-effects model

```
library(dplyr)
library(tidyverse)
library(lme4)
library(lmerTest) # gives p-values for fixed effects
library(emmeans)

# Open the file
validation_df = read.csv("path.csv")
validation_df = validation_df %>%
  select(ID, Sex, condition, Laqua, S1, FP)

# Long-format data set: creation of columns: Participant, Condition, Device
# and sweat [Na+] values. Remove NA values
data <- validation_df %>%
  mutate(
    Participant = substr(ID, 1, 1), # extract first letter (participant ID
  )
    Condition = ifelse(condition == "H", "Humid", "Dry")
  ) %>%
  pivot_longer(
    cols = c(Laqua, S1, FP),
    names_to = "Device",
    values_to = "Na"
  ) %>%
  drop_na(Na) # remove rows where Na is missing

data$Device <- factor(data$Device, levels = c("FP", "S1", "Laqua"))
data$Condition <- factor(data$Condition, levels = c("Dry", "Humid"))

# Linear mixed effect
model_Na <- lmer(Na ~ Device * Condition + (1 | Participant), data = data)
summary(model_Na)

# Post-Hoc
emmeans(model_Na, pairwise ~ Device | Condition)
```

Appendix 9: Custom R script - Paired comparisons

```
library(dplyr)
library(ggplot2)
library(tidyr)
library(rstatix)
library(grDevices)
library(gridExtra)

two.groups.paired.comparison = function(id, group, variable, parametric, y_
label,
                                     export_name, pathway, height_signif
icance, decimals){
  df = data.frame(id, group, variable)
  df <- df %>%
    filter(!is.na(variable)) %>% # Remove rows with NA in "variable"
    filter(id %in% id[duplicated(id)]) # Keep only IDs that are repeated

  # Descriptives
  summary_data <- df %>%
    group_by(group) %>%
    summarize(mean = mean(variable), sd = sd(variable))

  # Plot the data
  plot <- ggerrorplot(
    df, x = "group", y = "variable",
    xlab = "", ylab = y_label,
    desc_stat = "mean_sd",
    error.plot = "errorbar",
    add = c("mean_sd", "jitter"),
    color = "group",
    add.params = list(alpha = 0.4)
  ) +
    geom_point(data = summary_data, aes(x = group, y = mean, color = group)
, size = 3, shape = 16, stroke = 0) +
    scale_color_manual(values = c("#009E73", "#0072B2", "#009E73", "#0072B2
")) +
    # scale_y_continuous(breaks = seq(25, 30, by = 0.5)) +
    theme_bw() +
    theme(legend.position = "none")

  # Identify outliers
  df_wide <- df %>%
    pivot_wider(names_from = group, values_from = variable, names_prefix =
"")
  df_wide$differences = df_wide[[names(df_wide)[2]]]-df_wide[[names(df_wide
)[3]]]
  outliers = df_wide %>%
    identify_outliers(differences)
  if (nrow(outliers) == 0) {outliers[1,] = 0}

  # Compute Shapiro wilk test by groups. If significant: perform Wilcoxon t
est.
  normality = df_wide %>%
```

```

shapiro_test(differences)

# Paired comparison
if (parametric == "y") {
  # Student paired T-test for normal distribution
  stat.test <- df %>%
    t_test(variable ~ group, paired = TRUE, detailed = FALSE) %>%
    add_significance()
  # Effect size for normal distribution
  effect_size = df %>% cohens_d(variable ~ group, paired = TRUE)
  type.test = "Parametric test"} else {
  # Wilcoxon T-test if not normal distribution
  stat.test <- df %>%
    wilcox_test(variable ~ group, paired = TRUE, detailed = FALSE) %>%
    add_significance()
  # Effect size for non-normal distribution
  effect_size = df %>% wilcox_effsize(variable ~ group, paired = TRUE)
  type.test = "Non-parametric test"}

# Add significance to the graph
if(stat.test$p.signif[1] == "****"){stat.test$p.signif[1] = "****"}
stat.test.significance = stat.test
stat.test.significance$xmin = 1
stat.test.significance$xmax = 2
stat.test.significance$groups = list(c(stat.test.significance$group1[1],
stat.test.significance$group2[1]))
stat.test.significance$y.position = max(df$variable)*height_significance

plot = plot +
  stat_pvalue_manual(stat.test.significance, tip.length = 0, hide.ns = TR
UE)

# Export results
# Plot
setwd(pathway)
ggsave(paste("Comparison_", export_name, ".png", sep = ""), plot, width =
3, height = 3, dpi = 500)
# PDF
normality$significant = ifelse(normality$p < 0.05, "non-parametric", "par
ametric")
normality$p = round(normality$p, 3)
names(normality)[4] = "normality p"
normality$statistic = round(normality$statistic, 3)
stat.test$p.label = ifelse(stat.test$p < 0.001, "<0.001", ifelse(stat.tes
t$p < 0.01, "<0.01", ifelse(stat.test$p < 0.05, "<0.05", "ns")))
if (parametric == "y") {stat.test$df = round(stat.test$df, 2)}
stat.test$statistic = round(stat.test$statistic, 2)
summary_data$mean = round(summary_data$mean, decimals)
summary_data$sd = round(summary_data$sd, decimals)
summary_data = rbind(summary_data, c("diff", round(mean(df_wide$differenc
es), decimals), round(sd(df_wide$differences), decimals)))
effect_size$effsize = round(effect_size$effsize, 3)

layout_matrix <- rbind(c(1), c(2), c(3), c(4), c(5), c(6))

```

```

pdf(paste("Comparison_", export_name, ".pdf", sep = ""), width = 210 / 25
.4, height = 297 / 25.4) # A4
grid.arrange(plot, tableGrob(summary_data), tableGrob(stat.test), tableGr
ob(effect_size), tableGrob(normality), tableGrob(outliers),
              widths = c(1),
              heights = c(0.3, 0.1, 0.1, 0.1, 0.1, 0.1),
              layout_matrix = layout_matrix,
              top = paste("\n", names(df_wide)[2], " vs ", names(df_wide)[
3], " - " , y_label, "\n", type.test, "\n\n", sep = ""),
              left = "\n\n", # margins
              bottom = "\n\n",
              right = "\n\n")
dev.off()
}

```

