Applied Physiology, Nutrition, and Metabolism

Review

Physiological monitoring for occupational heat stress management: recent advancements and remaining challenges

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Abstract

Occupational heat stress poses a major threat to worker health and safety that is projected to worsen with global warming. To manage these adverse effects, most industries rely on administrative controls (stay times and work-to-rest allocations) that are designed to limit the rise in body core temperature in the "average" individual. However, due to the extensive inter- and intra-individual variation in thermoregulatory function, these administrative controls will result in some individuals having their work rate and productivity unnecessarily restricted (false positives), while others may be subject to rises in heat strain that compromise health (false negatives). Physiological monitoring has long been touted as a more effective approach for individualized protection from excessive heat stress. This has led to extensive interest in the use of wearable technology for heat stress management from both the scientific community and manufacturers of wearable devices, which has accelerated in the past decade. In this review, we evaluate the merits of the recent and emerging approaches to manage occupational heat strain with wearable physiological monitors. Against this background, we then describe the issues that we perceive to be unresolved regarding the use of wearable heat strain monitors and the research efforts needed to address those issues. Particular emphasis is directed to the efficacy of existing physiological indicators of heat strain, how to define upper limits for those indicators and the efforts required to rigorously validate emerging wearable heat strain monitoring devices.

Key words: hyperthermia, monitoring, safety, thermal strain, thermoregulation, work

Introduction

In many industries (e.g., construction, mining, firefighting, the military), workers are required to perform physically demanding work in hot environments, often whilst wearing heavy protective clothing (Flouris et al. 2018). Under such conditions, the body's physiological capacity to offset heat gain can often be overwhelmed, resulting in progressive rises in body temperature, cardiovascular demand and fluid depletion (Taylor et al. 2021). These increases in physiological (heat) strain cause marked reductions in productivity (Kjellström et al. 2019), and may lead to deadly heat-related illnesses (Gibb et al. 2024). Protracted workplace heat exposure can also cause psychophysical strain (e.g., discomfort, fatigue) and undetected aftereffects (e.g., cell and organ damage) that may aggravate underlying health conditions or progress to chronic illnesses (e.g., chronic kidney disease) (Kenny et al. 2010; Chapman et al. 2021). Unfortunately, due to the projected increases in the frequency and intensity of hot weather, occupational heat stress is expected to further compromise health and productivity and increasingly become an issue for workers in temperate climates (Ebi et al. 2021).

To manage the deleterious effects of heat stress on worker health and productivity, most industries rely on stay times and work-to-rest allocations (administrative controls) based on the environmental conditions, clothing worn and work intensity (Jacklitsch et al. 2016). However, due to the extensive individual variability in thermoregulatory functions (Foster et al. 2020), these controls unnecessarily restrict productivity in some individuals, while subjecting others to increases in heat strain that may compromise health. To provide more individualized protection, it has long been recommended that one or more physiological indices of heat strain (e.g., heart rate, body core temperature) should be monitored (Bernard and Kenney 1994). In theory, this approach maximizes productivity in more heat-tolerant individuals, while preventing heat-related illness is in the less heat-tolerant.

For this reason, there has been considerable interest from both the scientific community and manufacturers in developing physiological monitoring approaches and technology for occupational heat stress management over the past several decades. This has been aided by recent advancements in commercial-off-the-shelf (COTS) sensors and mathematical modelling techniques. To synthesize this work, several investigators have reviewed the topic (Buller et al. 2017, 2018; Friedl 2018; Notley et al. 2018; Cannady et al. 2024). However, these reviews often focused on the specifications of the monitors themselves (e.g., weight, dimensions), rather than the strengths and limitations of the approaches employed to quantify and manage heat strain (e.g., heart rate predictions of body core temperature). Further, less attention has been directed to emerging approaches (e.g., arterial wave form monitoring, biofluid sensing), which show promise, but have not yet been incorporated into commercially available devices for heat management. Finally, none have thoroughly described the key scientific challenges related to the use of physiological monitors that, in our view, must be resolved before such technology can serve as an effective, mainstream strategy for occupational heat stress management. These relate to the efficacy of physiological indicators for quantifying heat strain, how to set appropriate upper limits for those indicators, and how best to validate wearable heat strain monitors.

The purpose of this review is twofold. First, we describe the rationale for physiological monitoring in occupational heat stress management and the recent advancements in the use of wearable physiological monitors to manage occupational heat strain, with emphasis on promising emerging approaches. We discuss selected physiological monitoring systems as examples as an approach to heat strain management, although our focus is on the merits of those approaches, rather than the monitors themselves, as these have been discussed in detail elsewhere (Cannady et al. 2024). Second, we describe what we believe are unresolved scientific challenges related to the use of wearable heat strain monitoring technologies and discuss the research efforts needed to address them. We hope that this communication will serve as both a resource and roadmap for researchers and occupational health and safety practitioners seeking to implement wearable technologies to improve heat stress management in our warming climate.

Rationale for physiological monitoring

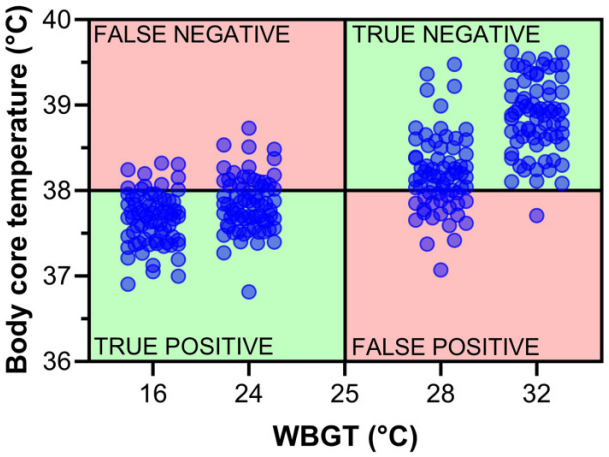
To manage occupational heat stress, safety organisations such as the Australian Institute of Occupational Hygienists and National Institute for Occupational Safety and Health provide guidance documents for heat management. These include practices directed at mitigating heat stress such as engineering (e.g., ventilation, shade) and administrative controls (e.g., work-to-rest allocations), and hygiene practices (e.g., personal cooling devices, fluid consumption schedule). However, due to the nature of most occupations, engineering controls and hygiene practices are often unfeasible because of logistical, cultural and financial aspects or offer limited effectiveness. Heat stress is therefore managed primarily with administrative controls that provide recommended stay times or work-to-rest ratios to moderate metabolic heat production or exposure time (Jacklitsch et al. 2016).

Perhaps the most well-known administrative controls are those from the American Conference of Governmental Industrial Hygienists (ACGIH), which comprise look-up tables with work-to-rest allocations based on a workers' metabolic rate and the prevailing wet-bulb globe temperature (WBGT) (ACGIH 2017). The guidelines contain two sliding scale limits, termed the action limit (AL) and threshold limit values (TLV), which aim to prevent rises in body core temperature greater than ~1 °C. Similar, albeit less conservative, look-up tables are also relied upon to manage heat stress by military organisations Worldwide (e.g., US, Australia, UK) (Notley and Fogarty 2022). However, occupational heat stress remains a major hazard for workers (Flouris et al. 2018). This is likely because these tables are designed to limit rises in body core temperature in the "average" individual, even though there is extensive inter- and intra-individual variation in thermoregulatory function (Foster et al. 2020). Consequently, when following such look-up tables, more heat tolerant workers will have their work rate unnecessarily restricted (false positives), while less heat tolerant workers may experience excessive increases in body core temperature that compromise safety (false negatives) (Notley et al. 2019*a*).

These challenges are illustrated in Fig. 1, where data from two recent experiments have been reanalyzed (Notley et al. 2021, 2022). In these reports, 76 nonheat acclimatized adults (15 women) each completed four trials involving 3 h of treadmill walking at a moderate intensity (metabolic heat production: 200 W/m^2) in single-layer cotton coveralls. Each trial differed only in the prevailing WBGT, with two conditions below the ACGIH action limit (AL) (16 and 24 °C) and two above (28 and 32 °C) (ACGIH 2017). When working below the AL, 75% of individuals displayed peak body core temperatures within recommended limits (<38 °C; true positives, green area). However, the remaining 25%, who were presumably less heat tolerant, demonstrated body core temperatures exceeding this limit (false negatives; pink shaded area). When working above the AL, 80% of participants exceeded this core temperature limit as expected, while 20% were working within safety limits in these conditions, despite being above the AL (false positives; pink area). Importantly, the magnitude of false positives and negatives are likely compounded in most instances, due to the challenges associated with accurately calculating the work-to-rest schedule when the work or environmental conditions are rapidly changing (Fogarty and Notley 2022).

For some time, physiological monitoring has been recommended to address these shortcomings (Bernard and Kenney 1994). This approach should theoretically prevent the over- or under-protection of individuals from heat-related illness (i.e., false positives and false negatives) by maximising work intensity and duration in more heat-tolerant individuals and preventing heat-related illness by moderating the work intensity or duration in the less heat-tolerant. Further, these physiological data can be used to inform individual readiness to perform certain tasks (e.g., shift rotations, job allocation) or identify the presence of other risk factors (e.g.,

Fig. 1. Example of the distribution of body core temperatures when conditions fall above and below the American Conference of Governmental Industrial Hygienists (ACGIH) action limit (AL). Data were reanalyzed from two recent experiments. In these reports (Notley et al. 2021, 2022), a total of 76 nonheat acclimatized adults (15 women) each completed four trials involving 3 h of treadmill walking at a moderate intensity (metabolic heat production: 200 W/m^2) in single-layer coveralls. Each trial differed only in the prevailing wet-bulb globe temperature (WBGT), which was 16, 24, 28, or 32 °C. Based on the ACGIH AL, work at this intensity can be performed continuously up to a WBGT of 25 °C, placing two conditions below the AL (16 and 24 °C) and two above it (28 and 32 °C). When working below the AL, 75% of individuals displayed peak body core temperatures within recommended limits (38 °C) and would be considered true positives (green area). However, 25% of those participants, who were presumably less heat tolerant, demonstrated body core temperatures exceeding this limit (false negatives; pink shaded area). When working above the AL, 80% of participants exceeded this core temperature limit as expected (true negatives; green area), albeit 20% of participants could have continued working safely in these conditions, despite being above the AL (false positives; pink area).



acute illness or infection). This approach also reduces the burden on the individual or supervisor to closely monitor the clothing worn, environmental conditions and work intensity, which is necessary when using current look-up tables. Real-time physiological monitoring therefore has the potential to significantly enhance worker health and productivity, particularly in instances where the work conditions are rapidly changing.

Recent advancements in heat strain monitoring approaches

Exposure to occupational heat stress is associated with numerous compensatory physiological responses linked to body temperature regulation. A comprehensive discussion of these processes is beyond the scope of this communication, although we encourage reading of reviews on the topic from González-Alonso et al. (2008), Hales et al. (2010), and Sawka et al. (2011). Theoretically, each of these responses could serve as an indicator of heat strain, although the most appropriate will reflect a balance between what can be measured or accurately predicted using wearable technologies in real-time, and the indicator(s) providing the best diagnostic information on the limits of thermal tolerance. In the following subsections, we review the approaches that have been recently applied to monitor heat strain, along with promising emerging approaches that have not yet been integrated into commercially-available systems.

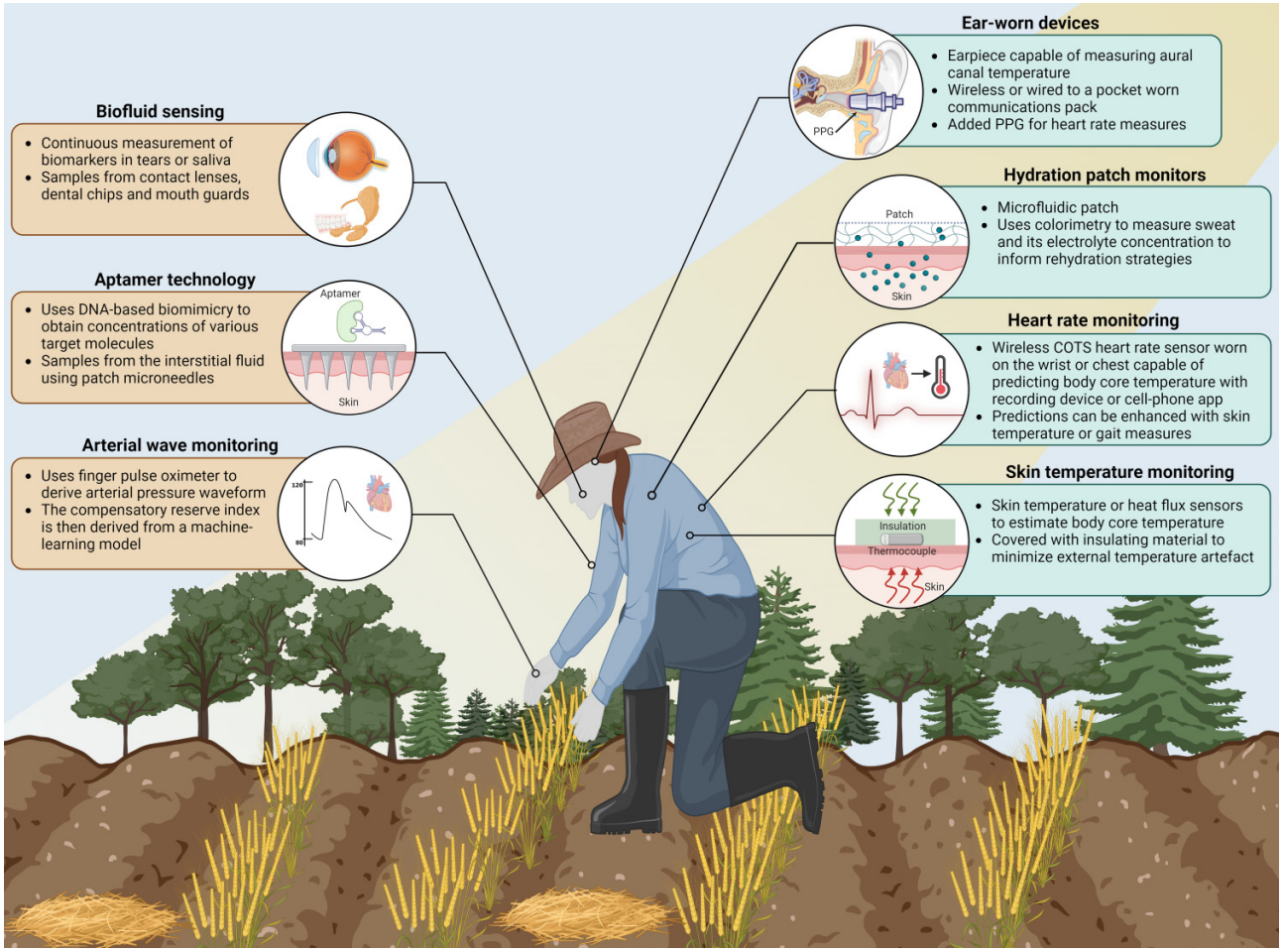
Body temperature monitoring

To maintain homeostasis, humans strive to regulate body temperature within a relatively narrow range. However, due to the nature of many occupations, workers frequently operate in hot, humid environments, which restrict heat dissipation and cause progressive rises in body heat storage, and thus, body core temperature. While the body core temperature threshold that may compromise safety is highly variable, exertional heat stroke is defined clinically as a body core temperature > 40 °C, coupled with central nervous system dysfunction (Epstein and Yanovich 2019). For this reason, body core temperature remains the primary target for occupational heat strain monitoring.

Unfortunately, the most precise and rapidly responding measurements of body core temperature (e.g., esophageal temperature) can be difficult to obtain in an occupational setting due to the need for invasive, wired, or expensive equipment (Taylor et al. 2014). As such, emphasis is often placed on less invasive sites such as the auditory canal (Fig. 2), which has been shown to loosely track esophageal temperature during work in the heat under controlled, laboratory conditions (Greenleaf and Castle 1972; Todd et al. 2014). However, since it can be influenced by external air and surface temperatures, it is important to minimize this bias when used in the workplace. This can be achieved by insulating the sensor (Muir et al. 2001) or through a zero-gradient approach (Keatinge and Sloan 1973), where a heating device is placed on the pinna to track and replicate aural canal temperature to minimize internal/external heat transfer.

In recent years, several manufacturers have developed ear-worn devices capable of aural canal temperature measurements (Table 1), although it remains unclear whether the measurements obtained are resistant to external temperature artefacts. For example, the Bodytrak® consists of an ear-piece containing an aural canal thermometer and external temperature sensor wired to a pocket worn communications pack, which transmits data to a cloud-based server for monitoring (Table 1). Although the manufacturers report an absolute error of 0.18 °C when compared to gastrointestinal temperature, we are not aware of independent efforts to validate the device. The Cosinuss° Two (Cosinuss° GmbH, Munich, Germany) is a similar system, with the additional benefit of being wireless. However, while activities directed at evaluating the validity of the Cosinuss° are sparse (Roossien et al. 2020, 2021; Ellebrecht et al. 2022), its accuracy has been reported to suffer during outdoor work, suggesting that it

Fig. 2. Schematic summary of recent applied (green text boxes; right side) approaches to occupational heat stress management with wearable physiological monitors. These have centred on body core temperature monitoring using in-ear sensors, skin temperature (heat flux) monitoring, heart rate predictions of body core temperature, often in conjunction with secondary variables (e.g., gait variability), and monitoring hydration state with microfluidic patches. There are also emerging approaches (orange text boxes; left side), which aim to utilize arterial wave form monitoring and biofluid sensing technology, to quantify alternative markers of physiological strain in the interstitial fluid for heat management. However, the technology supporting these sensors has not yet been incorporated into wearable monitors for occupational heat stress management at the time of writing. Abbreviations: PPG, photoplethysmogram; COTS, commercial-off-the-shelf. Created with BioRender.com.



may still be impacted by environmental temperature fluctuations (Roossien et al. 2021).

Skin surface temperature is another physiological indicator often incorporated into wearable physiological monitoring systems (Table 1). Given it is influenced by environmental (ambient and surface temperatures) and clothing parameters (insulation and permeability), metabolic heat production, as well as behavioural and autonomic heat loss responses, it offers limited value as an independent index of heat strain (Taylor et al. 2014). However, placing insulating material (e.g., foam or rubber) over a thermistor or thermocouple on the skin surface or using a zero-gradient method (as mentioned above) to minimize the influence of extraneous heat sources, allows skin temperature (and heat flux) to more closely track body core temperature (Fox and Solman 1971; Gunga et al. 2009).

Such heat flux technology has recently been incorporated into fully wireless systems worn on the chest or wrist to assess occupational heat strain (Fig. 2). For example, the CORE/CALERA Research sensor (greenTEG AG, Rümlang, Switzerland) uses a heat flux sensor and skin temperature sensor to estimate body core temperature using proprietary algorithms (Table 1). However, the CORE and similar heat-flux based systems may not provide the precision required to act as a suitable alternative to direct measures of body core temperature (Verdel et al. 2021; Daanen et al. 2023; Desroches et al. 2023; Goods et al. 2023). For example, when the CORE was compared to measured rectal temperature during exercise in temperate and hot environmental conditions, approximately 50% of estimates exceeded pre-defined acceptance limits (±0.3 °C) (Verdel et al. 2021).

Table 1. Examples of recently developed commercially available wearable physiological monitoring systems for heat strain management.

System	Measured variables[a]	Estimated variables	Design	Dimensions	Weight	Run time	Operating conditions	Other assets
Bodytrak (Inova Design Solutions Ltd.)	HR, T_{core}, HRV	n/a	In-ear device wired to communication pack (CommPack)	In-ear device: 8–13 mm. CommPack: not listed	n/a	8–12 h	n/a	Smart phone compatibility. Audible alerts. Data transmission to cloud.
Cosinuss° Two in-ear sensor® (Cosinuss°)	HR, HRV, T_{core}, SpO_2	n/a	Wireless in-ear device	45 × 38 × 18 mm	6.5 g	8 h with 1 h recharge	−15 to 55 °C	Smart phone compatibility.
CORE/CALERA (greenTEG AG)	T_{sk}, heat flux	T_{core}	Sensor worn as a patch or part of an arm or chest band	50 × 40 × 8.35 mm	17 g	6 days	n/a	Smart phone and 3rd-party device compatibility. Sweatproof. Waterproof.
BAND V2 (Slate Safety)	HR	T_{core}	Arm band with logging device	68.6 × 71.1 × 13.5 mm	82 g	24–100 h	−20 to 45 °C; 5%–95% RH	Smartphone compatibility. Light and vibration alerts. FCC and CE certified. Dust resistant. Submersible up to 150 feet.
KENZEN Smart Device (KENZEN)	HR, motion, T_{sk}	T_{core}	Arm band with logging device	64 × 56 × 7.5 mm	30 g	14–16 h with 4 h recharge	−10 to 50 °C; 0%–100% RH	Sweatproof. Waterproof. Vibration alerts.
ARMOR (Evalan)	HR	T_{core}, PSI	Arm band and logging device	n/a	n/a	n/a	n/a	Smartphone compatibility.
Connected Hydration (Epicore Biosystems Inc.)	T_{sk}, sweat rate, electrolyte concentration	n/a	Single use adhesive arm patch with attached sensor	Patch: 94 × 48 × 0.76 mm Sensor: 66 × 30 × 10 mm	21 g	1000 h	5 to 45°C	Smartphone compatibility. Hypoallergenic skin adhesive.

[a]Does not include nonphysiological measures (e.g., location). Abbreviations: HR (heart rate), HRV (heart rate variability), Tsk (skin temperature), Tcore (body core temperature), RH (relative humidity), n/a (information unavailable or not applicable), CE (conformity to European health and safety standards), FCC (Federal Communications Commission certified), SpO2 (oxygen saturation). The information presented was extracted from website documentation (BioHarnessTM 3.0; https://www.zephyranywhere.com/resources/documentation; BodyTrak: https://bodytrak.co/smart-safety-solution/bodytrak-1/; Cosinuss: https://store.cosinuss.com/products/cosinuss-two?variant=32175832924242; CORE/CALERA: https://shop.greenteg.com/core-body-temperature/caleraresearch. Band V2: https://slatesafety.com/products/band-v2/; KENZEN: https://kenzen.com/superior-science; ARMOR: https://evalan.com/products/armor/; Connected Hydration: https://www.epicorebiosystems.com/our-solutions/connected-hydration. Information on the costs of each device can be obtained by contacting the manufacturers via the website links above.

Another indirect approach that has become increasingly prevalent involves the estimation of body core temperature from heart rate (Fig. 2). The most well studied is the estimated core temperature (ECTemp) algorithm, developed by the United States Army Research Institute of Environmental Medicine (Buller et al. 2013). It uses a Kalman filter to estimate body core temperature from changes in heart rate, measured with a COTS monitor. The algorithm relies on the assumption that heart rate contains information about both metabolic heat production and convective heat loss (from skin blood flow) and should therefore track increases in body core temperature. It has been reported to have a small bias (-0.03 ± 0.32 °C), albeit with 95% of predictions falling within ± 0.63 °C of rectal or gastrointestinal temperature across a broad range of environmental and work conditions (Buller et al. 2013). However, while several wearable systems have adopted the ECTemp algorithm, including the ARMOR (Evalan, Amsterdam, The Netherlands), Eq Lifeband (Equivital, Cambridge, United Kingdom), and Zephyr Bioharness™ (Medtronics, Boulder, United States) (Cannady et al. 2024), it may have substantial false positive and false negative rates when used for heat stroke detection. For instance, Hintz et al. conducted a large study involving 47 058 daily peak body core temperature estimates obtained with the Zephyr Bioharness™ from 1364 US Air force trainees (Hintz et al. 2024). Of the 499 trainees flagged as potential exertional heat stroke cases by the system (ECTemp readings > 39.7 °C), only two developed heat stroke. Further, another 8 individuals developed heat stroke without being detected by the system. This resulted in a sensitivity (true positive rate) of 20% and specificity (true negative rate) of 99%.

To improve the sensitivity of heart-rate based algorithms, others have incorporated supplementary measurements of gait instability, skin temperature, and environmental conditions to anticipate heat stroke cases before they occur (Seng et al. 2016; Eggenberger et al. 2018; Laxminarayan et al. 2018, 2023; Nazarian et al. 2021; Buller et al. 2022). For example, Buller et al. (2022) recently incorporated a trunk-worn tri-axial accelerometer, capable of measuring gait-instability, with the ECTemp to predict the onset of exertional heat stroke. In that analysis, which included 3422 datasets from thermally stressful military training (e.g., loaded marching), six soldiers were diagnosed with heat stroke ≥ 3.5 min in advance of collapse. However, there were also 209 false positives, giving a positive predictive value of 2.8%. In another study (Laxminarayan et al. 2023), an algorithm was developed incorporating heart rate and skin temperature that could predict when body core temperature would exceed 38.5°C in 20 min time. During intermittent work in dry and humid heat ($n = 22$), sensitivity was reported to be 98% while specificity was 81%, albeit the positive predictive value of these estimates to identify heat stroke was not evaluated. Further, it currently remains unknown whether an additional 3.5 or 20 min lead time is sufficient to alert the individual or their supervisor to modify the level of heat stress to prevent incapacitation.

Integrated physiological responses

Heart rate and heart rate variability monitoring

Occupational heat stress not only represents a challenge to thermoregulation, but also to arterial blood pressure regulation. Indeed, in such conditions, cardiac output increases above what is required to provide oxygen to the working musculature to support thermoregulatory increases in skin blood flow (González-Alonso et al. 2008). To maintain arterial pressure, a coordinated response must occur. This involves compensatory elevations in heart rate that are proportional to both metabolic demand and the associated increases in body temperature, as well as the redistribution of blood volume from inactive skeletal muscle and visceral structures (e.g., liver and splanchnic regions). In instances where sweat losses cannot be matched by fluid intake, there is also a progressive reduction in blood (plasma) volume that causes further compensatory elevations in heart rate to maintain arterial pressure (González-Alonso et al. 2008). As such, it has been suggested that intolerance to work in the heat is more likely due to a cardiovascular insufficiency (Notley et al. 2024), and monitoring one or more of these cardiovascular adjustments may serve as a more precise heat strain indicator.

Given this physiological underpinning and the ease through which we can accurately measure heart rate with lightweight and relatively inexpensive wrist- and chest-worn sensors, heart rate (not as a method to predict core temperature) becomes an attractive index of occupational heat strain for wearable monitors (Fig. 2). However, heart rate is also inextricably linked to the metabolic demand of the task being performed, making it difficult to discriminate between increased heat strain and simply the increased demand for oxygen delivery. Further, it is heavily impacted by various intra- and inter-individual factors and the nature of the work being performed (i.e., static versus dynamic activity), which makes it difficult to set upper limits for heart rate that do not under- or over-protect each worker (discussed in the next section). As such, the merits of heart rate as a stand-alone marker of occupational heat strain require further investigation.

Although more complex to measure, indices of heart rate variability (HRV), which reflect the moment-to-moment variability of heart rate due to parasympathetic (vagal) and sympathetic modulation of cardiac pacemaker cells (Camm et al. 1996), are also being incorporated into wearable monitors with improvements in sensor technology. For example, in-ear systems such as Bodytrak® and Cosinuss° (Table 1), both incorporate photoplethysmography sensors to determine heart rate and some indices of HRV. In comparison to heart rate, it has been reported that nonlinear indices of HRV may have greater prognostic value in identifying adverse cardiovascular events compared to time- or frequency-domain derived HRV (Perkiömäki 2011). However, we are aware of only one attempt to examine their ability to predict the limits of tolerance during work in hot environments (De Barros et al. 2024). In that retrospective analysis, heart rate, percentage of maximum heart rate, percentage of heart rate reserve, the root-mean-square of successive differences (RMSSDs), the high

frequency (HF) power and the detrended fluctuation analysis component alpha 1 (DFA $\alpha 1$) within the first hour of heat exposure were used to identify the limits of thermal tolerance in a heterogeneous sample of men and women ($n = 48$) during 3 h moderate-intensity work in a hot environment. Discriminative ability, as indicated by the area under the receiver operating characteristic curve (ROC AUC), was highest for percentage heart rate reserve (ROC AUC [95% CI]: 0.80 [0.63, 0.90]), with all indices of HRV offering inferior performance (RMSSD: 0.74 [0.59, 0.88]; DFA $\alpha 1$; 0.66 [0.50, 0.81]; HF power; 0.59 [0.42, 0.75]). Despite the need for larger, more detailed studies, these outcomes suggest that measures of HRV may not provide value beyond that of heart rate for heat strain monitoring.

Hydration state monitoring

In many industries, sweat secretion can be excessive, ranging from between 1.0 and 1.5 $L \cdot h^{-1}$ (Brake and Bates 2003). Fluid losses of $\leq$ 3% body mass are usually well tolerated (and expected) when performing protracted work in hot environments (Taylor et al. 2021). However, more excessive fluid losses can increase heat strain (González-Alonso et al. 2008). Frequent heat strain and/or dehydration can also result in (subclinical) acute kidney injury that can progress to chronic kidney injury, which can be deadly (Chapman et al. 2021). Excessive fluid loss is therefore a factor that increases risk of both acute and chronic heat-related illness (Epstein and Yanovich 2019).

To avoid excessive dehydration, humans rely on osmoreceptors to detect plasma hypertonicity and release antidiuretic hormone to stimulate thirst and reduce urinary water loss (Mack and Nadel 2010). This thirst mechanism has been shown to effectively mitigate severe dehydration, provided water and food are readily available (Noakes 2011; Kenefick 2018). Further, since dietary sodium is usually sufficient to replace salts lost in sweat (Valentine 2007), supplementary electrolytes (isotonic fluids) are typically not required. However, wearable technology capable of sensing an individual's fluid losses may be beneficial during protracted work in hot environments, where food consumption is not possible and sweat losses can exceed fluid intake, resulting in "voluntary dehydration" (Adolph 1947).

Perhaps for these reasons, several manufacturers have developed personal monitors that aim to detect dehydration to assist with occupational heat strain management. These are typically microfluidic patches capable of measuring sweat loss and its electrolyte concentration through colorimetry (Fig. 2). For example, the EpiCore Biosystems Inc. (Cambridge, MA, United States) patch contains microfluidic sensors to collect these data along with a skin temperature sensor and accelerometer, all housed in a patch worn on the upper arm (Table 1). These data are then transmitted to the individual or supervisor via a companion cell phone application to provide dehydration alerts and rehydration recommendations. However, determining the exact rate of fluid consumption required to minimise whole-body sweat losses (and dehydration) with such a system is difficult and perhaps impossible. This is because local measures of sweat rate do not reflect whole-body sweat losses, primarily due to the extensive regional heterogeneity in sweat rate across the body surface (Taylor and Machado-Moreira 2013). Further, since sweat sodium concentration is flow (sweat rate) dependent, this regional heterogeneity in sweat rate also makes it difficult to accurately estimate electrolyte requirements (Taylor and Machado-Moreira 2013). As such, the utility of such monitors for heat strain management remains unclear.

An alternate concept for a more direct assessment of reduction in water balance might resemble a continuous boot-to-boot electrical impedance. The basis for this is that body resistance to an imperceptible 50 KHz current reflects total body water, providing a practical continuous assessment of fluid balance. Application of higher frequencies would detect only extracellular fluid and might add important information about fluid shifts during severe heat strain. Field application requires validation where potentially confounding factors in the stable measurement of resistance include skin temperature, postural changes, and skin wettedness.

Physiological strain indices

Given that work in the heat represents a challenge to thermoregulation and multiple integrated physiological processes, it has been suggested that any single measure cannot be considered as a complete indicator of heat strain (Buller et al. 2018). Further, healthy, asymptomatic individuals often display body core temperatures that are the same or higher than those who have collapsed from heat-related illnesses (Hunt et al. 2016). To obtain more detailed insight into the physiological strain experienced by an individual, multiple physiological indicators are often combined into a single heat strain index for use in wearable physiological monitors.

While numerous physiological heat strain indices exist (de Freitas and Grigorieva 2017), only the physiological strain index (PSI) (Moran et al. 1998) has seen consistent use in recent years. The PSI incorporates both heart rate and rectal temperature in an attempt to quantify the combined strain of the thermoregulatory and cardiovascular systems (Moran et al. 1998). Several years after the PSI was introduced, Buller (Buller et al. 2017) proposed a modification to the upper (critical) temperature limit (39.5 °C) within the PSI calculation to include mean skin temperature to account for the narrowing of the thermal gradient between the core and skin with increasing heat strain. Most recently, Davey et al. (2021) proposed another iteration of the PSI, where skin temperature was incorporated in the form of heat storage with the goal of providing a better prediction of when an individual reached their thermal tolerance limit.

Perhaps the most attractive feature of the PSI and subsequent derivations is that heat strain is scaled so that an individual with a body core temperature and heart rate equal to the lower and upper limits used in the calculation (typically 37.0–39.5 °C and 70–180 beats/min) has a score of 0 and 10, respectively. Taken together with the fact that many wearable monitoring systems possess the ability to measure heart rate and predict body core temperature, many manufactur-

ers have opted to display the PSI, often in the form of a traffic light system. For example, the ARMOR system (Table 1), classifies PSI scores of 1–6, 7–8, and 9–10 as green, amber, and red lights, (respectively), which reflect the presumption that individuals with a PSI of $\geq$ 7.5 are at high risk for heat-related illness and injury (Buller et al. 2008). However, a recent investigation indicated that the PSI was unable to differentiate between individuals who completed a series of simulated occupational heat stress exposures ($n = 101$) versus those who terminated the same exposures prematurely due to heat-related exhaustion ($n = 35$), irrespective of the way in which it was calculated (Davey et al. 2021). Further, of the individuals who terminated prematurely, only 58% had a PSI < 7.5. The upper limit of the PSI would have needed to be 4.8 to prevent 95% of instances of heat-related exhaustion in that experiment, which would be overly restrictive in most occupations.

To gain greater sensitivity when using the PSI to identify excessive heat strain, the ARMOR system also requires that an individual is visually checked by the supervisor for signs and symptoms of heat stroke when an amber or red traffic light (PSI > 7) is reached (Buller et al. 2021). These signs include a reduced level of consciousness, agitated/confused, wobbly gait, nausea/vomiting, and cramps, which are scored and summed to identify individuals who may be very likely, likely, or unlikely to suffer heat illness. Recommended actions are then provided to the supervisor to treat each classification. While this approach may be suitable for identifying heat stroke cases that have already occurred, it is subjective and less well-suited to determining when to moderate a heat exposure to prevent heat stroke, which should be the preferred objective.

Emerging approaches

Arterial wave form monitoring

To support oxygen delivery to the working musculature and thermoregulatory increases in skin blood flow during work in the heat, there is also a redistribution of blood volume away from inactive skeletal muscle and visceral structures (e.g., liver and splanchnic regions) (González-Alonso et al. 2008). When coupled with the reductions in plasma volume that occur when sweat losses are not matched by fluid intake, this displacement of blood away from the central circulation can result in a state of relative hypovolemia (reduced vascular volume), which will cause reductions in venous return that lower stroke volume, and eventually cardiac output. In most instances, an individual can compensate for these reductions through both cardiac (e.g., inotropic, chronotropic) and peripheral vascular mechanisms. However, this response is finite and increases in hypovolemia can lead to circulatory collapse and inadequate tissue perfusion, which will compromise physical work capacity and may be a precursor for heat stroke (Hales et al. 2010).

Recognizing that the compensatory cardiac and peripheral vascular adjustments that occur during hypovolemia are reflected in features of the arterial pressure waveform, Convertino et al. developed a method to determine the percentage of an individual's capacity to respond to hypovolemia (Convertino et al. 2013). This was termed the compensatory reserve index (CRI) (Fig. 2). It uses a machine-learning model to compare an individual's arterial pressure waveform at any one time to a database of thousands of waveforms collected during controlled reductions in central blood volume using lower-body negative pressure to estimate the CRI. Given that hyperthermia-mediated cutaneous vasodilation produces a "relative" hypovolemia by increasing the circulatory space that must be perfused with the same blood volume, the CRI may act as a sensitive indicator of heat strain (Convertino and Sawka 2018; Kimball et al. 2022). At least in a laboratory setting, it has been reported to identify the point of circulatory collapse during lower-body negative pressure with various environmental stressors with a sensitivity and specificity of 0.84–0.87 and 0.78–0.86, respectively. However, it is unclear if the lower-body negative pressure model is a suitable analog for exertional heat stress.

In addition, there is a need to develop wearable monitoring solutions to measure the CRI at the workplace. In a laboratory setting, the CRI can be determined accurately using arterial waveforms measured by volume-clamping based measurement devices (Kimball et al. 2022). However, these systems are too bulky for field use. More recently, investigators have explored other techniques for obtaining analog arterial waveforms, with the most common being the transmissive photoplethysmogram (Kimball et al. 2022). When combined with wearable sensor systems supported by machine learning, this approach provides a means to obtain the CRI in real-time outside of the laboratory. For example, the CipherOx CRI™ Tablet (Flashback Technologies, CO, USA) consists of a finger pulse oximeter and tablet computer that displays the CRI (Moulton et al. 2017). Unfortunately, such systems must clamp over the recording site (e.g., finger or earlobe), which is unsuitable for most workplaces and introduces movement artefact that degrades the arterial waveforms. To address these issues, several alternatives have been suggested (Kimball et al. 2022), and it is likely that a system suitable for occupational use will be available in the near future.

Bio-fluid sensing

Our discussion to this point has centred upon the controlled variables that are modified during work in the heat to regulate body temperature. However, occupational heat stress is also associated with a cascade of cellular changes detectable within the blood, saliva, and interstitial fluid, which may serve as markers of excessive heat strain. Consider the gastrointestinal heat stroke paradigm as an example, which has long been implicated in heat-related injury (Ogden et al. 2020). Exertional heat stress can adversely disrupt gastrointestinal barrier integrity, with the severity of disruption being dependent upon both the level of hyperthermia (Pires et al. 2017) and reduction in gut blood flow due to splanchnic vasoconstriction (Van Wijck et al. 2011). This disruption can cause gastrointestinal microbial translocation into the systemic circulation, which must be neutralized by natural antibodies and proteins (e.g., intestinal fatty acid-binding protein, lipopolysaccharide-binding protein, plasma

soluble cluster of differentiation 14). When this detoxification is unsuccessful, numerous pro-inflammatory cytokines (e.g., interleukin (IL) 1-β, IL-6, IL-8, tumor-necrosis factor-α) and anti-inflammatory cytokines (e.g., IL-1ra, IL-10) (Peake et al. 2015) are produced, which can lead to systemic inflammatory response syndrome, and eventually, multiple organ failure and death. As such, the real-time detection of the antibodies, proteins, or cytokines released during this process may give unique insight into the limits of heat tolerance.

At present, these gastrointestinal biomarkers and other potential blood-borne indicators of heat strain are typically determined in a laboratory setting from the analysis of whole-blood samples. However, there have been significant leaps in our ability to measure and analyze biomarkers in biofluids in recent years, which are likely to soon permit their real-time quantification. For example, recent developments in aptamer technology (DNA-based biomimicry), such as that employed by Nutromics Pty Ltd (Melbourne, Australia) (Dauphin-Ducharme et al. 2019), have made it possible to obtain real-time concentrations of various target molecules from the interstitial fluid using patch-type microneedle arrays (Tehrani et al. 2022), which is particularly promising given the close correlation between concentrations within interstitial fluid and blood (e.g., cortisol) (Friedel et al. 2023). Others have proposed wearable sensors housed within contact lenses (Elsherif et al. 2018), dental chips (Mannoor et al. 2012), and mouth guards (Kim et al. 2015), which may permit the continuous measurement biomarkers of importance in tears or saliva during occupational heat exposure (Fig. 2). Despite the potential utility of these devices, there is still extensive work that needs to be done to develop this technology and understand the relation between biomarker concentrations and thermal tolerance.

Research needs

It is evident that considerable scientific and technological advancements in wearable physiological monitoring for heat strain management have been made in recent years, which have the capacity to markedly enhance worker health and productivity. However, there are several critical gaps in our understanding that limit our ability to utilize wearable physiological monitoring as part of a greater heat-management program. In this section, we describe some of these challenges and the research efforts that we perceive are needed. We acknowledge that there are additional challenges (e.g., ethics, safety, integration into policy and protocols, worker trust/distrust in the technology, worker compliance) that must also be addressed, although these have been partly discussed elsewhere (Bernard and Kenney 1994; Buller et al. 2018; Friedl 2018; Notley et al. 2018; Morrissey et al. 2021).

Physiological limits for heat exposure

While we have improved our ability to measure or predict measures of heat strain in the workplace in recent years, we still possess a relatively rudimentary understanding of safety limits for those variables and how those limits may be impacted by the various inter- and intra-individual factors that modify tolerance to work in the heat. Further, it is important to recognize that an upper limit for heat exposure that prevents an acute injury or illness (i.e., heat exhaustion or heat stroke) may be too liberal to prevent chronic heat-related illnesses that develop over days or years (e.g., chronic kidney injury). This makes it challenging to identify the limits of strain for a given physiological indicator, and therefore, when alerts should be triggered to more closely monitor the individual or moderate a given heat exposure.

Consider body core temperature, which remains to be the primary target indicator of occupational heat strain for most manufacturers, although these points apply to all currently used indicators of heat strain (e.g., heart rate, PSI). While exertional heat stroke is clinically associated with central nervous system dysfunction and a body core temperature >40 °C (Epstein and Yanovich 2019), the body core temperatures associated with voluntary or involuntary termination of work in the heat varies substantially, due to both inter- and intra-individual factors (e.g., age, sex, aerobic fitness), which remain poorly understood. For example, using aggregate data from a series of field experiments (n = 131), Sawka et al. demonstrated that infantry soldiers can become heat exhausted with rectal temperatures as low as 37.8 °C (Sawka et al. 2001). In contrast, highly trained individuals have been reported to safely tolerate gastrointestinal temperatures exceeding 41.5 °C during sporting events (Racinais et al. 2019).

Given the broad range of body core temperature (~3.5 °C) that an individual may or may not be able to tolerate without complications, it becomes difficult, and perhaps impossible, to set generic limits to a given heat exposure based on body core temperature that will adequately protect all individuals from adverse health effects, while also avoiding unnecessary and significant reductions in productivity. For instance, if we revisit Sawka et al. (2001), setting a conservative limit of 38.5 °C, which is consistent with the upper limits for heat stress for heat acclimatized workers set by the ACGIH (ACGIH 2017), would result in ~10% of individuals suffering heat exhaustion and the remaining 90% being forced to cease work below their tolerance limit, unnecessarily reducing the volume and intensity of work that can be performed. Moving this limit to a less conservative threshold of 39 °C would reduce productivity loss, but may then result in ~30% of individuals being incapacitated by reaching their tolerance limit.

An obvious solution to gain greater discrimatory performance is to apply individualised upper limits, which are higher or lower depending on an individual's ability to tolerate a given rise in body core temperature (Notley et al. 2019*a*). However, the challenge then becomes developing a method to accurately and conveniently establish those limits, while considering the various intra-individual factors that may modulate the upper limit that one can safely tolerate (e.g., illness, hydration and acclimatization state, menstrual cycle, muscle damage) (Wyndham et al. 1965; Tenaglia et al. 1999; Sawka et al. 2015; King et al. 2019). Additionally, that challenge is complicated when one considers that these upper limits may need to be more conservative to prevent

chronic heat-related illness and avoid aggravating existing health conditions. It also remains uncertain whether this approach would be feasible during the completion of team-based tasks, where moderating the work intensity or exposure of one individual is not possible without disrupting the entire team.

Consequently, even if a wearable system was capable of precisely measuring body core temperature (or another physiological indicator), differentiating between safe and unsafe exposures with the sensitivity required to avoid major reductions in productivity is still a considerable challenge and a significant financial and administrative burden. This challenge highlights the urgent need for more mechanistic research directed at understanding the upper limits of heat tolerance and the modifiers of those limits. Such research must not only be dedicated to preventing acute heat injury, but also avoiding chronic heat-related injury and the aggravation of existing health conditions. It is likely that these thresholds cannot simply be described with sufficient sensitivity with a single measure of heat strain such as body core temperature, and this will be discussed in the following subsection. In the interim, one could consider setting conservative limits for wearable physiological monitors (e.g., body core temperature of 38 °C), although this would come with significant reductions in productivity that may lead some to question the benefits of wearable monitoring over existing population-based heat management tools (e.g., look-up tables).

Are we tracking the right indicators?

At present, manufacturers of wearable systems must select the indicator(s) of heat strain within their systems based on a trade off between what physiological variables best reflect heat strain and that which can be measured or accurately predicted using wearable sensors in real-time. However, due to the challenges associated with setting appropriate upper limits for moderating heat exposure noted above, one might question whether we are tracking the best physiological markers of heat strain within currently available systems. Indeed, while there has been extensive technical advancement in recent years, we still possess limited scientific understanding of what variables best reflect thermal strain and the onset of incapacitation.

As noted above, most commercial devices directed at occupational heat strain management utilize a measure or prediction of body core temperature in isolation or as part of a heat strain index (i.e., PSI). However, it has been known for some time that thermometric measurements of body core temperature poorly reflect heat stored within the body (Snellen 1969). This is primarily due to inter-compartmental time delays in heat exchange, which do not allow the temperature of those sites to reliably track heat stored throughout body, and the heterogeneity in the mass and specific heat capacity of body tissues (Notley et al. 2023). Further, while some of the pathophysiological responses associated with progression of heat stroke may have a temperature-dependency (e.g., gut epithelial membrane permeability), evidence of profound CNS dysfunction and other pathological events are more reliable indicators of exertional heat stroke (Laitano et al. 2019). As such, we are not of the view that measures or predictions of body core temperature, regardless of their precision, should be used in isolation for wearable heat strain monitors moving forward.

Instead, it may be more effective to incorporate measures or predictions of body core temperature into future wearable occupational heat strain monitors as one of many indicators that, together, provide a more precise indication of voluntary or involuntary cessation of work in the heat. Evidence supporting this notion can be found in Buller et al. who were able to improve the sensitivity of the ECTemp algorithm by incorporating a trunk-worn sensor, capable of measuring gait-instability (Buller et al. 2022). Similarly, by including measures of both skin temperature and heart rate, Laxminarayan et al. (2023) gained superior sensitivity for the detection of excessive hyperthermia than others have done when using any of these measures in isolation. However, there is still a need for more detailed research to quantify the variance in heat tolerance associated with both existing and novel physiological indicators, and to understand the value added by combining two or more of these indicators.

Sensor and algorithm validation

Given many of the physiological indicators of heat strain are difficult to measure at the workplace, manufacturers have utilised indirect approaches to estimate these indicators. As such, it is critical that appropriate studies are performed to validate these estimates against laboratory-based, direct methods, particularly since these monitors intend to act as a safety device. However, for some physiological monitoring systems, validation studies have not been well designed for these purposes.

Perhaps the most pertinent consideration when designing such experiments is that the work conditions (work type and intensity, clothing, and environment) must reflect those experienced by the workers that intend to benefit from the system. This is particularly important in occupations with extreme environmental stressors or that require the use of heavily insulated or nonpermeable protective clothing, which can create a hot, humid microclimate around the worker (e.g., firefighting, hazardous material disposal). For example, it is relatively uninformative to assess the validity of a wearable system reliant on predictions from heart rate and local skin temperature in participants wearing minimal clothing in an air-conditioned laboratory, when the intended use is for firefighters who may experience high skin temperatures from live fires that may compromise the validity of the system. Some investigators have satisfied this requirement by assessing the validity of wearable devices during laboratory-based occupational simulations (Cannady et al. 2024). However, the participants in those experiments are often assessed during a brief work period (<60 min) and provided with pre-trial instructions to standardize their physiological state (e.g., caffeine abstinence, arrive hydrated, avoid strenuous exercise). More commonly, workers perform prolonged (>8 h) shifts over multiple consecutive days, where they can experience the “perfect storm” of physiological stressors (e.g.,

fatigue, dehydration, muscle damage, sleep fragmentation) (Taylor et al. 2021), which may alter the validity of a wearable system. It is important that validity is assessed under controlled conditions as well as uncontrolled conditions that may alter a worker's physiological state.

Further, few investigators have considered the broad diversity of our workforce during the development and assessment of wearable physiological systems. It is well documented that older adults and females are forming an increasing proportion of the employees engaged in physically demanding occupations (BLS 2007; Toossi and Torpey 2017). Compared to young males, older adults display reductions in thermoregulatory function, which can exacerbate the rise in body core temperature under certain work and environmental conditions (Meade et al. 2019). This is owed partly to an attenuated cardiovascular response to heat stress, which may reduce the precision of wearable physiological monitors, particularly those based on heart rate predictions of body core temperature. Sex-related differences in thermoregulatory function among men and women of similar body size and aerobic fitness are generally small (Notley et al. 2017, 2019*b*, 2020), although women may be more sensitive to elevated thermoregulatory and cardiovascular strain during dehydration (Wickham et al. 2021). It follows that predictive equations developed primarily from young male data may poorly reflect the broader working population. To address this issue, the data used to develop and validate wearable monitoring systems must originate from diverse population samples including both men and women spanning a broad age range.

Conclusions

Over the past decade, there have been considerable developments in the approaches available to monitor occupational heat strain. These have centred on body core temperature monitoring, skin temperature (heat flux) monitoring, heart rate predictions of body core temperature in conjunction with secondary variables (e.g., gait variability), monitoring hydration state, and the monitoring of HRV. There are also emerging approaches, which aim to utilize arterial wave form monitoring and biofluid sensing technology, to quantify alternative markers of heat strain. However, while many of these approaches show promise, there are several key gaps in our understanding that must be resolved before we are able to effectively utilize wearable physiological monitoring as part of a greater heat-management program. These mostly concern the efficacy of physiological indicators for quantifying heat strain and how to set appropriate upper limits for those indicators to determine when to moderate heat exposure.

Take home message

Over the past decade, there has been considerable progress in the use of wearable technology for individualized occupational heat stress management. However, there are still critical gaps in our understanding that must be addressed.

Acknowledgements

We thank the following colleagues for helpful discussions during the development of this manuscript: Drs Nigel A.S. Taylor, Duncan Mitchell, Martin Stebbing, and Nicholas Smith.

Article information

History dates

Received: 4 September 2024
Accepted: 25 February 2025
Accepted manuscript online: 10 March 2025
Version of record online: 15 May 2025

Notes

This paper is part of a collection entitled "The Physiology of Extreme Temperatures: From Cold to Hot and Hazard to Health". https://cdnsciencepub.com/topic/apnm-extreme-temperature

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Glen Kenny served as Associate Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by another editorial board member.

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Competing interests

No conflicts of interest, financial or otherwise, are declared by the author(s).

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