NRC Research Press

REVIEW

On the use of wearable physiological monitors to assess heat strain during occupational heat stress

Sean R. Notley, Andreas D. Flouris, and Glen P. Kenny

Abstract: Workers in many industries are required to perform arduous work in high heat-stress conditions, which can lead to rapid increases in body temperature that elevate the risk of heat-related illness and even death. Traditionally, effort to mitigate work-related heat injury has been directed toward the assessment of environmental heat stress (e.g., wet-bulb globe temperature), rather than toward the associated physiological strain responses (e.g., heart rate and skin and core temperatures). However, because a worker's physiological response to a given heat stress is modified independently by inter-individual factors (e.g., age, sex, chronic disease, others) and intra-individual factors both within (e.g., medication use, fitness, acclimation and hydration state, others) and beyond (e.g., shift duration, illness, others) the worker's control, it becomes challenging to protect workers on an individual basis from heat-related injury without assessing those physiological responses. Recent advancements in wearable technology have made it possible to monitor one or more physiological indices of heat strain. Nonetheless, information on the utility of the wearable systems available for assessing occupational heat strain is unavailable. This communication is therefore directed toward identifying the physiological indices of heat strain that may be quantified in the workplace and evaluating the wearable monitoring systems available for assessing those responses. Finally, emphasis is placed on the barriers associated with implementing these devices to assist in mitigating work-related heat injury. This information is fundamental for protecting worker health and could also be utilized to prevent heat illnesses in vulnerable people during leisure or athletic activities.

Key words: wearable technology, heat strain, work performance, monitoring, body core temperature.

Résumé : Des travailleurs dans plusieurs milieux industriels doivent effectuer des tâches ardues dans des conditions de stress thermique intense pouvant mener à une augmentation rapide de la température corporelle et accroître le risque de troubles dus à la chaleur ou provoquer la mort. Traditionnellement, les actions pour amoindrir les troubles dus à la chaleur ont consisté dans l'évaluation du stress thermique environnemental (p. ex. température humide et radiante) plutôt qu'à la réponse au stress physiologique (p. ex. rythme cardiaque, températures cutanée et centrale). Toutefois, du fait que la réponse physiologique du travailleur à un stress thermique donné est modifiée indépendamment par des facteurs inter-individuels (p. ex. âge, sexe, maladie chronique et autres), intra-individuels (p. ex. utilisation de médicaments, condition physique, acclimatation, degré d'hydratation et autres) et en dehors de son contrôle (p. ex. durée du quart de travail, maladies et autres), le protéger contre les blessures dues à la chaleur sur une base individuelle sans évaluer les réponses physiologiques constitue un défi. Les progrès récents dans la technologie portable rendent possible le suivi d'un ou plusieurs indices physiologiques concernant la contrainte thermique. Toutefois, il n'y a pas de données disponibles sur l'utilité des systèmes portables dans l'évaluation des contraintes thermiques au travail. Cet article a pour objectif d'identifier les indices physiologiques de contrainte thermique quantifiables en milieu de travail et d'évaluer les systèmes de surveillance portables à cette fin. En dernier lieu, on met l'accent sur les obstacles associés à la mise en place de ces dispositifs conçus pour diminuer les blessures dues à la chaleur au travail. Ces renseignements sont essentiels pour la protection de la santé du travailleur et pourraient être utilisés pour prévenir les malaises dus à la chaleur chez les personnes vulnérables au cours d'activités récréatives et sportives dans la chaleur. [Traduit par la Rédaction]

Mots-clés : technologie portable, contrainte thermique, performance au travail, surveillance, température corporelle centrale.

Introduction

Performing arduous work in the heat represents a considerable challenge to body temperature regulation and the integrated physiological processes of blood pressure and body fluid regulation (Cheung et al. 2016), which is exacerbated by the requirement for workers to don heavy and often impermeable protective clothing (Taylor et al. 2016; McLellan and Havenith 2016). These conditions not only compromise productivity (Ioannou et al. 2017), but can also cause dangerous rises in body core temperature (T_c) that can lead to heat-related illnesses and even death (Leon and Bouchama 2015). Indeed, in the United States alone, more than 350 deaths were ascribed to occupational heat exposure between the years 2000 and 2010 (Gubernot et al. 2015). However, this mortality rate is likely an underestimation, because it is well es-

Received 6 March 2018. Accepted 25 April 2018.

S.R. Notley and G.P. Kenny.* Human and Environmental Physiology Research Unit, School of Human Kinetics, University of Ottawa, Ottawa, ON K1N 6N5, Canada.
A.D. Flouris. Human and Environmental Physiology Research Unit, School of Human Kinetics, University of Ottawa, Ottawa, ON K1N 6N5, Canada; Functional Architecture of Mammals in their Environment (FAME) Laboratory, Department of Exercise Science, University of Thessaly, Trikala, Greece.
Corresponding author: Glen P. Kenny (email: gkenny@uottawa.ca).

*Glen P. Kenny currently serves as an Associate Editor; peer review and editorial decisions regarding this manuscript were handled by Andrew Sheel and Terry Graham.

tablished that (*i*) surveillance of heat-related worker illnesses is inadequate (Rosenman et al. 2006); (*ii*) heat stroke is often misdiagnosed because of similarities to other illnesses in its clinical presentation and pathophysiology (Taiwo et al. 2010); and (*iii*) the criteria to define heat-related injuries and deaths often differ among physicians, medical examiners, coroners, and regions (i.e., state or province, country) (Donoghue et al. 1997). Moreover, given the increasing frequency and intensity of heat waves caused by global warming, the incidence of work-related heat illness is expected to rise and to increasingly become an issue for workers operating in temperate climates (Mora et al. 2017). Indeed, heat-related deaths in workers have been estimated to increase by as much as 37% for each ~0.55 °C (1 °F) rise in average daily summer temperature (Mirabelli and Richardson 2005), with workers facing a 4- to 7-fold greater risk of experiencing a heat-related illness during a heat wave (Xiang et al. 2015).

To protect workers from heat-related illnesses, environmental parameters alone, or environmental and clothing parameters, and the estimated rate of metabolic heat production are typically used to quantify the level of heat stress and to determine engineering and administrative controls or hygiene practices to prevent dangerous levels of heat strain (e.g., American Conference of Governmental and Industrial Hygiene (ACGIH) threshold limit values (TLV)). However, although this approach provides a convenient means of approximating the average level of physiological strain, the actual level of heat strain experienced by an individual in response to a given heat stress can vary markedly because of inter-individual factors (e.g., age, sex, chronic disease, others) and intra-individual factors both within (e.g., caffeine, alcohol and medication use, fitness, acclimation and hydration state, others) and beyond (e.g., consecutive work shifts, shift duration, illness, others) the worker's control. This individual variability can lead to over- or under-protection from heat-related illness, with the former reducing productivity in more heat-tolerant workers and the latter compromising safety in less heat-tolerant workers who may develop heat-related illness even in temperate conditions.

Personal monitoring of physiological strain (e.g., T_c and skin temperature, heart rate, sweat rate) can provide a real-time means of quantifying each worker's level of heat strain, and it has been suggested that it provides individualized protection from heat-related illness (NIOSH 2016). Recent technological advancements have led to rapid growth in the development of wearable physiological monitors and subsequent research on the utility of these systems. The use of wearable technology has been popularized for monitoring physical activity in the general population and, as outlined by a recent series of reviews, has also been used increasingly for identifying disease states, tracking rehabilitation, and optimizing performance (Sawka and Friedl 2018). However, although one of the reviews in that series details the application of computational techniques for indirectly monitoring occupational heat strain (Buller et al. 2018), an evaluation of the monitors available for assessing heat strain and the applicability of those systems for use as part of a heat-illness mitigation strategy in an occupational setting is currently unavailable. As such, the purpose of this paper is 3-fold: (*i*) to review the physiological responses that may be monitored in the workplace as precursors or indicators of heat-induced physiological strain (i.e., heat syncope and heat exhaustion); (*ii*) to evaluate currently available personal heat-strain monitoring systems with respect to equipment parameters (e.g., cost, size, mode of data transmission, accuracy) and the applicability of each system for use in an occupational setting (e.g., tolerance to environmental conditions, comfort, wearability); and (*iii*) to identify potential barriers and facilitators to implementing these devices in the workplace.

Physiological strain during work in hot conditions

In most industries, occupational heat stress originates from harsh environmental conditions (e.g., high air temperature and humidity, radiant heat sources, low air flow), the requirement to wear insulated and/or impermeable protective clothing, and the high metabolic heat load from performing physically demanding tasks, especially when wearing heavy equipment (Arbury et al. 2014). Unsurprisingly, performing arduous work in high heat-stress conditions is associated with progressive rises in T_c, cardiovascular strain, and fluid depletion, which can lead to heat stroke or death (Leon and Bouchama 2015). Excessive heat stress may also cause psychophysical strain (e.g., discomfort and fatigue) and may lead to labour losses by compromising worker productivity and safety (Ioannou et al. 2017). These physiological and psychophysical effects of heat stress on the worker and his or her performance characterize the heat-strain response. The sources of occupational heat stress and the resulting heat-strain responses with respect to varying environmental conditions and work activities (Cheung et al. 2016), personal protective clothing (McLellan and Havenith 2016), load carriage (Taylor et al. 2016), and worker age (Kenny et al. 2016) are detailed in a recent series of reviews and are summarized in Fig. 1.

Heat-strain monitoring to mitigate occupational heat injury

Over the past few decades, significant progress has been made in our understanding of human physiology during heat stress. However, despite extensive implementation of strategies to mitigate heat-related injury by industry, including self-monitoring by workers themselves and heat-stress assessment, heat exposure still causes high rates of morbidity and mortality (Arbury et al. 2014; Xiang et al. 2015). For these important reasons, incorporating a heat-strain monitoring program to identify signs of excessive heat strain and/or heat-related illness has been recommended (NIOSH 2016). In the following subsections, these strategies are summarized with respect to the level of protection offered to workers by each (Fig. 2).

Self-monitoring

It is well known that workers modify their behaviour (e.g., reduce work output, increase rest time, remove clothing) when heat strain is perceived to be excessive or when they experience symptoms of heat illness (Mairiaux and Malchaire 1985; Budd 2001; Ioannou et al. 2017). However, it has been suggested that self-monitoring is inappropriate when a worker is provided productivity incentives (Mairiaux and Malchaire 1985), and there is evidence that some workers may suffer excessive heat strain and heat stroke even when self-pacing is permitted (Cuddy and Ruby 2011). As such, self-monitoring provides only low-level protection to worker health (Fig. 2; level IV).

Heat-stress monitoring

To better prevent excessive heat strain, many industries assess the level of heat stress using environmental parameters alone (e.g., wet-bulb globe temperature (WBGT)), or environmental and clothing parameters, and the estimated rate of metabolic heat production. This information is used to identify conditions that may cause excessive heat strain or to mathematically model the level of heat strain that may be experienced by a worker according to the anatomical and thermal properties of the body and the heat-loss responses of sweating and skin blood flow (Richards and Fiala 2004). In conditions that are considered to be dangerous, engineering (e.g., ventilation and shade) and administrative controls (e.g., work-to-rest allocations) and/or hygiene practices (e.g., personal cooling devices and fluid consumption schedule) are prescribed to prevent heat-related injury. However, because heat strain may be modified by inter-individual factors and

Fig. 1. A summary of the potential sources of occupational heat stress, the resulting effects of that heat stress (i.e., heat strain), and the inter-individual factors and intra-individual factors both within and beyond the workers' control that may modify these effects. Heat stress in the workplace represents the combined heat load from the environment and clothing and the heat generated from metabolic processes (metabolic heat), whereas the resulting physiological, psychophysical, and performance effects characterize the heat-strain response. Excessive heat stress can result in labour loss and multiple physiological adjustments that can progress to heat-related illness if left unchecked (redrawn from Hales et al. 1996). [Colour online.]

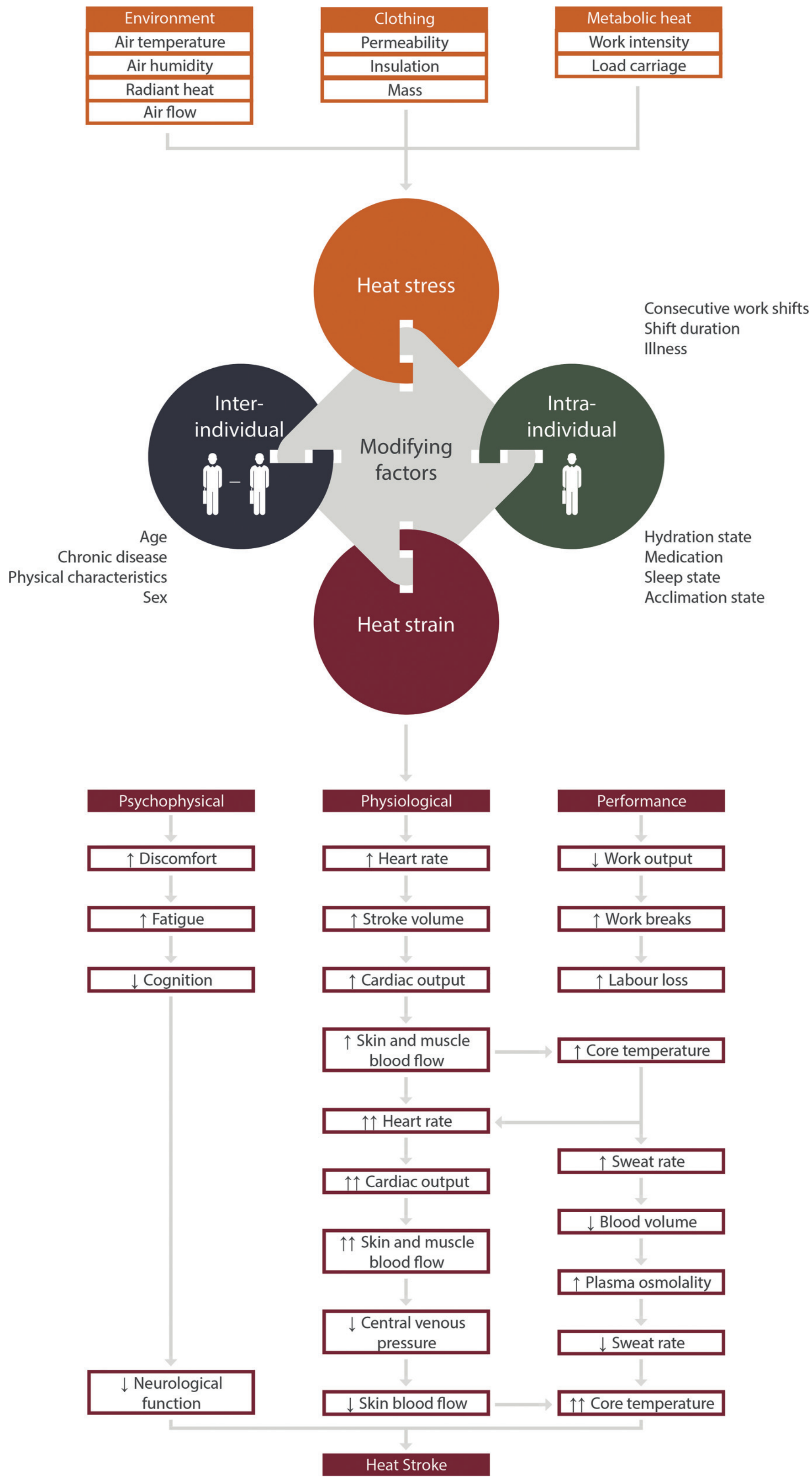
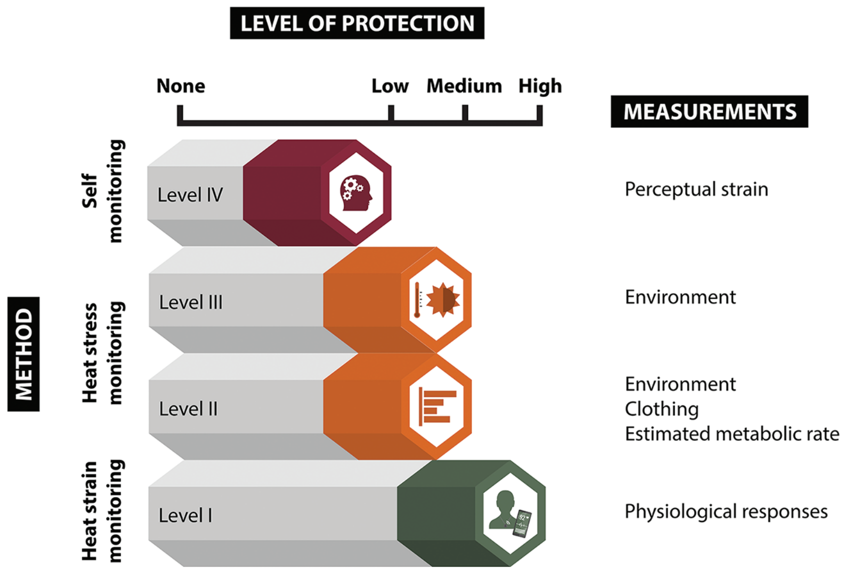


Fig. 2. An illustration of the methods available to prevent heat-related illness during work in hot environments and the associated level of protection offered by each (low (level IV), moderate (levels III and II), and high (level I)), including self-monitoring of the strain perceived, heat-stress monitoring using either environmental parameters alone or a combination of environmental, clothing, and metabolic data, and the monitoring of physiological data using wearable technologies. [Colour online.]



intra-individual factors both within and beyond the worker's control (Fig. 1), the individual variability in heat strain in response to a given level of heat stress is extensive (Fig. 3A). For example, age-related reductions in whole-body heat loss can exacerbate heat strain during work in the heat in older, relative to young, workers (Larose et al. 2013*a*, 2013*b*, 2014). Therefore, the assessment of heat stress alone can result in the over- or under-protection of workers from heat-related illness (Meade et al. 2015, 2016*b*; Lamarche et al. 2017). The former would lead to the early termination of work and a reduction in productivity in more heat-tolerant workers (false positive), whereas the latter would compromise the safety of less heat-tolerant workers, who may develop heat-related illness even in mild conditions (false negative). For instance, a recent laboratory-based evaluation of the effectiveness of the ACGIH TLV, which recommends work-to-rest allocations (administrative controls) to prevent excessive rises in T_c (≥38.0 °C), revealed that this threshold would be surpassed during work shifts ≥4 h in some young (Meade et al. 2016*b*) and in all older (Lamarche et al. 2017) workers, even when work is performed within these limits (Fig. 3B). Several instances of peak core temperatures exceeding the ACGIH guidelines for acclimated workers (≥38.5 °C), as well as 2 instances of more severe heat strain (T_c ≥39.5 °C), have also been observed in field-based research conducted by our group (Meade et al. 2015). Therefore, heat-stress monitoring using environmental parameters alone (level III) or measures of the environment, clothing, and metabolic rate (level II) provide only moderate protection to worker health (Fig. 2).

Heat-strain monitoring

To provide more individualized protection, one or more physiological indices of heat strain can be monitored to directly quantify the level of heat strain experienced by a worker in real time, while considering both the intra- and the inter-individual factors that may independently modify heat strain (Fig. 1). This approach therefore prevents the over- or under-protection of workers from heat-related illness (i.e., false positives and false negatives) by ensuring that productivity is maximized in more heat-tolerant employees when working in high heat-stress conditions and that heat-related illness is prevented in less heat-tolerant workers when working in temperate conditions. Furthermore, these physiological data can be used to provide alert thresholds to management to ensure that safety limits are not exceeded and to provide physiological feedback to workers to ensure that they control their work rate to optimize productivity while preventing excessive heat strain. Indeed, physiological monitoring has been shown to improve the level of protection offered by self-monitoring (Buller et al. 2018). Heat-strain monitoring, therefore, forms the highest level of protection to worker health (Fig. 2; level I). However, although heat-strain monitoring is included in current heat-exposure guidelines when the level of heat stress exceeds a specific threshold (e.g., ACGIH TLV), information on the physiological responses that provide the best indices of heat strain in the workplace and the potential utility of the wearable systems currently available to measure those responses is lacking.

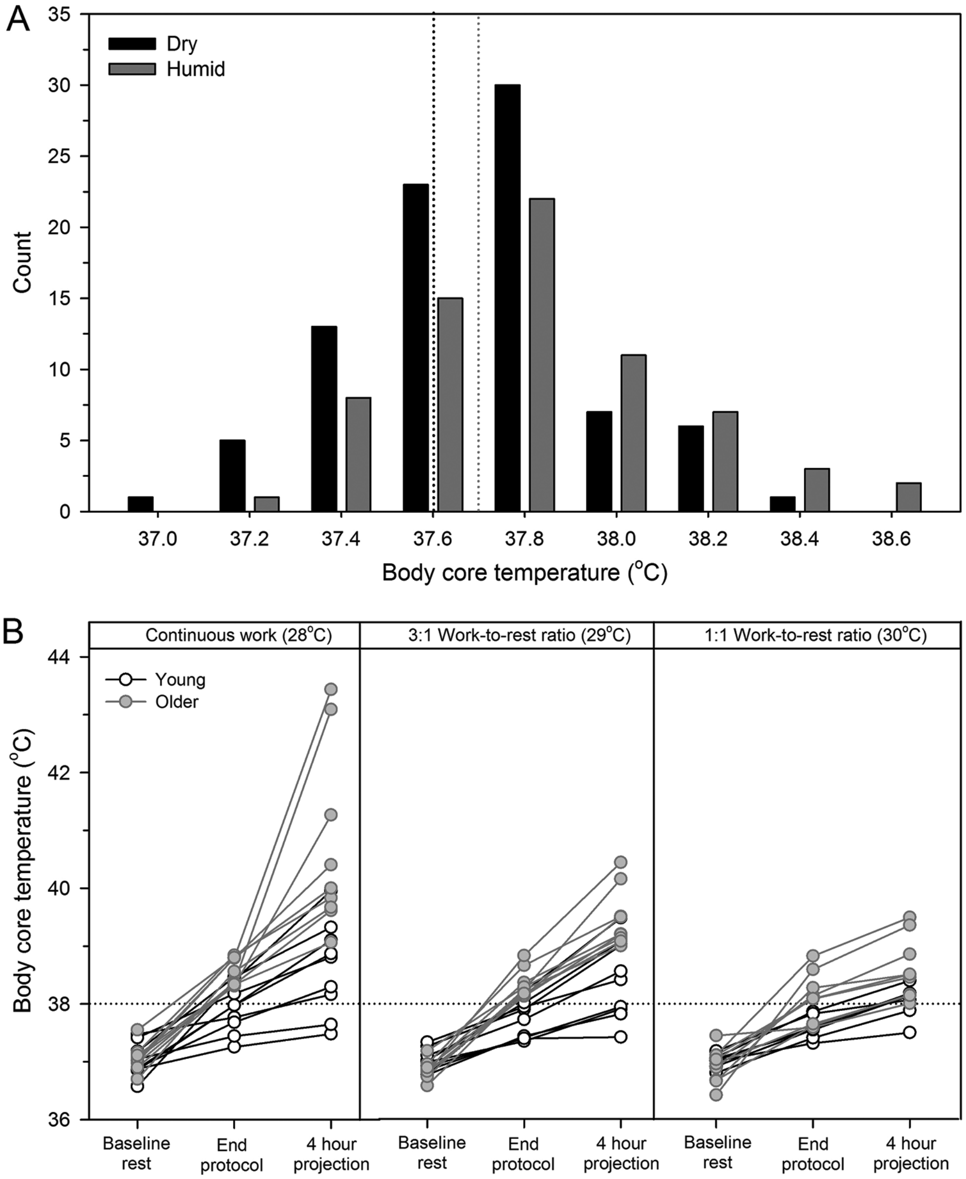
Indices of occupational heat strain

Occupational heat stress is associated with several physiological adjustments to regulate body temperature, blood pressure, and fluid volume (Fig. 1). However, although these responses may represent indices of heat strain, quantifying them in an occupational setting can be challenging, even with recent technological advancements. In this section, we identify the physiological responses that may be measured in the workplace as a means of quantifying excessive heat strain and potentially safeguarding worker health. Although monitoring whole-body sweat losses or the resulting changes in hydration state represent potential means of quantifying occupational heat strain, emphasis is placed on the indices that may be determined either directly or indirectly using currently available wearable technologies. This includes the methods available to noninvasively measure T_c or indirectly estimate T_c, using measurements of skin surface temperature and cardiovascular strain.

T_c

The inability to regulate T_c during work in the heat is perhaps the most direct index of heat strain (Haldane 1905). Excessive rises in T_c (≥40.0 °C) can rapidly lead to organ failure and death if medical care is unavailable (Leon and Bouchama 2015). As such, the ACGIH recommends that T_c should not exceed 38.0 °C and 38.5 °C for extended periods for unacclimatized and acclimatized workers, respectively, and provides specific work/rest ratios de-

Fig. 3. (A) Histogram of peak body core (rectal) temperature in men (21–70 years of age) during four 15-min bouts of cycling at a fixed metabolic heat production rate (400 W), each separated by a 15-min recovery, in dry (35 °C, 20% relative humidity; *n* = 86; black lines and bars) and humid (35 °C, 60% relative humidity; *n* = 69; grey lines and bars) heat. Data are individual responses (5-min average of the final exercise bout) with means (dotted lines) redrawn from 3 separate studies (Larose et al. 2013*a*, 2013*b*, 2014). (B) Body core (rectal) temperature for young (*n* = 9; 21 ± 3 years of age; black lines and symbols) and older (*n* = 9; 58 ± 5 years; grey lines and symbols) males during a 2-h work simulation performed in accordance with the American Conference of Governmental and Industrial Hygiene threshold limit value (TLV) guidelines for moderate- to heavy-intensity work (360 W fixed rate of heat production) in different wet-bulb globe temperatures (WBGT). Participants completed 3 trials, including continuous cycling at 28.0 °C WBGT and 15-min intermittent work bouts performed with different work-to-rest cycles of either 3:1 at a WBGT of 29.0 °C or 1:1 at 30.0 °C. Data are individual responses obtained during baseline rest, at the end of the 2-h protocol, and at a 4-h theoretical projected time point. The horizontal dashed line indicates the TLV upper-limit body core temperature threshold for non-heat-acclimated workers (38 °C). All data were redrawn from Meade and colleagues (2015) and Lamarche and colleagues (2017).



pending on the WBGT and the work intensity necessary to achieve this (ACGIH 2017). Nonetheless, the most clinically relevant measurements of T_c (e.g., rectum, esophagus) can be difficult to obtain in an occupational setting. For some, the invasive nature of the measurement technique can be distracting and may cause physical discomfort, especially when used for prolonged durations. Moreover, many of these measurement systems are nonreusable and may be costly. In the following subsections, we describe the methods currently available to approximate T_c in the workplace. These methods have been reviewed elsewhere (Taylor et al. 2014; Werner 2014) and are summarized below with emphasis on their utility for use in an occupational setting.

Gastrointestinal temperature

Gastrointestinal temperature, measured using an ingestible, telemetric pill, is commonly used to provide measures of T_c from ingestion to passing. Telemetric pill temperatures have been reported to share acceptable agreement with esophagus and rectal temperatures during work in the heat (Ganio et al. 2009). However, there are important factors to consider when employing this technique. For example, a phase delay during transient thermal states typically occurs with the measurement of T_c using the telemetric pill (Pearson et al. 2012). There is also a high degree of within- and between-subject variability in the transit time (i.e., time from ingestion to passing; range, 5–83 h) of telemetric pills (Roach et al. 2010). Furthermore, because ~12% of telemetric pills display systematic bias, calibration against a certified reference thermometer should be performed prior to use to correct for this issue (Hunt et al. 2017). Other considerations include food and fluid consumption, which can also introduce measurement bias. This possibility is greatest within ~30 min of ingestion and may last up to 11.5 h (Wilkinson et al. 2008), although this artefact can be minimized by delaying data collection by 2–6 h after ingestion (Ganio et al. 2009).

Oral temperature

Oral temperature, as estimated from the sublingual area by placing a thermometer underneath the tongue, has long been used to quantify occupational heat strain in conjunction with heart rate during recovery (Brouha 1960). Oral temperature is known to track rectal temperature during work in the heat, albeit at a 0.3–0.5 °C lower temperature (Strydom et al. 1965). Although this method can be performed easily using a digital or disposable thermometer, 3 precautionary steps must be considered to ensure that oral temperature is representative of T_c. First, because oral temperature can be influenced by evaporative cooling in the oral cavity during breathing (McCaffrey et al. 1975), mouth breathing should be avoided for several minutes while the thermometer is placed underneath the tongue (i.e., to ensure equilibration with body temperature). Second, because the consumption of hot or cold food or fluids may also transiently modify T_c (Woodman et al. 1967), food and fluid consumption should be restricted immediately prior to measurements (Beaird et al. 1996). Finally, given that there are regional temperature differences within the oral cavity, the thermometer placement should be standardized to the posterior sublingual pocket to best reflect T_c (Erickson 1980).

Tympanic and aural temperature

Surrounded by the pinna (auricle), the aural canal is a small tube running from the outer ear to the middle ear and ending with the tympanic membrane. Both the aural and the tympanic membrane temperature are representative of brain temperature, with the tympanic membrane, because of its more direct brain blood supply and deeper position within the aural canal, providing the more precise index of T_c (Brinnel and Cabanac 1989). However, because measuring a true tympanic membrane temperature requires a sensor that is in constant contact with that membrane, as verified using an otoscope to avoid perforation (Flouris and Cheung 2010), it is unsuitable for use in an occupational setting. Fortunately, commercially available handheld infrared thermometers can detect radiation emitted from the tympanic membrane and therefore provide a noninvasive, cost-effective means of measuring tympanic membrane temperature, provided the ear canal is cleaned prior to measurement (i.e., to remove wax) and that the curvature of the aural canal does not prevent direct sight of the tympanic membrane (Doezema et al. 1995).

In addition to infrared thermometers, the aural canal temperature may be measured using an insulated, ear-moulded plug thermometer, which also closely tracks both esophageal and rectal temperature during work in the heat (Todd et al. 2014). However, because external air and surface temperatures (both heat and cold) can modify temperature in the highly vascular structures of the pinna and the face that supply blood to the aural canal (Teunissen et al. 2011), it is important to minimize this bias when using aural canal temperature to approximate occupational heat strain. This can be achieved using a zero-gradient approach, which involves the placement of a heating device on the pinna to track and replicate the aural canal temperature; this may also be used to actively minimize heat transfer between the aural canal and the external environment (Keatinge and Sloan 1975).

Body surface temperature

The body surface (skin) represents the medium between the body core and the external environment. As such, skin temperature is not only influenced by environmental (e.g., high ambient and surface temperatures) and clothing (e.g., clothing insulation and permeability) parameters, but also by metabolic heat production, as well as by behavioural and autonomic heat-loss responses (skin blood flow and sweating), which can vary as a function of inter-individual as well as intra-individual factors both within and beyond the worker's control (Fig. 1). In cooler conditions, in which cutaneous vasoconstriction minimizes the thermal gradient for dry heat exchange, regional differences in skin temperature are extensive (Werner and Reents 1980). However, in hotter environments, or when wearing protective clothing, skin temperature rises and becomes more uniform as increases in cutaneous vasodilatation facilitate blood-borne heat transfer to the skin surface (Werner and Reents 1980). Skin temperatures from various regions may therefore be used to estimate T_c, and ultimately, occupational heat strain.

Mercury-in-glass or electric thermometers

In the home or clinical setting, T_c is often approximated from skin temperature measurements obtained from the axillary region using mercury-in-glass (i.e., expansion thermometers) or electric thermometers (Werner 2014). Because the thermometer is naturally insulated from the external environment in this region, axilla temperature represents a cost-effective method for estimating heat strain. It is important to note, however, that axilla temperature can be modified by variations in air temperature, skin temperature, and sweating in the axillary region, which can result in estimates of T_c that can differ from rectal temperature by 0.94–1.25 °C during work in the heat (Ganio et al. 2009). Furthermore, obtaining measures of axilla temperature in an occupational setting may require workers to cease work and remove their protective clothing. In instances where this is not possible, axilla temperature can be obtained quickly during rest periods.

Insulated and zero-gradient skin temperature

Wired or wireless skin-temperature sensors, including button-sized themosensors (e.g., iButton, Maxim Integrated, San Jose, Calif., USA), thermocromatic thermometers (i.e., liquid crystal strips), and infrared thermography, may be used to estimate T_c from the skin surface. However, because the temperature recorded may be influenced by external heat sources (e.g., hot machinery, furnaces; Gunga et al. 2008), it is important to insulate skin temperature sensors adequately to better approximate T_c. Placing insulating material (e.g., foam or rubber) over a thermistor or thermocouple on the skin surface attenuates external heat transfer, allowing skin temperature to more closely track variations in rectal (Richmond et al. 2013; Roberge et al. 2017), esophageal (Gunga et al. 2008), and muscle (Flouris et al. 2015) temperature during work in hot environments. Others have employed a zero-gradient method, which uses a heated insulating layer to actively minimize the influence of extraneous heat sources on skin temperature, so that skin temperature may more closely track T_c (Fox and Solman 1971). Using this method, forehead skin temperature has been reported to display an average bias ± SD of only −0.05 ± 0.18 °C during work in the heat compared with rectal and esophageal temperature (Teunissen et al. 2011).

Heart rate

In addition to supporting blood pressure regulation and maintaining oxygen delivery to the working musculature, increases in heart rate facilitate compensatory cardiovascular adjustments (cutaneous blood flow and cardiac output) to regulate T_c during work in the heat (Sawka 1988). Because these increases in heart rate occur in proportion to elevations in both metabolic demand and T_c (Haldane 1905), heart rate can be averaged during work or assessed during recovery periods between bouts of work to assess occupational heat strain (Brouha 1960) or to predict T_c (Buller et al. 2013). Furthermore, heart rate can be measured conveniently using low-cost, portable, and lightweight monitors equipped with a wireless transmitting device, which can be used to set predetermined thresholds to alert workers or management that excessive strain may be present. However, the factors that can independently modify heart rate (e.g., inter-individual factors, inter-individual factors both within and beyond the worker's control, nature of the work activity, others) must be considered carefully when assessing heat strain using heart rate. The following subsections discuss the use of average or recovery heart rate and the prediction of T_c using heart rate to assess occupational heat strain.

Average heart rate during work

In many occupations, workers may perform sporadic periods of high-intensity work, which may cause the heart rate to briefly exceed a static upper limit in the absence of excessive heat strain (i.e., false positive). Similarly, prolonged work eliciting a heart rate just below an upper threshold may represent a period of excessive heat strain that goes undetected (i.e., false negative). As such, it has been recommended that a moving average heart rate be used to define the upper limits for safe work during activity (Bernard and Kenney 1994). ACGIH guidelines stipulate that a peak heart rate ≥180 beats·min^{-1} (as assessed over several minutes) minus age should not be exceeded during a work day (ACGIH 2017), whereas Minard and colleagues (1971) suggested that a daily average heart rate of ≥120 beats·min^{-1} would be indicative of excessive heat strain.

Recovery heart rate

Because an increase in heat strain is also paralleled by a slower decline in heart rate after activity (Brouha 1960), others have proposed the use of recovery heart rate (measured by either pulse palpation or portable monitor) to assess heat strain (Fuller and Smith 1981). This approach is advantageous in that it does not require a heart rate monitor with the capability of recording and averaging data; it typically involves the measurement of heart rate and oral temperature over the final 30 s of a 3-min period during seated rest after a period of work (Fuller and Smith 1981). The number of beats obtained during the last 30 s of each minute is then doubled to obtain recovery heart rates (beats·min^{-1}) for the first, second, and third minutes. A heart rate ≥90 beats·min^{-1} in the first minute, or a ≤10 beats·min^{-1} difference between the first and the third minute, coupled with an oral temperature ≥37.5 °C, are considered indicative of excessive heat strain that may be present or will occur if work is continued.

Heart rate predictions of core temperature

More recently, a Kalman filter (Kalman 1960), which is often used in engineering and econometrics to track and predict data trends, has been used with acceptable precision to estimate T_c from time-dependent changes in heart rate (±0.63 °C) in a variety of both laboratory and field experiments involving work in the heat (Buller et al. 2013). Given that heart rate can be measured conveniently, a commercially available heart rate monitor incorporating this model may provide a valid, practical, and economically viable means of obtaining real-time estimates of T_c to prevent excessive occupational heat strain.

Physiological and perceptual strain indices

To this point, emphasis has been placed on the use of a single physiological variable to assess occupational heat strain. However, because work in the heat represents a challenge to body temperature regulation as well as to the integrated physiological processes of blood pressure and body fluid regulation, the validity of this approach has been questioned (Moran et al. 1998; Frank et al. 2001; Buller et al. 2018; Flouris and Kenny 2017). Indeed, even though T_c has long been considered the primary indicator of heat strain (Haldane 1905), it is known that healthy, asymptomatic individuals often display T_c values that are the same or higher than those of individuals who have collapsed from heat-related illnesses (Hunt et al. 2016). For this reason, several investigators have attempted to combine multiple physiological or perceptual measures into a single heat-strain index, with the most well-recognized indices suitable for use in the workplace being the Cumulative Heat-Strain Index (CHSI) (Frank et al. 1996), the Physiological Strain Index (PSI) (Moran et al. 1998), and the Perceptual Strain Index (PeSI) (Tikuisis et al. 2002). These indices are discussed below, with calculations provided in Supplement 1[1].

CHSI

The CHSI represents the integrated cardiovascular and thermoregulatory costs of maintaining heat balance and is calculated as the product of heart rate and the change in rectal temperature over time (eq. 1.1; Frank et al. 1996). By considering these variables as complementary, it is possible to detect excessive heat strain in individuals who may display a low heart rate but a high core temperature (or vice versa). Moreover, expressing heart rate and rectal temperature as change scores reduces individual variability. Although the CHSI has been used to evaluate heat strain during laboratory-based studies (Frank et al. 2001), this index has been shown to lack sensitivity within the early stages of work (<60 min) and during recovery (Moran et al. 1998). Furthermore, it is reliant on work being performed for the same duration to draw comparisons between workers, as well as continuous measures of rectal temperature, which are impractical to obtain in a field setting. Although the CHSI has been used to evaluate occupational heat strain with gastrointestinal temperature (ingestible pill) as an alternative to rectal temperature (Rodríguez-Marroyo et al. 2011), to our knowledge, no study has been designed to evaluate the utility of the CHSI when computed using a surrogate index of rectal temperature.

PSI

The PSI incorporates both heart rate and rectal temperature to quantify the combined strain on the thermoregulatory and cardiovascular systems (eq. 1.2; Moran et al. 1998). The strain placed on each system is scored out of 5, then summed to represent physiological strain on a 10-point scale (0 = no strain, 10 = very high strain). The index is suitable in instances in which rectal temperature ranges from 36.5 to 39.5 °C and heart rate is between 60 and 180 beats·min^{-1}, and it has been used to assess heat strain in various arduous occupations (Brearley et al. 2015; Meade et al. 2015, 2016*a*). However, because it is known that healthy individuals often display T_c values that are similar to or even greater than that of patients with heat illness (Cuddy and Ruby 2011; Hunt et al. 2016), Buller and colleagues (2018) proposed a modification to the upper (critical) temperature limit (39.5 °C) within the PSI calculation to consider the narrowing of the thermal gradient between the core and skin associated with increasing heat strain. This modification incorporates measures of mean skin temperature and is termed the adaptive physiological strain index (eq. 1.3). Although the derivation of the PSI, like the CHSI, is reliant on continuous measures of rectal temperature, it has been suggested

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/apnm-2018-0173.

that surrogate measures that are more suitable for use in an occupational setting (e.g., tympanic membrane temperature measured with an infrared thermometer) can be used interchangeably with rectal temperature to compute the PSI (Lee et al. 2011).

Perceptual strain indices

Given the challenges of measuring physiological data in the workplace, subjective scales of thermal sensation and rating of perceived exertion have been used as surrogate indices of physiological strain, with the most well-known being the PeSI (eq. 1.4; Tikuisis et al. 2002). Although this index shows good agreement with physiological strain indices such as the PSI in a laboratory setting (Tikuisis et al. 2002; Borg et al. 2015), a mismatch between perceptual and physiological strain can occur in the workplace (Walker et al. 2017). Furthermore, individuals who routinely experience high levels of physiological strain may consistently underestimate that strain (Wright et al. 2013). As such, perceptual strain indices must be used with caution to assess occupational heat strain.

Wearable technologies for monitoring occupational heat strain

Recent technological advancements have led to increases in the development of wearable monitors that purport to provide a noninvasive and portable means of quantifying many of the physiological responses noted above, including T_c, skin surface temperature, and cardiovascular strain, that may be measured in the workplace as a means of quantifying excessive heat strain and potentially safeguarding worker health in hot environments. In this section, we evaluate the utility of these monitoring systems with respect to equipment parameters (e.g., cost, mode of data transmission, accuracy, portability, and tolerance to environmental conditions) and the applicability of each system as a strategy to detect and mitigate work-related heat strain.

Commercially available heat-strain-monitoring systems

Currently available wearable physiological monitoring systems may be grouped loosely into 3 categories: (*i*) torso-worn vests or belts, (*ii*) in-ear monitors, and (*iii*) hip-worn loggers. The potential utility of such systems for use in an occupational setting is discussed below. The technical specifications and characteristics (e.g., size, mass, measurements obtained, data storage, others) of some of the systems currently available within each category are provided in Table 1.

Torso-worn vests or belts

Many wearable physiological monitoring systems comprise a polyester vest (e.g., Hexoskin, Carré Technologies Inc., Montreal, Que., Canada) or a chest belt and shoulder strap (e.g., Equivital EQ02 LifeMonitor, Cambridge, UK; and BioHarness 3.0, Zephyr Performance Systems, Annapolis, Md., USA) with built-in data logger. These devices are designed to be worn under clothing and possess various sensors for the derivation of heart rate, heart rate variability, breathing and ventilation rate, activity level, peak acceleration, steps, cadence, and sleep positions, with some systems (e.g., BioHarness 3.0) providing estimates of T_c from time-dependent changes in heart rate (Buller et al. 2013). Most systems are also compatible with third-party wired or wireless devices so that additional measurements (e.g., oxygen saturation, galvanic skin response, gastrointestinal temperature, skin temperature, and global positioning) may be obtained. Data may be monitored in real time and synced to an online server for storage using a Bluetooth-enabled mobile device or via computer. Some systems (e.g., Equivital) also provide managers and supervisors with a heat-strain index, which incorporates sensor, environmental, and global positioning data, to identify workers who may be experiencing excessive heat strain or who may be likely to experience a heat-related event if work is continued. Vest-style systems such as the Hexoskin have been reported to share acceptable agreement with criterion methods for the measurement of heart rate (95% limits of agreement, ±3 beats·min^{-1}) during daily activities performed in temperate conditions (Villar et al. 2015) and during exercise in hot, humid environments (correlation coefficient (r), ≥0.99; Al Sayed et al. 2017). Similarly, torso-worn belt systems including the Equivital display acceptable agreement (95% limits of agreement) with laboratory-based methods for the measurement of heart rate (±6.6 beats·min^{-1}), skin temperature (±0.88 °C), and core temperature (±0.24 °C) during work in a simulated hot, humid environment (Liu et al. 2013). However, although the estimates of T_c from time-dependent changes in heart rate obtained using the BioHarness have been reported to display differences from rectal temperature that would be unacceptably large in some instances (means ± SD difference, −0.1 ± 0.4 to 0.3 ± 0.4 °C; Seo et al. 2016), measures of heart rate obtained using this system have been shown to be highly correlated (r = 0.87–0.96) with criterion methods during graded exercise in the heat (Kim et al. 2013). These systems have been used to assess physiological strain in various industries (Taylor et al. 2015; Cuddy et al. 2015; Brearley et al. 2015; Hunt et al. 2016) and provide an effective and relatively noninvasive means of monitoring occupational heat strain.

In-ear sensors

Heat strain may be quantified from estimates of T_c using a small ear-sensor assembly wired directly to a compact logger. The most common is the Questemp II (3M, St. Paul, Minn., USA), which comprises a speaker and an ear-moulded plug that surrounds a thermistor and a second sensor to monitor environmental temperature. The aural thermistor provides real-time estimates of T_c from the aural canal, whereas the second sensor compensates for external temperature artefacts (i.e., high or low ambient and surface temperatures). However, although it has been reported to provide measurements of peak T_c that differ significantly from rectal temperature (means ± SD difference, 0.95 ± 0.67 °C) during intermittent work in various ambient conditions (18, 23, and 27 °C WBGT) (Green et al. 1999), additional insulation around the ear canal (e.g., protective ear covers) has been shown to improve the precision of this device relative to rectal temperature (means ± SD difference, 0.02 ± 0.54 °C) during continuous work in the heat (30 °C WBGT) (Muir et al. 2001). Given their compact, robust design and acceptable precision when insulated adequately, in-ear sensors such as the Questemp II appear to provide a suitable method for monitoring occupational heat strain. However, because it has been suggested that relying on only a single measure of heat strain (i.e., T_c) may be inadequate (Moran et al. 1998; Frank et al. 2001; Buller et al. 2018; Flouris and Kenny 2017), the utility of in-ear sensors for the assessment and detection of excessive heat strain may be improved with the concomitant monitoring of heart rate.

Hip-worn loggers

Systems composed of a hip-worn logger equipped with one or more wired accessory sensors to measure various physiological responses (e.g., heart rate, breathing rate, skin temperature, cardiac output, activity level, muscle activity) have also been developed for portable physiological monitoring (e.g., BioNomadix, BIOPAC Systems Inc., Goleta, Calif., USA; and BioRadio, Great Lakes Neurotechnologies, Cleveland, Ohio, USA). Although these systems can be configured to monitor multiple variables (i.e., by adding or removing sensors), the external wiring associated with these accessory sensors may be cumbersome in an occupational setting, particularly when worn underneath personal protective clothing. Furthermore, to our knowledge, the measurement precision of hip-worn systems such as the BioNomadix and BioRadio has not been assessed in an occupational setting.

Table 1. Technical specifications of currently available wearable physiological monitoring systems.

System	Measures*	Design	Dimensions† (mm)	Weight (g)	Data storage capacity and sample rate	Run time	Operating conditions	Cost‡	Other assets
Hexoskin (Carré Technologies Inc., Montreal, Que., Canada)	HR, HRV, f_b, V_T, $\dot{V}_E$, location, motion	Sensor vest with logger	Logger: 13 × 42 × 72	Logger: 40; garment: ~90	1 Gb at 1–256 Hz	≥14 h with 1.5-h recharge	N/A	$	Smartphone compatibility.
LifeMonitor EQ02 (Equivital, Cambridge, UK)	HR, HRV, f_b, T_{sk}, location, motion, T_c (GI pill)	Sensor chest belt with logger	Logger: 78 × 55 × 11	Chest belt: 100; logger: 38	8 Gb at 15–256 Hz	≥24 h with ~1-h recharge	–10 to +50 °C; 0%–95% RH	$$$$	Black Ghost software. Smartphone compatibility. Water and dust resistance. FDA and CE approval. Approved for hazardous areas.
BioHarness 3.0 (Zephr Performance Systems, Annapolis, Md., USA)	HR, HRV, f_b, location, motion, T_{sk} (to estimate T_c)	Sensor chest belt with logger	Logger: 28 × 7	Chest belt: N/A; logger: 18	≤500 h at 1–250 Hz	12–28 h with 3-h recharge	–30 to 60 °C; 0%–95% RH	$$	Water and dust resistance. May be integrated into clothing.
Questemp II (3M, St. Paul, Minn., USA)	T_c (aural canal)	Ear plug sensor wired to portable logger	Logger: 130 × 64 × 25	Ear plug sensor: 4.2; logger: 283	12.5 h at 0.1 Hz	60 h with disposable 9-V battery	0 to 70 °C; 0%–95% RH	$$$	Water and dust resistance. Audible alerts. CE certified. Approved for hazardous areas.
BioNomadix (BIOPAC Systems, Inc., Goleta, Calif., USA)	HR, HRV, f_b, T_{sk}, muscle and brain activity, CO, motion	Data logger with receiver and transmitter module(s)	Logger: 94 × 58 × 23; receiver: 40 × 110 × 190; module(s): 60 × 40 × 20	Logger: 121; receiver: 380; transmitter modules: 54 each	8 Gb at ≤2 000 Hz	24 h with 12-h recharge	5 to 45 °C; 0%–95% RH	$$$$	Audible and vibration alerts. May be integrated into clothing. FCC and CE certified.
BioRadio (Great Lakes Neurotechnologies, Cleveland, Ohio, USA)	HR, HRV, f_b, BP, SpO2, GSR, muscle and brain activity, T_{sk}, motion	Hip-worn logger with wired accessory sensor(s)	Logger: 99 × 61 × 20	Logger: 113	8 Gb at 250–1 600 Hz	8 h with 3- to 4-h recharge	na	$$$$	CE certified.

Note: The information presented was extracted from Website documentation (Hexoskin: https://www.hexoskin.com/pages/downloads; Equivital: http://www.equivital.co.uk/products/tnr/sense-and-transmit; Questemp II: http://www.raeco.com/products/heatstress/questemp-II.html; BioHarness 3.0; https://www.zephyranywhere.com/resources/documentation; BioNomadi: https://www.biopac.com/product-category/research/bionomadix-wireless-physiology/; BioRadio: https://glneurotech.com/bioradio/bioradio-specifications/). BP, blood pressure; CE, conformity to European health and safety standards; CO, cardiac output; f_b, breathing frequency; FCC, Federal Communications Commission; FDA, US Food and Drug Administration; GI, gastrointestinal; GSR, galvanic skin response; HR, heart rate; HRV, heart rate variability; na, information unavailable or not applicable; RH, relative humidity; SpO_2, oxygen saturation; T_c, core temperature; T_{sk}, skin temperature; $\dot{V}_E$, minute ventilation; V_T, tidal volume.

*Does not include indirectly derived variables.

†Dimensions are length × width × height.

‡Approximate system cost (<$1 000 USD ($), $1 000–2 000 ($$), $2 000–3 000 ($$$), >$3 000 ($$$$)).

Published by NRC Research Press

Key barriers to implementing wearable physiological monitoring in the workplace

A heat-strain monitor for use in occupational settings must possess several unique features to act as a feasible and successful strategy to mitigate heat-related injury. To get a better sense of these features, a survey containing 3 open-ended questions was administered to 19 health and safety advisors from the electric power generation industry across North America (Supplement 2[1]). Each question was aimed at gathering information related to the complications associated with using the physiological monitoring systems described above in their workplace, the features of a heat-strain monitor they perceive as desirable, and the factors that may reduce worker compliance with heat-strain monitoring. From the responses obtained, 4 key barriers were identified, including the accuracy and durability of each system in harsh industrial environments; the method of data collection, transmission, and interpretation; the potential costs of implementing heat-strain monitoring; and the possibility that physiological monitoring may modify worker behaviour (i.e., reactive error). These barriers are summarized within the following subsections.

Accuracy and durability in harsh industrial environments

The portable physiological monitoring systems discussed above are designed primarily for wireless patient monitoring in a laboratory, hospital, or home setting, or for the ambulatory monitoring of physiological data in a sporting context. However, because of the nature of many industries, workers are exposed not only to hot and humid environments, but also to noxious gases, dirt and debris, high surface temperatures, contact with electrically charged equipment and materials, and water immersion. These harsh work conditions present a challenge for the operation of all equipment, including portable physiological monitoring systems. As such, for a physiological monitoring system to act as a potential strategy to mitigate occupational heat strain, each system must retain its functionality and precision under such conditions. Although some systems are certified for use in hazardous areas and possess water and dust resistance, future research is needed to evaluate the utility of these systems in harsh industrial environments for wearable monitoring to be implemented successfully into a heat-strain management program.

Data collection, transmission, and interpretation

Of greatest concern for the immediate implementation of a heat-strain monitor is the method of data collection. First, it remains uncertain if wearable monitors can be incorporated into the personal protective clothing systems worn in all industries. Furthermore, in many industries, materials that are nonflammable or flame resistant, noncombustible, hypoallergenic, and resistant to arc flash and electromagnetic fields must be used in the construction of a wearable heat-strain monitor to satisfy existing safety requirements. Although some of the systems available satisfy such requirements, others would require modification to the materials used. For example, a worker wearing a heat-strain monitor that is integrated into clothing may suffer extensive burns in the event of an arc flash if flammable and conductive materials were used. In addition, given that a work shift may last ≥12 h, the run time (battery life) and subsequent recharging time represent important considerations. Nonetheless, most systems have a run time of ≥12 h, with a recharge time of <8 h or the use of disposable batteries, which ensures the device is suitable for use during prolonged, consecutive work shifts.

The method of data transmission and integration represents an additional consideration in the implementation of personal heat-strain monitors in the workplace. Most available monitoring systems provide partner software that can be used with a computer or smartphone to track physiological data from the worker(s) being monitored. However, although some systems integrate physiological and environmental data to provide management with a heat-strain index for each worker, or audible alerts to notify the wearer when a given measure of heat strain exceeds a predetermined level, other systems provide limited guidance as to when a given level of heat strain may compromise health. Future development of such systems must be directed toward providing guidance to workers and management to aid in the interpretation of physiological data to better identify signs and symptoms of excessive heat strain.

Cost

A physiological monitor with the capacity to mitigate heat-related illness is of great benefit in reducing the costs associated with heat-related injuries and maximizing productivity in more heat-tolerant workers in conditions that exceed safe work limits (e.g., ACGIH TLV). However, the high cost associated with purchasing wearable monitors for all employees is prohibitive for most companies. Some systems also require additional and ongoing costs such as the purchase of integrated clothing and nonreusable gastrointestinal temperature pills, as well as repair and maintenance costs. Of course, these costs could be reduced by monitoring workers only during "high-risk" work and/or weather conditions and/or by monitoring employees who, because of their age, health status, or physically demanding occupation, may be more vulnerable to heat-related illness. However, although we possess some knowledge of the inter-individual factors (e.g., age, sex, chronic disease) that may make a worker more susceptible to heat-related injury (Flouris et al. 2017), it is difficult to consider the intra-individual factors both within (e.g., caffeine, alcohol, and medication use; fitness; acclimation and hydration state; and others) and beyond (e.g., consecutive work shifts, shift duration, illness, others) the worker's control (Fig. 1) that may predispose a worker who is ordinarily at low risk of heat-related injury. As such, there is a general need for more cost-effective systems for wearable physiological monitoring to mitigate heat-related illness.

Modification to worker behaviour

Although most of the heat-strain monitors identified above are relatively small and lightweight and thus would be unlikely to encumber a worker during activity, it is possible that physiological monitoring per se may modify worker behaviour (reactivity). This may be characterized by an increase in work intensity and a reluctance to cease work even when experiencing excessive heat strain, or a reduction in work effort to avoid displaying greater fatigue than coworkers. Unfortunately, the former may counter-intuitively exacerbate heat strain, whereas the latter may reduce productivity. Although such behaviour modifications may be minimized if physiological monitoring was routine or if management intervened, future research is needed to identify if and to what extent physiological monitoring may modify worker behaviour.

Furthermore, it is known from anecdotal evidence obtained during field studies conducted by our group (Kenny et al. 2012; Meade et al. 2015, 2016*a*, 2017; Ioannou et al. 2017) that many workers express a general displeasure with having their physiological responses monitored. This stems from several factors, including the workers' perception that (*i*) heat strain does not adversely influence their health or work performance, (*ii*) wearing a heat-strain monitor in addition to their protective clothing is inconvenient and uncomfortable, and (*iii*) physiological data may be used to assess their productivity. Although this perception may be modified through more extensive education on the dangers of excessive heat strain or by the integration of a heat-strain monitor within protective clothing (e.g., within coveralls or a hand-held radio), this represents an important area of future research for successfully implementing heat-strain monitoring as part of a heat-management program.

Conclusions

In this paper, we (*i*) reviewed the physiological responses that may be monitored in the workplace as indicators of heat-induced physiological strain, (*ii*) evaluated currently available personal heat-strain-monitoring systems with respect to equipment parameters and the applicability of each system for use in occupational settings, and (*iii*) identified potential barriers to the successful implementation of these devices as part of a heat-management program. The main take-home messages discussed are as follows:

- Occupational heat strain may be quantified from measures of T_c, skin surface temperature, fluid loss, and cardiovascular strain, although some precautionary steps must be considered to ensure that these measures are representative of a worker's state of heat strain.
- Using wearable technology to monitor one or more indices of heat strain provides individualized and real-time protection from excessive heat strain and may be particularly valuable during high-risk work and/or weather conditions and/or for workers who are more susceptible to heat-related injury because of their age, health status, or occupation.
- Despite the benefits of currently available wearable monitoring systems, they are costly and, for the most part, have not yet been validated in harsh industrial environments or designed to satisfy existing safety requirements (e.g., flame and arc resistance). Furthermore, most systems are lacking effective guidance in the interpretation of physiological data to identify the signs and symptoms of excessive heat strain. It also remains unknown whether physiological monitoring may adversely affect worker behaviour.
- Future product development should be directed toward physiological monitoring solutions that are cost effective, compliant with existing safety regulations, and well tolerated by workers, to be suitable for use as part of a company-wide, heat-strain management strategy. Monitoring devices that satisfy these requirements are fundamental for protecting worker health and could also be applied to the broader public to mitigate heat injury in vulnerable people during leisure or athletic activities.

Conflict of interest statement

The authors declare that they have no conflict of interest.

Acknowledgements

Support for this work was provided by the Electric Power Research Institute (funds held by Dr. Glen P. Kenny). Dr. Kenny is supported by a University of Ottawa Research Chair Award.

References

Al Sayed, C., Vinches, L., and Hallé, S. 2017. Validation of a wearable biometric system's ability to monitor heart rate in two different climate conditions under variable physical activities. E-Health Telecommunication Systems and Networks. **6**(2): 19–30. doi:10.4236/etsn.2017.62002.

American Conference of Governmental Industrial Hygienists (ACGIH). 2017. TLVs and BEIs Based on the Documentation of the Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices. ACGIH, Cincinnati, Ohio, USA.

Arbury, S., Jacklitsch, B., Farquah, O., Hodgson, M., Lamson, G., Martin, H., et al. 2014. Heat illness and death among workers – United States, 2012–2013. MMWR. Morb. Mortal. Wkly. Rep. **63**(31): 661–665. PMID:25102413.

Beaird, J.S., Bauman, T.R., and Leeper, J.D. 1996. Oral and tympanic temperatures as heat strain indicators for workers wearing chemical protective clothing. Am. Ind. Hyg. Assoc. J. **57**(4): 344–347. doi:10.1080/15428119691014873. PMID:8901235.

Bernard, T.E., and Kenney, W.L. 1994. Rationale for a personal monitor for heat strain. Am. Ind. Hyg. Assoc. J. **55**(6): 505–514. doi:10.1080/15428119491018772. PMID:8017291.

Borg, D.N., Stewart, I.B., and Costello, J.T. 2015. Can perceptual indices estimate physiological strain across a range of environments and metabolic workloads when wearing explosive ordnance disposal and chemical protective clothing? Physiol. Behav. **147**: 71–77. doi:10.1016/j.physbeh.2015.04.018. PMID:25865709.

Brearley, M., Harrington, P., Lee, D., and Taylor, R. 2015. Working in hot conditions—a study of electrical utility workers in the Northern Territory of Australia. J. Occup. Environ. Hyg. **12**(3): 156–162. doi:10.1080/15459624.2014.957831. PMID:25265189.

Brinnel, H., and Cabanac, M. 1989. Tympanic temperature is a core temperature in humans. J. Therm. Biol. **14**(1): 47–53. doi:10.1016/0306-4565(89)90029-6.

Brouha, L. 1960. Physiology in Industry: Evaluation of Industrial Stresses by the Physiological Reactions of the Worker. Pergamon Press, New York, N.Y., USA.

Budd, G.M. 2001. Assessment of thermal stress—the essentials. J. Therm. Biol. **26**(4–5): 371–374. doi:10.1016/S0306-4565(01)00046-8.

Buller, M.J., Tharion, W.J., Cheuvront, S.N., Montain, S.J., Kenefick, R.W., Castellani, J., et al. 2013. Estimation of human core temperature from sequential heart rate observations. Physiol. Meas. **34**(7): 781–798. doi:10.1088/0967-3334/34/7/781. PMID:23780514.

Buller, M.J., Welles, A.P., and Friedl, K.E. 2018. Wearable physiological monitoring for human thermal-work strain optimization. J. Appl. Physiol. **124**(2): 432–441. doi:10.1152/japplphysiol.00353.2017. PMID:28798200.

Cheung, S.S., Lee, J.K., and Oksa, J. 2016. Thermal stress, human performance, and physical employment standards. Appl. Physiol. Nutr. Metab. **41**(6): S148–S164. doi:10.1139/apnm-2015-0518. PMID:27277564.

Cuddy, J.S., and Ruby, B.C. 2011. High work output combined with high ambient temperatures caused heat exhaustion in a wildland firefighter despite high fluid intake. Wilderness. Environ. Med. **22**(2): 122–125. doi:10.1016/j.wem.2011.01.008. PMID:21664560.

Cuddy, J.S., Sol, J.A., Hailes, W.S., and Ruby, B.C. 2015. Work patterns dictate energy demands and thermal strain during wildland firefighting. Wilderness Environ. Med. **26**(2): 221–226. doi:10.1016/j.wem.2014.12.010. PMID:25772825.

Doezema, D., Lunt, M., and Tandberg, D. 1995. Cerumen occlusion lowers infrared tympanic membrane temperature measurement. Acad. Emerg. Med. **2**(1): 17–19. doi:10.1111/j.1553-2712.1995.tb03072.x. PMID:7606604.

Donoghue, E.R., Graham, M.A., Jentzen, J.M., Lifschultz, B.D., Luke, J.L., and Mirchandani, H.G. 1997. Criteria for the diagnosis of heat-related deaths: National Association of Medical Examiners. Position paper. Am. J. Forensic Med. Pathol. **18**(1): 11–14. doi:10.1097/00000433-199703000-00002. PMID:9095294.

Erickson, R. 1980. Oral temperature differences in relation to thermometer and technique. Nurs. Res. **29**(3): 157–164. PMID:6901014.

Flouris, A.D., and Cheung, S.S. 2010. The validity of tympanic and exhaled breath temperatures for core temperature measurement. Physiol. Meas. **31**(5): N35–N42. doi:10.1088/0967-3334/31/5/N01. PMID:20348612.

Flouris, A.D., and Kenny, G.P. 2017. Heat remains unaccounted for in thermal physiology and climate change research. F1000Research, **6**: 221. doi:10.12688/f1000research.10554.2. PMID:28357050.

Flouris, A.D., Webb, P., and Kenny, G.P. 2015. Noninvasive assessment of muscle temperature during rest, exercise, and postexercise recovery in different environments. J. Appl. Physiol. **118**(10): 1310–1320. doi:10.1152/japplphysiol.00932.2014. PMID:25814638.

Flouris, A.D., McGinn, R., Poirier, M.P., Louie, J.C., Ioannou, L.G., Tsoutsoubi, L., et al. 2018. Screening criteria for increased susceptibility to heat stress during work or leisure in hot environments in healthy individuals aged 31–70 years. Temperature, **5**(1): 86–99. doi:10.1080/23328940.2017.1381800.

Fox, R.H., and Solman, A.J. 1971. A new technique for monitoring the deep body temperature in man from the intact skin surface. J. Physiol. **212**: 8–10. PMID:5548025.

Frank, A., Moran, D., Epstein, Y., Belokopytov, M., and Shapiro, Y. 1996. The estimation of heat tolerance by a new cumulative heat strain index. *In* Environmental Ergonomics: Recent Progress and New Frontiers. *Edited by* Y. Shapiro, D. Moran, and Y. Epstein. Freund, London, UK. pp. 194–197.

Frank, A., Belokopytov, M., Shapiro, Y., and Epstein, Y. 2001. The cumulative heat strain index–a novel approach to assess the physiological strain induced by exercise-heat stress. Eur. J. Appl. Physiol. **84**(6): 527–532. doi:10.1007/s004210000368. PMID:11482547.

Fuller, F.H., and Smith, P.E., Jr. 1981. Evaluation of heat stress in a hot workshop by physiological measurements. Am. Ind. Hyg. Assoc. J. **42**(1): 32–37. doi:10.1080/15298668191419316. PMID:7223635.

Ganio, M.S., Brown, C.M., Casa, D.J., Becker, S.M., Yeargin, S.W., McDermott, B.P., et al. 2009. Validity and reliability of devices that assess body temperature during indoor exercise in the heat. J. Athl. Train. **44**(2): 124–135. doi:10.4085/1062-6050-44.2.124. PMID:19295956.

Green, J.M., Clapp, A.J., Gu, D.L., and Bishop, P.A. 1999. Prediction of rectal temperature by the Questemp II personal heat strain monitor under low and moderate heat stress. Am. Ind. Hyg. Assoc. J. **60**(6): 801–806. doi:10.1080/00028899908984505. PMID:10635547.

Gubernot, D.M., Anderson, G.B., and Hunting, K.L. 2015. Characterizing occupational heat-related mortality in the United States, 2000–2010: an analysis using the census of fatal occupational injuries database. Am. J. Ind. Med. **58**(2): 203–211. doi:10.1002/ajim.22381. PMID:25603942.

Gunga, H.C., Sandsund, M., Reinertsen, R.E., Sattler, F., and Koch, J. 2008. A non-invasive device to continuously determine heat strain in humans. J. Therm. Biol. **33**(5): 297–307. doi:10.1016/j.jtherbio.2008.03.004.

Haldane, J.C. 1905. The influence of high air temperatures. Epidemiol. Infect. **5**(4): 404–409. PMID:20474239.

Hales, J.R.S., Hubbard, R.W., and Gaffin, S.L. 1996. Limitations of heat tolerance. *In* Handbook of Physiology. Section 4, Vol. II: Environmental Physiology. *Edited by* C.M. Blatteis and M.J. Fregley American Physiological Society, Bethesda, Md., USA. pp. 285–355.

Hunt, A.P., Billing, D.C., Patterson, M.J., and Caldwell, J.N. 2016. Heat strain during military training activities: the dilemma of balancing force protection and operational capability. Temperature, **3**(2): 307–317. doi:10.1080/23328940.2016.1156801.

Hunt, A.P., Bach, A.J., Borg, D.N., Costello, J.T., and Stewart, I.B. 2017. The systematic bias of ingestible core temperature sensors requires a correction by linear regression. Front. Physiol. **8**: 260. doi:10.3389/fphys.2017.00260. PMID:28496414.

Ioannou, L.G., Tsoutsoubi, L., Samoutis, G., Bogataj, L.K., Kenny, G.P., Nybo, L., et al. 2017. Time-motion analysis as a novel approach for evaluating the impact of environmental heat exposure on labor loss in agriculture workers. Temperature, **4**(3): 330–340. doi:10.1080/23328940.2017.1338210.

Kalman, R.E. 1960. A new approach to linear filtering and prediction problems. J. Basic Eng. **82**(1): 35–45. doi:10.1115/1.3662552.

Keatinge, W.R., and Sloan, R.E. 1975. Deep body temperature from aural canal with servo-controlled heating to outer ear. J. Appl. Physiol. **38**(5): 919–921. doi:10.1152/jappl.1975.38.5.919. PMID:1126903.

Kenny, G.P., Vierula, M., Maté, J., Beaulieu, F., Hardcastle, S.G., and Reardon, F. 2012. A field evaluation of the physiological demands of miners in Canada's deep mechanized mines. J. Occup. Environ. Hyg. **9**(8): 491–501. doi:10.1080/15459624.2012.693880. PMID:22715930.

Kenny, G.P., Groeller, H., McGinn, R., and Flouris, A.D. 2016. Age, human performance, and physical employment standards. Appl. Physiol. Nutr. Metab. **41**(6): S92–S107. doi:10.1139/apnm-2015-0483. PMID:27277571.

Kim, J.H., Roberge, R., Powell, J.B., Shafer, A.B., and Williams, W.J. 2013. Measurement accuracy of heart rate and respiratory rate during graded exercise and sustained exercise in the heat using the Zephyr Bioharness™. Int. J. Sports Med. **34**(6): 497–501. doi:10.1055/s-0032-1327661. PMID:23175181.

Lamarche, D.T., Meade, R.D., D'Souza, A.W., Flouris, A.D., Hardcastle, S.G., Sigal, R.J., et al. 2017. The recommended Threshold Limit Values for heat exposure fail to maintain body core temperature within safe limits in older working adults. J. Occup. Environ. Hyg. **14**(9): 703–711. doi:10.1080/15459624.2017.1321844. PMID:28609164.

Larose, J., Wright, H.E., Stapleton, J., Sigal, R.J., Boulay, P., Hardcastle, S., et al. 2013*a*. Whole body heat loss is reduced in older males during short bouts of intermittent exercise. Am. J. Physiol. **305**(6): R619–R629. doi:10.1152/ajpregu.00157.2013.

Larose, J., Wright, H.E., Sigal, R.J., Boulay, P., Hardcastle, S., and Kenny, G.P. 2013*b*. Do older females store more heat than younger females during exercise in the heat? Med. Sci. Sports Exerc. **45**(12): 2265–2276. doi:10.1249/MSS.0b013e31829d24cc. PMID:23715429.

Larose, J., Boulay, P., Wright-Beatty, H.E., Sigal, R.J., Hardcastle, S., and Kenny, G.P. 2014. Age-related differences in heat loss capacity occur under both dry and humid heat stress conditions. J. Appl. Physiol. **117**(1): 69–79. doi:10.1152/japplphysiol.00123.2014. PMID:24812643.

Lee, J.Y., Nakao, K., Takahashi, N., Son, S.Y., Bakri, I., and Tochihara, Y. 2011. Validity of infrared tympanic temperature for the evaluation of heat strain while wearing impermeable protective clothing in hot environments. Ind. Health, **49**(6): 714–725. doi:10.2486/indhealth.MS1291. PMID:22020015.

Leon, L.R., and Bouchama, A. 2015. Heat stroke. Compr. Physiol. **5**: 611–47. doi:10.1002/cphy.c140017. PMID:25880507.

Liu, Y., Zhu, S.H., Wang, G.H., Ye, F., and Li, P.Z. 2013. Validity and reliability of multiparameter physiological measurements recorded by the Equivital LifeMonitor during activities of various intensities. J. Occup. Environ. Hyg. **10**(2): 78–85. doi:10.1080/15459624.2012.747404. PMID:23259751.

Mairiaux, P., and Malchaire, J. 1985. Workers self-pacing in hot conditions: a case study. Appl. Ergon. **16**(2): 85–90. doi:10.1016/0003-6870(85)90209-1. PMID:15676536.

McCaffrey, T.V., McCook, R.D., and Wurster, R.D. 1975. Effect of head skin temperature on tympanic and oral temperature in man. J. Appl. Physiol. **39**(1): 114–118. doi:10.1152/jappl.1975.39.1.114. PMID:1150577.

McLellan, T.M., and Havenith, G. 2016. Protective clothing ensembles and physical employment standards. Appl. Physiol. Nutr. Metab. **41**(6): S121–S130. doi:10.1139/apnm-2015-0474. PMID:27277562.

Meade, R.D., Lauzon, M., Poirier, M.P., Flouris, A.D., and Kenny, G.P. 2015. An evaluation of the physiological strain experienced by electrical utility workers in North America. J. Occup. Environ. Hyg. **12**(10): 708–720. doi:10.1080/15459624.2015.1043054. PMID:26011148.

Meade, R.D., Lauzon, M., Poirier, M.P., Flouris, A.D., and Kenny, G.P. 2016*a*. The physical demands of electrical utilities work in North America. J. Occup. Environ. Hyg. **13**(1): 60–70. doi:10.1080/15459624.2015.1077966. PMID:26317802.

Meade, R.D., Poirier, M.P., Flouris, A.D., Hardcastle, S.G., and Kenny, G.P. 2016*b*. Do the threshold limit values for work in hot conditions adequately protect workers? Med. Sci. Sports Exerc. **48**(6): 1187–1196. doi:10.1249/MSS.0000000000000886. PMID:26938043.

Meade, R.D., D'Souza, A.W., Krishen, L., and Kenny, G.P. 2017. The physiological strain incurred during electrical utilities work over consecutive work shifts in hot environments: a case report. J. Occup. Environ. Hyg. **14**(12): 986–994. doi:10.1080/15459624.2017.1365151. PMID:28825865.

Minard, D., Goldsmith, R., Farrier, P.H., and Lambiotte, B.J. 1971. Physiological evaluation of industrial heat stress. Am. Ind. Hyg. J. **32**(1): 17–28. doi:10.1080/0002889718506402.

Mirabelli, M.C., and Richardson, D.B. 2005. Heat-related fatalities in North Carolina. Am. J. Publ. Health, **95**(4): 635–637. doi:10.2105/AJPH.2004.042630. PMID:15798122.

Mora, C., Dousset, B., Caldwell, I.R., Powell, F.E., Geronimo, R.C., Bielecki, C.R., et al. 2017. Global risk of deadly heat. Nat. Clim. Change, **7**(7): 501. doi:10.1038/nclimate3322.

Moran, D.S., Montain, S.J., and Pandolf, K.B. 1998. Evaluation of different levels of hydration using a new physiological strain index. Am. J. Physiol. Regul. Integr. Comp. Physiol. **275**(3): R854–R860. doi:10.1152/ajpregu.1998.275.3.R854. PMID:9728084.

Muir, I.H., Bishop, P.A., Lomax, R.G., and Green, J.M. 2001. Prediction of rectal temperature from ear canal temperature. Ergonomics, **44**(11): 962–972. doi:10.1080/00140130110068933. PMID:11693247.

NIOSH. 2016. NIOSH Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments. By B. Jacklitsch, W.J. Williams, K. Musolin, A. Coca, J.-H. Kim, and N. Turner. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication 2016-106, Cincinnati, Ohio, USA.

Pearson, J., Ganio, M.S., Seifert, T., Overgaard, M., Secher, N.H., and Crandall, C.G. 2012. Pulmonary artery and intestinal temperatures during heat stress and cooling. Med. Sci. Sports Exerc. **44**(5): 857–862. doi:10.1249/MSS.0b013e31823d7a2b. PMID:22015711.

Richards, M.G.M., and Fiala, D. 2004. Modelling fire-fighter responses to exercise and asymmetric infrared radiation using a dynamic multi-mode model of human physiology and results from the sweating agile thermal manikin. Eur. J. Appl. Physiol. **92**(6): 649–653. doi:10.1007/s00421-004-1115-4. PMID:15133675.

Richmond, V.L., Wilkinson, D.M., Blacker, S.D., Horner, F.E., Carter, J., Havenith, G., and Rayson, M.P. 2013. Insulated skin temperature as a measure of core body temperature for individuals wearing CBRN protective clothing. Physiol. Meas. **34**(11): 1531–1543. doi:10.1088/0967-3334/34/11/1531. PMID:24149937.

Roach, G.D., Sargent, C., Darwent, D., Kennaway, D.J., and Ferguson, S.A. 2010. Lost in transit: the journey of ingestible temperature sensors through the human digestive tract. Ergonomia, **32**: 49–61.

Roberge, R.J., Kim, J.H., Yorio, P., Coca, A., Seo, Y., Quinn, T., et al. 2017. Umbilical temperature correlation with core and skin temperatures at rest, in the heat and during physical activity. Int. J. Hypertherm. **33**(7): 724–732. doi:10.1080/02656736.2017.1315180.

Rodríguez-Marroyo, J.A., Villa, J.G., López-Satue, J., Pernía, R., Carballo, B., García-López, J., and Foster, C. 2011. Physical and thermal strain of firefighters according to the firefighting tactics used to suppress wildfires. Ergonomics, **54**(11): 1101–1108. doi:10.1080/00140139.2011.611895. PMID:22026953.

Rosenman, K.D., Kalush, A., Reilly, M.J., Gardiner, J.C., Reeves, M., and Luo, Z. 2006. How much work-related injury and illness is missed by the current national surveillance system? J. Occup. Environ. Med. **48**(4): 357–365. doi:10.1097/01.jom.0000205864.81970.63. PMID:16607189.

Sawka, M.N. 1988. Body fluid responses and hypohydration during exercise-heat stress. *In* Human Performance Physiology and Environment Medicine at Terrestrial Extremes. *Edited by* K.B. Pandolf, M.N. Sawka, and R.R. Gonzalez. Benchmark Press, Ind., USA. pp. 227–266.

Sawka, M.N., and Friedl, K.E. 2018. Emerging wearable physiological monitoring technologies and decision aids for health & performance. J Appl. Physiol. **124**: 430–431. doi:10.1152/japplphysiol.00964.2017. PMID:29097633.

Seo, Y., DiLeo, T., Powell, J.B., Kim, J.H., Roberge, R.J., and Coca, A. 2016. Comparison of estimated core body temperature measured with the BioHarness and rectal temperature under several heat stress conditions. J. Occup. Environ. Hyg. **13**(8): 612–620. doi:10.1080/15459624.2016.1161199. PMID:26954265.

Strydom, N.B., Wyndham, C.H., Williams, C.G., Morrison, J.F., Bredell, G.A., and Joffe, A. 1965. Oral/rectal temperature differences during work and heat stress. J. Appl. Physiol. **20**(2): 283–287. doi:10.1152/jappl.1965.20.2.283.

Taiwo, O.A., Mobo, B.H., Jr., and Cantley, L. 2010. Recognizing occupational illnesses and injuries. Am. Fam. Physician, **82**(2): 169–174. PMID:20642271.

Taylor, N.A.S., Tipton, M.J., and Kenny, G.P. 2014. Considerations for the measurement of core, skin and mean body temperatures. J. Therm. Biol. **46**: 72–101. doi:10.1016/j.jtherbio.2014.10.006. PMID:25455943.

Taylor, N.A.S., Burdon, C.A., van den Heuvel, A.M., Fogarty, A.L., Notley, S.R., Hunt, A.P., et al. 2015. Balancing ballistic protection against physiological strain: evidence from laboratory and field trials. Appl. Physiol. Nutr. Metab. **41**(2): 117–124. doi:10.1139/apnm-2015-0386. PMID:26771198.

Taylor, N.A.S., Peoples, G.E., and Petersen, S.R. 2016. Load carriage, human performance, and employment standards. Appl. Physiol. Nutr. Metab. **41**(6): S131–S147. doi:10.1139/apnm-2015-0486. PMID:27277563.

Teunissen, L.P.J., de Haan, A., de Koning, J.J., Clairbois, H.E., and Daanen, H.A.M. 2011. Limitations of temperature measurement in the aural canal with an ear mould integrated sensor. Physiol. Meas. **32**(9): 1403–1416. doi:10.1088/0967-3334/32/9/004. PMID:21788686.

Tikuisis, P., McLellan, T.M., and Selkirk, G. 2002. Perceptual versus physiological heat strain during exercise-heat stress. Med. Sci. Sports Exerc. **34**(9): 1454–1461. doi:10.1097/00005768-200209000-00009. PMID:12218738.

Todd, G., Gordon, C.J., Groeller, H., and Taylor, N.A. 2014. Does intramuscular thermal feedback modulate eccrine sweating in exercising humans? Acta Physiol. **212**(1): 86–96. doi:10.1111/apha.12327.

Villar, R., Beltrame, T., and Hughson, R.L. 2015. Validation of the Hexoskin wearable vest during lying, sitting, standing, and walking activities. Appl. Physiol. Nutr. Metab. **40**(10): 1019–1024. doi:10.1139/apnm-2015-0140. PMID: 26360814.

Walker, A., Rattray, B., and Brearley, M. 2017. Perception or reality: Can thermal perceptions inform management of firefighters in the heat? J. Occup. Environ. Hyg. **14**(4): 306–312. doi:10.1080/15459624.2016.1240871. PMID:27791486.

Werner, J. 2014. Measurement of temperatures of the human body. *In* Comprehensive Biomedical Physics. Vol. 5. *Edited by* A. Brahme. Elsevier, Amsterdam, Netherlands. pp. 107–126.

Werner, J., and Reents, T. 1980. A contribution to the topography of temperature regulation in man. Eur. J. Appl. Physiol. **45**(1): 87–94. doi:10.1007/BF00421205. PMID:7191808.

Wilkinson, D.M., Carter, J.M., Richmond, V.L., Blacker, S.D., and Rayson, M.P. 2008. The effect of cool water ingestion on gastrointestinal pill temperature. Med. Sci. Sports Exerc. **40**(3): 523–528. doi:10.1249/MSS.0b013e31815cc43e. PMID:18379216.

Woodman, E.A., McConnell Parry, S., and Simms, L. 1967. Sources of unreliability in oral temperatures. Nurs. Res. **16**: 276–279.

Wright, H.E., Larose, J., McLellan, T.M., Miller, S., Boulay, P., and Kenny, G.P. 2013. Do older firefighters show long-term adaptations to work in the heat? J. Occup. Environ. Hyg. **10**(12): 705–715. doi:10.1080/15459624.2013.821574. PMID:24195537.

Xiang, J., Hansen, A., Pisaniello, D., and Bi, P. 2015. Extreme heat and occupational heat illnesses in South Australia, 2001-2010. Occup. Environ. Med. **72**(8): 580–586. doi:10.1136/oemed-2014-102706. PMID:26081622.