June 2017

Ability of Physiological Strain Index to Discriminate Between Sustainable and Unsustainable Heat Stress

Dwayne Wilson
University of South Florida, desertfoxmd@gmail.com

Ability of Physiological Strain Index to Discriminate Between Sustainable and Unsustainable Heat Stress

by

Dwayne Wilson

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Public Health
Department of Environmental and Occupational Health
College of Public Health
University of South Florida

Major Professor: Thomas E. Bernard, Ph.D.
René R. Salazar, Ph.D
Yougui Wu, Ph.D.

Date of Approval:
June 27, 2017

Keywords: ROC Curve, Heart Rate, Core temperature, rectal Temperature

DEDICATION

This thesis is dedicated to my wife Tracy M. Wilson whose patient endurance has allowed me to climb ever higher. She has been a pillar of support through all my difficult times. You fulfill the proverb which states “The man who finds a wife finds a treasure, and he receives favor from the Lord (New Living Translation). May the light of curiosity be forever present in your eyes and may we enjoy the good things of this world together.

ACKNOWLEDGMENTS

I would like to thank Thomas E. Bernard for providing invaluable guidance in bringing this project to fruition. I would also like to thank the other members of the committee, Drs. Yougui Wu and René Salazar, for their thoughtful insights. I would like to thank Ximena P. Garzón for her diligent work on this project. Lastly, my studies were supported in part by the Sunshine ERC at USF (CDC/NIOSH T42-OH008438). Data were from a previous CDC/NIOSH project (R01- OH03983).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Introduction: Assessment of heat strain is an alternative approach to assessing heat stress exposures. Two common measures of heat strain are body core temperature (T_C) and heart rate (HR). In this study T_C was assessed by rectal temperature (T_{re}). Physiological Strain Index (PSI) was developed to combine both T_{re} and HR into one metric. Data collected from progressive heat stress trials were used to (1) demonstrate that PSI can distinguish between Sustainable and Unsustainable heat stress; (2) suggest values for PSI that demonstrate a sustainable level of heat stress; and (3) determine if clothing or metabolic rate were effect modifiers.

Methods: Two previous progressive heat stress studies included 494 trials with 988 pairs of Sustainable and Unsustainable exposures over a range of relative humidity (rh), metabolic rates (M) and clothing using 29 participants. To assess the discrimination ability of PSI, conditional logistic regression and logistic regression were used. The accuracy of PSI was assessed using Receiver Operating Characteristic curves (ROC).

Results: The present study found that primary (T_{re}, HR, and T_{sk}) and derived (PSI and $\Delta T_{re\text{-}sk}$) HSMs can accurately predict Unsustainable heat stress exposures based on AUCs that ranged from 0.73 to 0.86. Skin temperature had the highest AUC (0.86) with PSI in the mid-range (0.79).

The values of the HSMs associated with a predicted probability of 0.25 were considered as screening values (PSI < 2.6, $\Delta T_{re\text{-}sk}$ > 1.9 °C, T_{re} < 37.5, HR < 109, and T_{sk} < 35.8). The value of using any one of these individual indicators is that they act as a screening tool to decide if an exposure assessment is needed.

Metabolic rate was found to be a confounder for all the HSMs except for RT_{sk}. It was not statistically significant for HSMs derived models (PSI and $\Delta T_{re\text{-}sk}$). And its effect modification was not significant in any model.

Conclusions: Based on the ROC curve, PSI can accurately predict Unsustainable heat stress exposures (AUC 0.79). HR alone has a similar capacity to distinguish Unsustainable exposures (AUC 0.78) under relatively constant exposure (metabolic rate and environment) for an hour or so. Screening limits with high sensitivity, however, have low thresholds. This limits the utility of these heat strain metrics. To the extent that the observed strain is low, there is good evidence that the exposure is Sustainable.

INTRODUCTION

Heat stress is a recognized occupational hazard. Commonly described heat-related disorders include heat cramps, heat rash, dehydration, heat exhaustion, heat syncope, and heat stroke (T. E. Bernard, 2012). Agriculture, construction, and mining (extraction) operations are particularly vulnerable to death due to heat stress related injuries. A case-control study in Maricopa County, Arizona found that there were 444 cases of heat-associated deaths in the years 2002-2009 (Petitti, Harlan, Chowell-Puente, & Ruddell, 2013). Of those who died from a heat-associated illness, 332 (75%) were men. 115 (35%) of these men worked in the agriculture, construction, or extraction industries. The odds ratio for heat-associated deaths in men working in Arizona's construction/extraction and agriculture industries is 2.32 and 3.50, respectively, compared to a control group of adult males 18+ years of age.

In 2012-2013, the Center for Disease Control and Prevention (CDC) investigators examined federal enforcement cases resulting in citations under the "general duty clause" of the Occupational and Safety and Health Act (Williams-Steiger, 1970). There were twenty cases of heat illness of which thirteen were fatalities. Of the 13 fatalities, nine of the deaths occurred in the first three days of working on the job. The other four fatalities occurred on the worker's first day (Arbury et al., 2014).

Occupational heat stress has three recognized workplace risk factors (ACGIH, 2017; NIOSH, 2016). One risk factor is the ambient environment. The ambient environment is composed of the air temperature, humidity, convection, and radiation. Convective heat is the exchange of heat between the skin and surrounding air. Radiant heat is the net heat flow from a hotter surface to a cooler surface (T. E. Bernard, 2012). Work demands is another risk factor, which represents internal heat generation. The remaining risk factor is clothing, which may reduce evaporative cooling. The evaluation of heat stress builds on the importance of quantifying the three job risk factors. While the Occupational Safety and Health Administration (OSHA) does not have a standard for heat stress, its technical manual follows the approach of the National Institute for Occupational Safety and Health (NIOSH) and the ACGIH® (OSHA, 2016). The wet bulb globe temperature (WBGT) method exposure limits are based on a level of heat stress that is sustainable (Garzón-Villalba, Wu, Ashley, & Bernard, 2017a, 2017c).

There are situations when making a traditional exposure assessment is not practical (e.g., maintenance tasks, unusual work conditions, etc.) and to provide some evidence that the heat stress is well-managed. Heat strain indicators have been used for decades as tools for monitoring physiological responses to work in hot working environments and providing limits to exposures (Brouha, 1960; Dinman, Stephenson, Horvath, & Colwell, 1974; Fuller & Smith, 1981; Horvath, 1976; Logan & Bernard, 1999; NIOSH, 1972, 1986, 2016; OSHA, 2016). For the purposes of the research reported here, there are five potential Heat Strain Metrics (HSMs):

- Direct HSMs, which are typically measured during a heat strain evaluation
    - Rectal Temperature (T_{re}) and RT_{re}
    - Heart Rate (HR) and RHR

    - Average Skin Temperature (T_{sk}) and RT_{sk}
- Derived HSMs, which are intended to provide interpretive data
    - Core to Skin Gradient ($\Delta T_{re\text{-}sk}$)
    - Physiological Strain Index (PSI)

Rather than use physiological responses to limit an exposure or suggest high heat strain, this paper considers their use to confirm that the exposures are sustainable. One heat strain indicator, Physiological Strain Index (PSI), is frequently mentioned in the literature dealing with human responses to heat stress, and PSI will be the reference HSM for the study.

The goal of the current study was to determine if indicators of physiological strain could accurately discriminate Sustainable from Unsustainable heat exposure. There were three objectives for undertaking this study: (1) demonstrate that each indicator can distinguish between Sustainable and Unsustainable heat stress; (2) suggest values that demonstrate a sustainable level of heat stress; and (3) determine if metabolic rate and clothing were effect modifiers.

LITERATURE REVIEW

While exposure assessment is the usual approach to determine if a heat stress condition is acceptable, heat strain metrics (HSMs) have been used to demonstrate adequate control of the exposures or to stop an exposure. One method that has been proposed is the Physiological Strain Index (PSI), which accounts for both body core temperature and heart rate in an a priori relationship.

Rationale for PSI

Important measures of heat strain are rectal temperature (T_{re}) and heart rate (HR). At rest, the T_{re} is 37.0 ± 0.7 (Cranston, Gerbrandy, & Snell, 1954; Sund-Levander, Forsberg, & Wahren, 2002; Tanner, 1951). Looking at limits on occupational heat stress, WHO (1969) suggested 38 ˚C as a limit on T_{re} for prolonged daily exposures to heavy work. WHO also recognized that 39 °C was safe under closely monitored conditions. The ACGIH (2017) Threshold Limit Value® for Heat Stress and Strain suggested a limiting T_{re} to 38.5 ˚C, which allows a margin to safely leave a heat stress exposure (T. E. Bernard & Kenney, 1994). Malchaire et al. (2001) examined the literature for a limiting core temperature and concluded that temperatures ≥ 39 ˚C were likely to be associated with excessive heat strain. This premise was underpinned by Sawka et al. (1992) who found that cases of exhaustion rarely occurred when T_{re} was < 38 ˚C, and all observed heat exhaustion cases occurred before reaching 40 ˚C.

Heart rate (HR) is another index of heat strain. Ostchega, Porter, Hughes, Dillon, and Nwankwo (2011) reported an average resting heart rate of 73 ± 3 bpm for adults aged between 20 and 59. Brouha (1960) observed that HR during work and recovery varies according to work load and ambient condition; he found a linear relation between HR increments and ambient temperature. In 1963, Maxfield and Brouha reported that during environmental stress, the recovery of HR was prolonged with the increase in work load and increase of environmental temperature. To maintain a compensable level of heat stress, WHO (1969) reported a HR of 120 bpm for young, healthy men exposed to steady moderate work (from their Fig 2). Minard, Goldsmith, Farrier, and Lambiotte (1971) demonstrated that daily average heart rates above 120 would lead to a loss of aerobic work capacity for steel workers over a shift. Kuhlemeier and Wood (1979) recommended a maximum heart rate for prolonged work at 125 bpm. T. E. Bernard and Kenney (1994) suggested heart rate thresholds around 125 bpm for exposures of 90 minutes. ACGIH (2017) recommended discontinuing a heat stress exposure (unsustainable heat stress) if the worker presents a sustained HR ≥ 180 - Age. This recommendation is based on a heat stress management practice in Australia.

Recognizing the prior use of T_{re} and HR to evaluate heat strain, Moran, Shitzer, and Pandolf (1998) proposed PSI. PSI uses heart rate and rectal temperature to represent both the cardiovascular and thermoregulatory systems. PSI assumes that both contribute equally to the strain by assigning the same weight function to each.

$$PSI = 5\,(T_{ret} - T_{re0}) / (39.5 - T_{re0}) + 5\,(HR_t - HR_0) / (180 - HR_0).$$

PSI evaluates heat strain on a common scale of 0 to 10, where 0 represents no strain and 10 represents strenuous (near maximal) physiological conditions.

Validity Studies for PSI

Moran et al. (1998) looked at the ability of PSI to evaluate heat stress. It was determined that PSI was able to linearly correlate with increasing levels of strain when climatic conditions such as heat and humidity (40°C and 40% relative humidity) were held constant. The test subjects were a heterogeneous mix that varied in their physical fitness, acclimation status, and tolerance to heat. As a result, strain levels varied over in individuals when environmental conditions were held constant. Mild physiological strain was rated for one test subject at 3-4 after 120 minutes. Moderate strain was rated in a second test subject at a PSI of 4-6 after 120 minutes. Heavy physiological strain in a third test subject was rated at 8.5 on PSI scale after 120 minutes. Moran et al. (1998) also performed a validation study which involved a database of seven men wearing protective clothing and exercising in hot-dry and hot-wet environments. In the study, it was determined that PSI was able to significantly differentiate ($P<0.05$) between two work climates. PSI rated the exposure in the hot–dry climate at higher physiological strain for test subjects. The PSI index used in this study was compared against the cumulative heat strain index (CHSI) and heat strain index (HSI). It was determined that unlike HSI and other models, PSI can be computed while the test subject is exposed to stress without the need to wait until the end of exposure to analyze the strain (Moran et al., 1998). Also, PSI can be applied any time because it involves only two variables. This includes rest or recovery periods. Moran et al. (1998) concluded that PSI has the potential to be widely accepted and used universally because it overcomes the limits of other heat strain indexes which are valid only under certain specific conditions.

Dehydration

Ekblom, Greenleaf, Greenleaf, and Hermansen (1970) conducted research on temperature regulation in man. They specifically looked at the role of hypohydration and its effects on temperature regulation during exercise. Their research confirmed that hypohydration increases physiological strain when exercising in the heat. In fact, increases in core temperature during exercise were observed with only a 1% loss of water from total body weight compared to euhydration (Ekblom et al., 1970). It has been proposed that hypohydration causes associated changes in blood volume (Nadal,1980) or changes in plasma osmolality (Harrison, Edwards, & Fennessy, 1978) which influence the thermoregulatory system. For example, hypohydration causes a decrease in stroke volume which prompts an increase in heart rate to compensate for the volume loss. In addition, hypohydration causes a decrease in blood flow to the skin which impairs the body's ability to dissipate heat. Sawka and others clearly demonstrates that hypohydration increased T_{re} and HR during exercise in the heat (Sawka, 1992; Sawka & Pandolf, 1990).

Moran et al. (1998) evaluated the relationship between hydration level and PSI. The study involved a database that was obtained from eight endurance-trained men dehydrated to four different levels (1.1, 2.3, 3.4, and 4.2% of body weight). After 2-h of strenuous exercise (65% of maximum aerobic capacity) at 33°C and 50% relative humidity, values of PSI were correlated with hypohydration levels ($P<0.01$). PSI increased from 6.5 to 8.7 for hypohydration levels of 1.1 to 4.2%.

Gender

Physiological responses to exercise-heat stress may be different between males and females. Factors that may account for this difference include hormonal fluctuations of estrogen and progesterone associated with the menstrual cycle. The menstrual cycle may alter women's performance and tolerance to exercise-heat stress (Rothchild & Barnes, 1952; Sato, Kang, Saga, & Sato, 1989). In addition, compared to men, women have lower cardiorespiratory fitness, lower body weight, lower body surface area, and a higher percent of body fat (Moran, Shapiro, Laor, Izraeli, & Pandolf, 1999). Investigators have shown that under the same thermal load, women compared to men had higher core and skin temperatures. Women also had higher skin temperatures and lower sweating rates compared to men (Nunneley, 1977). It was determined that acclimatization eliminated most of these gender-related physiological differences except sweat rate (Andérson, Ward, & Mekjavić, 1995; Wyndham, Morrison, & Williams, 1965). Sawka, Wenger, and Pandolf (1995) concluded that men and women have similar heat tolerances and body temperature responses to exercise in the heat if the genders are matched for aerobic fitness.

Moran et al. (1999) conducted a study to examine the ability of PSI to assess gender heat strain differences at various climatic conditions and exercise intensities. The test subjects consisted of one group of women (n=9) that was matched by Vo_2 with a group of men (n=8) with a third group of very fit males (MF). There were three levels of environment: comfortable [20°C,1.16kPa (50%RH)], Hot-Dry [40°C, 2.58kPa (35%RH)], and Hot-Wet [35C, 3.93KPa (70% RH)]. And three levels of metabolic rate: low (300 W) moderate (500 W), and high (650 W). As expected, there were significant differences ($P<0.05$) in PSI between M than MF for all exposure conditions; between W and MF at the high exercise intensity for the three climatic conditions; and at the moderate exercise intensity for the two hot climates. There was no difference in PSI for the matched W and M groups. The study also demonstrated that PSI could be used to rank order combined climatic conditions and exercise intensity.

Age

Older men and women experience more physiological strain during exposure to a hot environment than younger individuals (Drinkwater & Horvath, 1978; Wagner, Robinson, Tzankoff, & Marino, 1972). It is difficult to say if these findings are related to age or to factors such as certain disease states, decreased physical activity, and/or lowered aerobic fitness. Other studies suggest that “habitually active” middle-aged men displayed the same acute exercise-heat tolerance as when they were younger. In addition, middle aged men acclimatized to heat at the same rate and degree as when they were younger (Robinson, Belding, Consolazio, Horvath, & Turrell, 1965). More recent studies by (Pandolf, 1997) pointed out that aerobic fitness, body fat, and body weight are important factors in maintaining work-heat tolerance with aging. Research conducted by Kenney (1988) showed that there was no difference in physiological strain between unacclimatized younger and older individuals when maximal aerobic capacity, surface area, and surface to mass ratio are matched. Richmond, Davey, Griggs, and Havenith (2015) suggested in his research that the physiological strain in acute heat stress or acclimatization for matched older and younger males is the same or improved for middle aged men.

Moran, Kenney, Pierzga, and Pandolf (2002) conducted a study to evaluate PSI for different age groups during exercise-heat stress (EHS). In one part of the study they applied the PSI to young males and middle-aged men who were acclimatized. The two groups were matched for aerobic capacity, body weight, and surface area. PSI was higher for young males as compared to middle aged men during all 10 days of acclimatization.

Suggested Thresholds for PSI

In the same paper in which they explored gender differences, Moran et al. (1999) used some professional judgment on the level of strain associated with ranges of PSI. Low exercise activity across the three climatic conditions was ranked as little to low strain with PSI values ranging from 2-4. Moderate exercise intensity across the three climatic conditions was ranked as little to moderate strain with a PSI value of 2-6. High exercise intensity across the three climatic conditions was ranked as low to very high strain with PSI values of 2-9.

Buller, Latzka, Yokota, Tharion, and Moran (2008) suggested a limit of 7.5, which was a little lower than the limiting heat strain allowed by their IRB (PSI = 8), to classify a person as at-risk. Using the ACGIH limits of 38.5 °C and 140 bpm (for age = 40), the PSI value is 6.1. Using WHO's limit of 38.0 °C and heart rate of 120 bpm as sustainable limits, the equivalent PSI is 5.1. These values were somewhat higher than the little to low strain range of 2-4 (Moran et al., 1999).

Skin Temperature

T_{sk} plays a fundamental role in thermoregulation (Van Marken Lichtenbelt et al., 2006). Such mechanism can be modified by the use of working clothes. T_{sk} has being used in combination with other HSMs to monitor core body temperature and prevent heat strain (Cuddy, Buller, Hailes, & Ruby, 2013; Niedermann et al., 2014). Despite that it is generally 2 ˚C to 4 ˚C below T_{re}, T_{sk} can be used to estimate core temperature when there is no other methodology available (Buller et al., 2008; Fuller & Smith, 1981; Gunga, Sandsund, Reinertsen, Sattler, & Koch, 2008; Kim & Lee, 2015; NIOSH, 2016).

Pandolf and Goldman (1977) recommended that if the difference between T_{re} and T_{sk} be < 1˚C the exposure to heat should be stopped; and NIOSH (2016) repeats that recommendation. Assuming that a core temperature limit of 38.0 °C is a target, a skin temperature of 37 °C would be a reasonable limit. Because of the reference to the difference between core and skin temperature, this was the other derived HSM.

Effect Modification

In general, HSMs will increase with the level of heat stress. The association of physiological heat strain indicators and metabolic rate (M) is difficult to assess, and many investigators agree that core temperature is mainly determined by M below certain environmental temperatures (Kuhlemeier & Wood, 1979; Lind, 1963a, 1963b; Lind, Humphreys, Collins, Foster, & Sweetland, 1970; NIOSH, 2016).

Clothing may contribute to increased skin temperature to facilitate the dissipation of heat to the environment. Depending the characteristics of the ensembles, clothing can restrict the dry heat exchange, by radiation conduction and convection (McLellan, Pope, Cain, & Cheung, 1996) on individuals exposed to hot environments, leading them to unbearable heat strain (Havenith, 1999). Further, as the evaporative resistance increases, the gradient from the skin to the environment must increase to meet the same level of evaporative cooling. This is achieved by higher skin temperatures.

METHODS

The HSM data for this paper were from two previous studies at USF (Thomas E Bernard, Victor Caravello, Skai W Schwartz, & Candi D Ashley, 2008; T. E. Bernard, C. L. Luecke, S. K. Schwartz, K. S. Kirkland, & C. D. Ashley, 2005) approved by the USF institutional review board. Those studies had a progressive heat stress protocol which began with a cool environment that allowed the subjects to easily achieve thermal equilibrium. Once equilibrium was established, air temperature and water vapor pressure were slowly increased every 5-minute at constant rh until thermal equilibrium was disrupted. The transition from a stable core temperature to values that were steadily increasing was the critical condition. For this paper, a compensable observation was selected 15 minutes before the critical condition. An uncompensable observation was marked at 15 minutes after the critical condition (see Figure 1). The compensable and uncompensable observations were chosen to be close the critical point while providing confidence that the characterizations of compensable and uncompensable were correct (Garzón, Wu, Ashley, & Bernard, 2017). For each trial, the outcome was classified as Sustainable if the condition was compensable, and Unsustainable if the condition was uncompensable. The critical point was classified as Unsustainable if T_{re} was ≥ 38 °C and if the change in T_{re} increased by more than 0.1 °C over the preceding 20 minutes, or as Sustainable if T_{re} was < 38 °C, or if the change in T_{re} was ≤ 0.1°C over the preceding 20 minutes (Garzón et al., 2017).

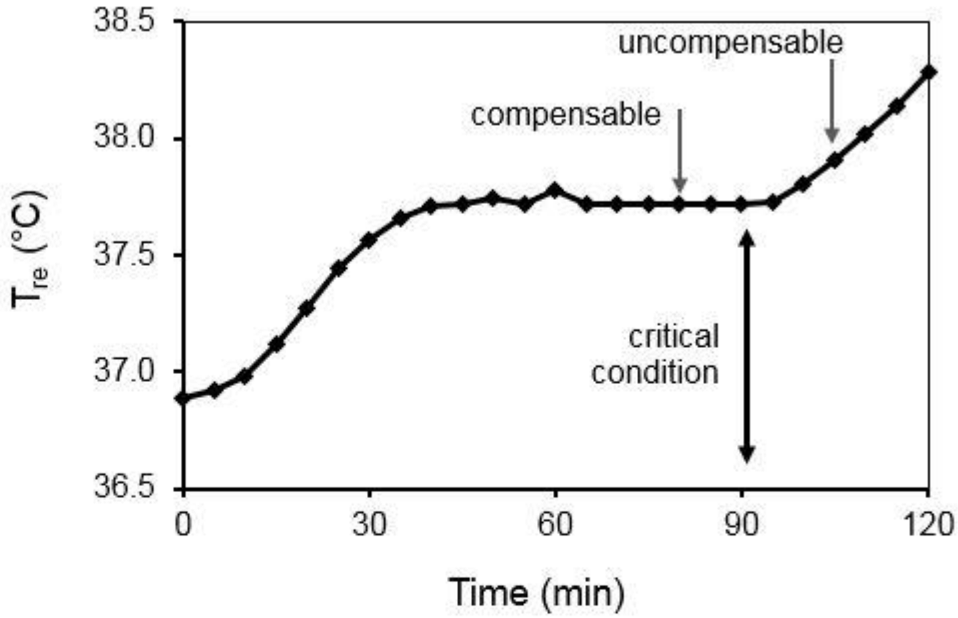

Figure 1. The time course of Tre for an example trial with arrows to indicate the critical condition, the compensable condition established 15 minutes before the critical condition, and uncompensable after it (Garzón-Villalba et al., 2017a)

During each trial, the direct HSMs ($T_{re,}$ HR, and T_{sk}), as well as ambient conditions were monitored continuously and recorded every 5 minutes. Metabolic rate was calculated from the measurement of oxygen consumption via expired gases sampled every 30 minutes in a trial.

The two USF studies considered five clothing ensembles that included work clothes (140 g m^{-2} cotton shirt and 270 g m^{-2} cotton pants), and cotton coveralls (310 g m^{-2}) plus three nonwoven protective clothing ensembles: (1) particle-barrier (Tyvek® 1424 and 1427; similar to Tyvek® 1422A); (2) water-barrier, vapor-permeable (NexGen® LS 417; microporous membrane), and (3) vapor-barrier (Tychem QC®, polyethylene-coated Tyvek). One study (T. E. Bernard, C. L. Luecke, S. W. Schwartz, K.

S. Kirkland, & C. D. Ashley, 2005) had a targeted work demand of 160 W m^{-2} to approximate moderate work over three levels of relative humidity (20, 50 and 70%). The other study (T. E. Bernard, V. Caravello, S. W. Schwartz, & C. D. Ashley, 2008) had targeted work demands of 115, 175 and 250 W m^{-2} to approximate light, moderate, and heavy work at a rh of 50%. In both studies, each participant wore each of the five clothing ensembles. The present study had a crossover design, in which each participant contributed three observations per trial; and each participant completed 15 trials.

All study participants were acclimatized by 2-h exposures over five successive days to dry heat (50 °C and 20% rh) at 160 W m^{-2} while wearing shorts and tee shirt. The characteristics of the 29 participants who took part in these trials are summarized in Table 1.

Table 1. Physical Characteristics (mean ± standard deviation) of Participants

	N	Age [yrs]	Height [cm]	Weight [kg]	Body Surface Area [m^2]
Relative Humidity Study (T. E. Bernard et al., 2005)					
Men	9	29 ± 6.8	183 ± 6	97 ± 19	2.18 ± 0.20
Women	5	32 ± 9.1	161 ± 7	64 ± 17	1.66 ± 0.23
Metabolic Rate Study (T. E. Bernard et al., 2008)					
Men	11	28 ± 10	176 ± 11	82 ± 12	1.98 ± 0.47
Women	4	23 ± 5	165 ± 6	64 ± 18	1.70 ± 0.22
Pooled					
Men	20	29 ± 9	179 ± 34	89 ± 23	2.07 ± 0.41
Women	9	28 ± 8	163 ± 7	64 ± 17	1.74 ± 0.29

No differences were found between work clothes and cotton coveralls in previous investigations (T. E. Bernard et al., 2008; T. E. Bernard et al., 2005; Caravello, McCullough, Ashley, & Bernard, 2008), therefore the two ensembles were categorized as woven cotton clothing in this study. There were 190 trials for woven cotton clothing, 119 for particle barrier, 91 for water barrier, and 94 for vapor barrier over the two studies (see Table 2).

Table 2. Number of observations as Sustainable and Unsustainable overall and by fabric type, and the associated number of trials.

	All	Woven	Particle Barrier	Water Barrier	Vapor Barrier
Sustainable	749	294	184	131	140
Unsustainable	733	276	173	142	142
Trials	494	190	119	91	94

Statistical Analysis

For PSI, the baseline values of T_{re} and HR were assigned fixed values based on population means; specifically, 37.0 °C and 75 bpm. The observed PSI values had a nominal range of 0 to 10. The other derived HSM, the difference between T_{re} and T_{sk} ($\Delta T_{re\text{-}sk}$), was unscaled with a range of a couple of degrees Celsius. Each of the direct HSMs were expressed as a ratio over a nominal range from rest to highest acceptable value based on our judgment (Garzón-Villalba, Wu, Ashley, & Bernard, 2017b) and multiplied by 10. The baseline and ceiling values for T_{re} and HR were the same as PSI, and 35 ºC and 37 ºC for skin temperature. HSMs are described here and in Table 6.

$$PSI = 5\,(T_{re} – 37.0)/(39.5 – 37.0) + 5\,(HR - 75)/(180 - 75)$$

$$\Delta T_{re\text{-}sk} = T_{re} - T_{sk}$$

$$RT_{re} = 10\,[(T_{re} – 37) / (39-37)]$$

$$RHR = 10\,[(HR – 75) / (180-75)]$$

$RT_{sk} = 10 [(T_{sk} – 35) / (37-35)]$

Proc Univariate SAS 9.4 (SAS Institute Inc. Cary NC, 2013) was used to assess the characteristics and distribution of the independent quantitative variables.

The Outroc option of Proc Logistic SAS 9.4 (SAS Institute Inc. Cary NC, 2013) was used to generate ROC curves and their AUCs for each of the HSMs. ROC's sensitivity of 0.95 was chosen as optimal operating point (OOP) (Gallop, 2001) to reliably determine if an exposure was Unsustainable or not.

Dose-response curves (Probability of Unsustainable versus HSM) were developed using logistic regression models with only the critical condition data. Each set of HSM data was rank ordered from the lowest to highest HSM value. Next, the odds were estimated for each observation as the number of trial critical conditions at or below the observed HSM value divided by the number of critical conditions above the HSM plus 1. From these rank-ordered data, the logistic regression was computed as the ln(odds) = a + b HSM, using SAS Proc Lotistic SAS 9.4 (SAS Institute Inc. Cary NC, 2013).

Testing the Effects of Clothing and Metabolic Rate

A dummy categorical variable representing the 4 types of fabrics (woven cotton clothing, particle-barrier, water-barrier, and vapor-barrier) was created to assess clothing effects on the unadjusted models. The unadjusted association between the clothing variable and the dichotomous outcome was assessed using Proc Logistic SAS 9.4 (SAS Institute Inc. Cary NC, 2013); that is, ln(odds) = $\alpha + \beta_1$ CLOTHING. A model using HSM as main predictor was adjusted for clothing to assess it for confounding and effect modification; ln(odds) = $\alpha + \beta_1$ HSM + β_2 CLOTHING. In those models in which the association changed 10% or more, effect modification was tested with an interaction term; ln(odds) = $\alpha + \beta_1$ HSM + β_2 CLOTHING + β_3 CLOTHINGxHSM. The same steps were performed with M as a continuous variable in place of CLOTHING.

RESULTS

Descriptive Statistics

The USF heat stress studies comprised 494 trials, with 988 pairs of Sustainable and Unsustainable exposures, over three levels of relative humidity (20, 50 and 70%), three levels of metabolic rate (mean values of 150, 180 and 255 W m^{-2}) and four types of clothing fabrics (woven cotton, particle barrier, water barrier and vapor barrier) using 29 participants. The characteristics of the study's volunteers are reported Table 1.

The work ensembles distribution by outcome and by number of trials is presented in Table 2. Table 3 provides descriptive statistics (mean, standard deviation) of the HSMs (PSI, ΔT_{re-sk}, T_{re}, HR, and T_{sk}) by the classification of the observation across all trial conditions.

Table 3. Averages values of the HSMs for the Sustainable and Unsustainable observations

Classification	N	PSI	ΔT_{re-sk}	T_{re}	HR	T_{sk}
Sustainable	749	2.8 ± 1.2	2.1 ± 1.0	37.6 ± 0.3	109 ± 17	35.6 ± 1.0
Unsustainable	733	4.4 ± 1.4	1.1 ± 0.8	37.9 ± 0.3	129 ± 20	36.8 ± 0.8

HSM Models to Predict Unsustainable

Individual HSMs (PSI, ΔT_{re-sk}, RT_{re}, RHR, and RT_{sk}) were the predictors in logistic regression models on which the outcome was Sustainable versus Unsustainable. The accuracy of PSI and the others HSM to predict Unsustainable was assessed with ROC curves and their corresponding AUCs. As a principal finding, Table 4 provides the ROC AUC with 95% confidence interval (CI) for the unadjusted models (each HSM alone) and HSM models adjusted for metabolic rate and for clothing. As a standard point of comparison, a sensitivity of 0.95 was chosen as OOP (Gallop, 2001) to determine if an exposure was Unsustainable. Finally, the AUC for PSI alone was a point of comparison for the other AUCs, where the level of significance is listed. The AUCs for the unadjusted HSMs are also illustrated in Figure 2.

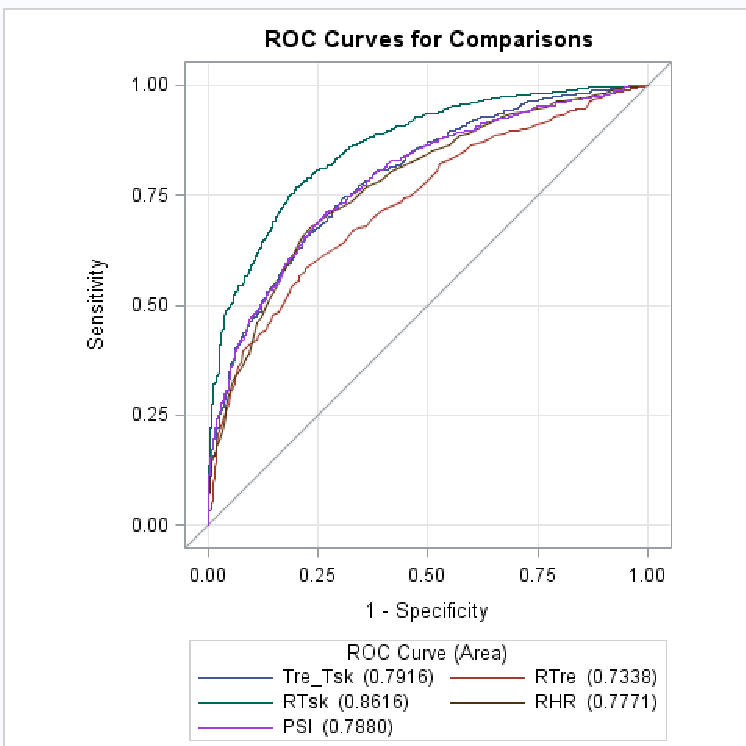

Figure 2. Contrast of the HSM ROC curves against the PSI ROC curve.

Table 4. For the unadjusted and adjusted heat strain metrics (HSMs), the areas under the ROC curves (AUCs) with 95% confidence interval (CI), the observed specificity at a screening sensitivity of 0.95, and the level of statistical significant of the AUC referenced to the unadjusted PSI

Models	AUC (CI)	Specificity at sensitivity = 0.95	AUC comparison to PSI p-value
Unadjusted HSM Models			
PSI	0.79 0.77-0.81	0.26	……..
$\Delta T_{re\text{-}sk}$	0.79 0.77-0.81	0.29	0.84
RT_{re}	0.73 0.71-0.76	0.14	<.0001
RHR	0.78 0.75-0.80	0.25	0.04
RT_{sk}	0.86 0.84-0.88	0.45	<.0001
HSM Models Adjusted for M			
PSI+M	0.79 0.77-0.81	0.25	0.97
$\Delta T_{re\text{-}sk}$ + M	0.82 0.80-0.84	0.33	0.07
RT_{re} + M	0.73 0.71-0.76	0.16	<.0001
RHR + M	0.78 0.75-0.80	0.24	<.0001
RT_{sk} + M	0.86 0.84-0.88	0.50	<.0001
Models Adjusted for Clothing			
PSI + clothing	0.79 0.77-0.81	0.25	0.82
$\Delta T_{re\text{-}sk}$ + clothing	0.79 0.77-0.81	0.29	0.84
RT_{re} + clothing	0.73 0.71-0.76	0.16	<.0001
RHR + clothing	0.78 0.75-0.80	0.24	0.04
RT_{sk} + clothing	0.86 0.047-0.10	0.45	<.0001

The second objective in the present study was to suggest values for PSI and the other HSMs that demonstrate a sustainable level of heat stress. Logistic regression models were built using the HSMs predictors from a data set with only data from the critical condition, which was a mix of Sustainable and Unsustainable states. The models are reported in Table 5.

Table 5 Logistic regression models for each of the HSMs

HSM	Logistic Regression Model
PSI	log[p/(1-p)] = -4.44 + 1.30 PSI
$\Delta T_{re\text{-}sk}$	log[p/(1-p)] = +3.52 - 2.44 $\Delta T_{re\text{-}sk}$
RT_{re}	log[p/(1-p)] = -3.81 + 1.06 RT_{re}
RHR	log[p/(1-p)] = -4.58 + 1.08 RHR
RT_{sk}	log[p/(1-p)] = -3.29 + 0.52 RT_{sk}

Figure 3 illustrates the relationship between probability of Unsustainable and PSI based on the critical data and the associated logistic regression model.

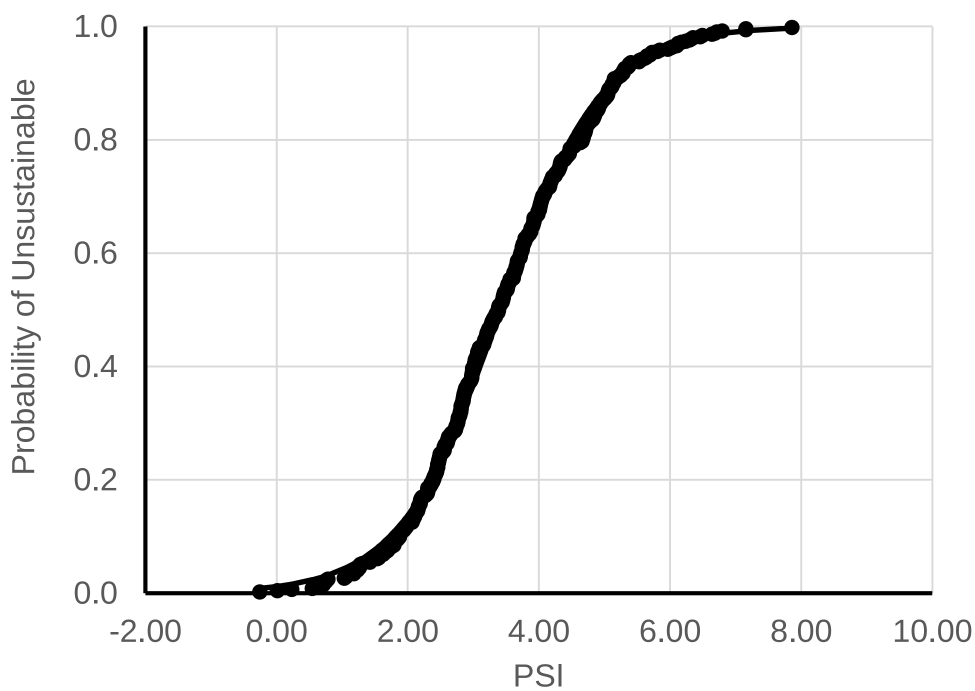

Figure 3. Relationship of PSI to the probability of Unsustainable heat stress

Table 6 summarizes the values for each HSM based on their probability distribution for Unsustainable.

Table 6. The values for each of the HSMs at the probability of Unsustainable at five levels.

	Probability of Unsustainable				
HSM	0.05	0.25	0.5	0.75	0.95
PSI	1.2	2.6	3.4	4.3	5.7
$\Delta T_{re\text{-}sk}$	2.6	1.9	1.4	1.0	0.2
T_{re}	37.2	37.5	37.7	37.9	38.3
HR	91	109	120	130	148
T_{sk}	35.1	35.8	36.3	36.7	37.4

Models Adjusted for Clothing and Metabolic rate

To fulfill the third objective, clothing was fitted as main predictor in the HSM conditional logistic models. Its association with the outcome was not statistically significant (*p*-value 0.79). Next, clothing was assessed for confounding and effect modification in all the HSM models and was found not statistically significant in any model.

M increased the association more than 10% on all the models except the one using ΔT_{re}-T_{sk} as predictor; thus M may be considered a confounder. Its interaction term was found not statistically significant so M cannot be considered as an effect modifier.

DISCUSSION

The overall goal of this study was to see how well PSI and other heat strain metrics (HSMs) can distinguish Sustainable from Unsustainable heat stress exposures. The heat stress exposures covered four levels of clothing (woven cotton and non-woven versions of particle barrier, water barrier and vapor barrier), three levels of relative humidity (20, 50 and 70%) and three levels of metabolic rate (treatment-level averages of 115, 175 and 250 W m^{-2}). The 29 participants contributed to 494 trials. The three observations in each trial were within a range of about 6 °C-WBGT. In summary, the USF progressive heat studies(T. Bernard, Caravello, Schwartz, & Ashley, 2007; Thomas E Bernard et al., 2008) gave us the opportunity to explore if HSMs can be used to predict Unsustainable exposures; to suggest screening values when those exposures are present; and to determine if clothing and metabolic rate play a role as effect modifiers.

Evaluation of the AUC

The ROC curve is a well-recognized method to articulate the ability of a metric to distinguish between two states. AUC summarizes that ability where 1.0 is a perfect ability to discriminate and 0.5 is simply a 50/50 chance. While the validity of the PSI is well-established as a metric for heat strain, this is one of a few times that it has been used to determine a specific heat stress state. The PSI had an AUC of 0.79, which from a traditional academic point system (Tape, 2006) represented a fair ability to discriminate Unsustainable heat stress exposures. Its accuracy did not change after the adjustment with metabolic rate or clothing.

Among the other HSMs, RT_{sk} clearly exhibited the highest AUC at 0.86. This can be considered a good discriminator between Unsustainable and Sustainable (Tape, 2006). Such accuracy did not change after the adjustment with M or clothing. This was similar to the finding for woven clothing alone (0.85) (Garzón-Villalba et al., 2017b). The unexpected utility of skin temperature was likely due to the quasi-steady-state exposure with small monotonic increases in heat stress. Related to skin temperature, was the difference from core temperature. This derived HSM had an AUC of 0.79, which was not statistically different from PSI in this paper and didn't change with the adjustment for M or clothing. This value is consistent with that for woven clothing alone (0.77) (Garzón-Villalba et al., 2017b). The small improvement seen for the four kinds of clothing may represent more utility for the non-woven fabrics.

PSI is a derived metric from core temperature and heart rate. RT_{re} and RHR had AUCs of 0.73 and 0.78, respectively. It was clear that HR had the higher ability to discriminate and was nearly the same as PSI. That would suggest that it had the greater influence on PSI. Because this study focused on a steady exposure at a relatively low end of the heat stress spectrum, the relative contributions of heart rate and core temperature to PSI need to be considered more fully. Another consideration in the application of PSI to heat stress is the likely collinearity between T_{re} and HR.

HSM Screening Values

The second purpose of this undertaking was to articulate the distribution of PSI and the other HSMs and suggest values that might be used as a screening threshold to decide if a heat stress evaluation is necessary. Table 3 clearly demonstrated higher average values of the HSMs for the Unsustainable observations over the Sustainable observations. The exception was ΔT_{re-sk}, which was less. This would be expected for higher heat strain. In a rough sense, this demonstrated the differences that would be expected from the AUCs. A previous USF paper that looked only at woven clothing argued that a screening value at a probability of 0.25 of being Unsustainable represented a sensitivity of 0.95 (Garzón-Villalba et al., 2017c).

Looking at PSI first and considering the distributions in Table 6, a screening value of PSI = 2.6 would be reasonable. This compared well to 2.5 for the woven clothing found earlier (Garzón-Villalba et al., 2017b) and still less than the 5.1 that used well established values of T_{re} and HR as acceptable. Based on the screening values of T_{re} and HR presented in the following paragraphs, the PSI would still be 2.6, which is not surprising because of the dependent data.

The other derived metric, ΔT_{re-sk}, had a screen difference of 1.9 °C. This was the same as for woven clothing alone (Garzón-Villalba et al., 2017b) and is a larger gradient than recommended by Pandolf and Goldman (1977). It should be noted that the decision goals were different. The current suggestion was based on Sustainable exposure versus a decision to bring an exposure to an end.

T_{re} is an accurate measure for body core temperature (Moran & Mendal, 2002), which is the reason why it is used for laboratory investigations. In the present study, the screening value was 37.5, which is the same as for woven clothing alone (Garzón-Villalba et al., 2017b). While this is below the WHO's scientific group recommended value of 38 ˚C, this should be viewed as a population goal and not an indicator for an individual (Garzón-Villalba et al., 2017b).

HR is another physiological metric that is widely used (Brouha, 1960; Maxfield & Brouha, 1963; NIOSH, 2016). It changes with work load and with environmental conditions (Brouha, 1960; Maxfield & Brouha, 1963). This study assessed HR under different combinations of clothing, metabolic rate, and ambient humidity near the upper threshold for Sustainability. The screening value for HR from Table 6 was 109. This was higher than the 105 for woven clothing alone but still lower than the 120s that was found by others (Garzón-Villalba et al., 2017b)

The screening value for T_{sk} was 35.8 °C, which was also the same as for woven clothing alone.

As we found previously for woven clothing alone (Garzón-Villalba et al., 2017b), the individual physiological heat indicators were not practical predicators of sustainable heat stress for potential use as a real-time administrative control. For long steady exposures to heat stress, PSI < 2.6, ΔT_{re-sk} > 1.9 °C, T_{re} < 37.5, HR < 109, and T_{sk} < 35.8 were individually indicative of sustainable heat stress. The only utility is that if any of the observed physiological heat strain indicators is less than their threshold values, there is good reason to believe the exposure is sustainable.

Effect of Clothing and Metabolic Rate

One of the objectives of the present study was to assess if effect modification due to clothing was present on the association between HSMs and Unsustainable. To assess such effect, a single variable which comprised the four types of fabrics, using woven cotton clothing as the comparison group. Clothing was not significant in the conditional logistic model and effect modification was not statistically significant.

The present study found an effect of M on the association between HSMs and Unsustainable. M was not statistically significant as main predictor in the conditional logistic regression. While M was significant as covariate in the model with HSMs, its interaction term was not. Consequently, M can be considered as a confounder for the main association but not as effect modifier. Because of variability in individuals, the role of M is difficult to interpret (Garzón-Villalba et al., 2017b).

Limitations

There were two major limitations in this study, which were the same as for woven clothing alone (Garzón-Villalba et al., 2017b). One was a dataset designed to examine the transition from Sustainable to Unsustainable heat stress levels. For that reason, the conclusions were not generalizable to acute heat stress and high, unsustainable levels of heat stress. The second limitation was the practical consideration that the measurement is based on a relatively steady heat exposure for an hour.

Another possible limitation of this study is that the data obtained in both USF studies were collected in laboratory trials under controlled conditions with acclimatized participants who were not similar to those present in real work settings. As a result, generalization could be affected. Nonetheless, this probable lack of generalization could have been attenuated by the fact that the study volunteers were exposed to a large range of metabolic rates (170 to 500 W) and environmental conditions (large range of humidity from 20% to 70% relative humidity).

Conclusions

In the context of the three research objectives:

1. The present study found that primary (T_{re}, HR, and T_{sk}) and derived (PSI and $\Delta T_{re\text{-}sk}$) HSMs can accurately predict Unsustainable heat stress exposures based on AUCs that ranged from 0.73 to 0.86. Skin temperature had the highest AUC with PSI in the mid-range.
2. The values of the HSMs associated with a predicted probability of 0.25 were considered as screening values. The value of using any one of these individual indicators is that they act as a screening tool to decide if an exposure assessment is needed.
3. Metabolic rate was found to be a confounder for all the HSMs except for RT_{sk}. It was not statistically significant on neither HSMs derived models (PSI and $\Delta T_{re\text{-}sk}$). And its effect modification was not significant in any model.

The results of this study suggested that HSMs might be an intermediate step between recognition and exposure assessment.

REFERENCES

ACGIH. (2017). *Heat stress, TLVs and BEIs: Threshold limit values for Chemical Substances and Physical Agents & Biological Exposure Indices*. Cincinnati: ACGIH.

Andérson, G. S., Ward, R., & Mekjavić, I. B. (1995). Gender differences in physiological reactions to thermal stress. *European journal of applied physiology and occupational physiology, 71*(2), 95-101.

Arbury, S., Jacklitsch, B., Farquah, O., Hodgson, M., Lamson, G., Martin, H., & Profitt, A. (2014). Heat Illness and Death Among Workers—United States, 2012–2013. *MMWR. Morbidity and mortality weekly report, 63*(31), 661-665.

Bernard, T., Caravello, V., Schwartz, S., & Ashley, C. (2007). WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. *Journal of occupational and environmental hygiene, 5*(1), 1-5.

Bernard, T. E. (2012). Thermal Stress. In B. A. Plog & P. J. Quinlan (Eds.), *Fundamentals of Industrial Hygiene* (6th ed. ed., pp. 335-361). Itasca, IL: National Safety Council.

Bernard, T. E., Caravello, V., Schwartz, S. W., & Ashley, C. D. (2008). WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. *J. Occup. Environ. Hyg., 5*(1), 1-5. doi:784715198 [pii]
10.1080/15459620701732355 [doi]

Bernard, T. E., Caravello, V., Schwartz, S. W., & Ashley, C. D. (2008). WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. *Journal of occupational and environmental hygiene, 5*(1), 1-5.

Bernard, T. E., & Kenney, W. L. (1994). Rationale for a personal monitor for heat strain. *American Industrial Hygiene Association, 55*(6), 505-514.

Bernard, T. E., Luecke, C. L., Schwartz, S. K., Kirkland, K. S., & Ashley, C. D. (2005). WBGT clothing adjustments for four clothing ensembles under three relative humidity levels. *Journal of occupational and environmental hygiene, 2*(5), 251-256.

Bernard, T. E., Luecke, C. L., Schwartz, S. W., Kirkland, K. S., & Ashley, C. D. (2005). WBGT clothing adjustments for four clothing ensembles under three relative humidity levels. *J Occup Environ Hyg, 2*(5), 251-256. doi:WJ2806W61Q0487V4 [pii]
10.1080/15459620590934224 [doi]

Brouha, L. (1960). Physiology in industry. Evaluation of industrial stresses by the physiological reactions of the worker. *Physiology in industry. Evaluation of industrial stresses by the physiological reactions of the worker.*(Edn 2).

Buller, M. J., Latzka, W. A., Yokota, M., Tharion, W. J., & Moran, D. S. (2008). A real-time heat strain risk classifier using heart rate and skin temperature. *Physiological measurement, 29*(12), N79.
Caravello, V., McCullough, E. A., Ashley, C. D., & Bernard, T. E. (2008). Apparent evaporative resistance at critical conditions for five clothing ensembles. *Eur J Appl Physiol, 104*(2), 361-367. doi:10.1007/s00421-007-0655-9 [doi]
Cranston, W., Gerbrandy, J., & Snell, E. (1954). Oral, rectal and oesophageal temperatures and some factors affecting them in man. *The Journal of physiology, 126*(2), 347-358.
Cuddy, J. S., Buller, M., Hailes, W. S., & Ruby, B. C. (2013). Skin temperature and heart rate can be used to estimate physiological strain during exercise in the heat in a cohort of fit and unfit males. *Military medicine, 178*(7), e841-e847.
Dinman, B., Stephenson, R. R., Horvath, S., & Colwell, M. (1974). Work in Hot Environments: I. Field Studies of Work Load, Thermal Stress and Physiologic Response. *Journal of Occupational and Environmental Medicine, 16*(12), 785-791.
Drinkwater, B., & Horvath, S. (1978). Heat tolerance and aging. *Medicine and science in sports, 11*(1), 49-55.
Ekblom, B., Greenleaf, C. J., Greenleaf, J. E., & Hermansen, L. (1970). Temperature regulation during exercise dehydration in man. *Acta Physiologica, 79*(4), 475-483.
Fuller, F. H., & Smith, P. E. (1981). Evaluation of heat stress in a hot workshop by physiological measurements. *The American Industrial Hygiene Association Journal, 42*(1), 32-37.
Gallop, R. J. (2001). Determination and Interpretation of the OOP for ROC's with PROC LOGISTIC. *Proceeding of NESUG*, 777-782.
Garzón-Villalba, X. P., Wu, Y., Ashley, C. D., & Bernard, T. E. (2017a). Ability to Discriminate Between Sustainable and Unsustainable Heat Stress Exposures—Part 1: WBGT Exposure Limits. *Annals of Work Exposures and Health*.
Garzón-Villalba, X. P., Wu, Y., Ashley, C. D., & Bernard, T. E. (2017b). Ability to Discriminate Between Sustainable and Unsustainable Heat Stress Exposures—Part 2 Physiological Indicators. *Annals of Work Exposures and Health*.
Garzón-Villalba, X. P., Wu, Y., Ashley, C. D., & Bernard, T. E. (2017c). Heat Stress Risk Profiles for Three Non-Woven Coveralls. *Journal of Occupational & Environmental Hygiene (in revision)*.
Garzón, X. P., Wu, Y., Ashley, C. D., & Bernard, T. E. (2017). Ability to discriminate between sustainable and unsustainable heat stress exposures. Part 1: WBGT exposure limits. *Annals of Work Exposures and Health, (in press)*.
Gunga, H.-C., Sandsund, M., Reinertsen, R. E., Sattler, F., & Koch, J. (2008). A non-invasive device to continuously determine heat strain in humans. *Journal of Thermal Biology, 33*(5), 297-307.
Harrison, M. H., Edwards, R., & Fennessy, P. (1978). Intravascular volume and tonicity as factors in the regulation of body temperature. *Journal of applied physiology, 44*(1), 69-75.
Havenith, G. (1999). Heat balance when wearing protective clothing. *Annals of occupational hygiene, 43*(5), 289-296.

Horvath, S. (1976). Heat stress studies in aluminum reduction plants. *Standards for Occupational Exposures to Hot Environments (HEW Pub. No.[NIOSH] 76-100), SM Horvath (ed.) Cincinnati, OH: National Institute for Occupational Safety and Health*.

Kenney, W. L. (1988). Control of heat-induced cutaneous vasodilatation in relation to age. *European journal of applied physiology and occupational physiology, 57*(1), 120-125.

Kim, S., & Lee, J.-Y. (2015). Skin sites to predict deep-body temperature while wearing firefighters' personal protective equipment during periodical changes in air temperature. *Ergonomics*, 1-8.

Kuhlemeier, K., & Wood, T. (1979). Laboratory evaluation of permissible exposure limits for men in hot environments. *The American Industrial Hygiene Association Journal, 40*(12), 1097-1103.

Lind, A. (1963a). A physiological criterion for setting thermal environmental limits for everyday work. *Journal of applied physiology, 18*(1), 51-56.

Lind, A. (1963b). Physiological effects of continuous or intermittent work in the heat. *Journal of applied physiology, 18*(1), 57-60.

Lind, A., Humphreys, P., Collins, K., Foster, K., & Sweetland, K. (1970). Influence of age and daily duration of exposure on responses of men to work in heat. *Journal of applied physiology, 28*(1), 50-56.

Logan, P. W., & Bernard, T. E. (1999). Heat stress and strain in an aluminum smelter. *American Industrial Hygiene Association Journal, 60*(5), 659-665.

Malchaire, J., Piette, A., Kampmann, B., Mehnert, P., Gebhardt, H., Havenith, G., . . . Alfano, G. (2001). Development and validation of the predicted heat strain model. *The Annals of occupational hygiene, 45*(2), 123-135.

Maxfield, M. E., & Brouha, L. (1963). Validity of heart rate as an indicator of cardiac strain. *Journal of applied physiology, 18*(6), 1099-1104.

McLellan, T., Pope, J., Cain, J., & Cheung, S. (1996). Effects of metabolic rate and ambient vapour pressure on heat strain in protective clothing. *European journal of applied physiology and occupational physiology, 74*(6), 518-527.

Minard, D., Goldsmith, R., Farrier, P. H., & Lambiotte, B. J. (1971). Physiological evaluation of industrial heat stress. *The American Industrial Hygiene Association Journal, 32*(1), 17-28.

Moran, D. S., Kenney, W. L., Pierzga, J. M., & Pandolf, K. B. (2002). Aging and assessment of physiological strain during exercise-heat stress. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 282*(4), R1063-R1069.

Moran, D. S., & Mendal, L. (2002). Core temperature measurement. *Sports Medicine, 32*(14), 879-885.

Moran, D. S., Shapiro, Y., Laor, A., Izraeli, S., & Pandolf, K. B. (1999). Can gender differences during exercise-heat stress be assessed by the physiological strain index? *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 276*(6), R1798-R1804.

Moran, D. S., Shitzer, A., & Pandolf, K. B. (1998). A physiological strain index to evaluate heat stress. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 275*(1), R129-R134.

Niedermann, R., Wyss, E., Annaheim, S., Psikuta, A., Davey, S., & Rossi, R. M. (2014). Prediction of human core body temperature using non-invasive measurement methods. *International journal of biometeorology, 58*(1), 7-15.
NIOSH. (1972). Criteria for a recommended standard......Occupational Exposure to Hot Environments. Washington D.C.: U.S. Department of Health and Human Services.
NIOSH. (1986). Occupational Exposure to Hot Environments. Washington D.C.: U.S. Department of Health and Human Services.
NIOSH. (2016). Criteria for a Recommended Standard: Occupational Exposure to Heath and Hot Environments. By Jacklitsch B, Williams WJ, Musolin K, Coca A, Kim J-H, Turner N. Cincinnati, OH, 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.
Nunneley, S. A. (1977). Physiological responses of women to thermal stress: a review. *Medicine and science in sports, 10*(4), 250-255.
OSHA. (2016). Heat Stress Retrieved 11/02/2016, from United States Department of Labor https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html
Ostchega, Y., Porter, K. S., Hughes, J., Dillon, C. F., & Nwankwo, T. (2011). Resting pulse rate reference data for children, adolescents, and adults: United States, 1999-2008. *Natl Health Stat Report*(41), 1-16.
Pandolf, K. B. (1997). Aging and human heat tolerance. *Experimental aging research, 23*(1), 69-105.
Pandolf, K. B., & Goldman, R. F. (1977). *The convergence of skin and rectal temperatures as a criterion for heat tolerance*. Retrieved from
Petitti, D. B., Harlan, S. L., Chowell-Puente, G., & Ruddell, D. (2013). Occupation and environmental heat-associated deaths in Maricopa County, Arizona: A case-control study. *PloS one, 8*(5), e62596.
Richmond, V. L., Davey, S., Griggs, K., & Havenith, G. (2015). Prediction of core body temperature from multiple variables. *Annals of occupational hygiene, 59*(9), 1168-1178.
Robinson, S., Belding, H., Consolazio, F., Horvath, S., & Turrell, E. (1965). Acclimatization of older men to work in heat. *Journal of applied physiology, 20*(4), 583-586.
Rothchild, I., & Barnes, A. C. (1952). The effects of dosage, and of estrogen, androgen or salicylate administration on the degree of body temperature elevation induced by progesterone. *Endocrinology, 50*(4), 485-496.
SAS Institute Inc. Cary NC. (2013). SAS 9.4. Cary, NC, USA.
Sato, K., Kang, W., Saga, K., & Sato, K. (1989). Biology of sweat glands and their disorders. I. Normal sweat gland function. *Journal of the American Academy of Dermatology, 20*(4), 537-563.
Sawka, M. N. (1992). Physiological consequences of hypohydration: exercise performance and thermoregulation. *Med Sci Sports Exerc, 24*(6), 657-670.
Sawka, M. N., & Pandolf, K. B. (1990). Effects of body water loss on physiological function and exercise performance. *Perspectives in exercise science and sports medicine, 3*, 1-38.
Sawka, M. N., Young, A. J., Latzka, W. A., Neufer, P. D., Quigley, M. D., & Pandolf, K.

B. (1992). Human tolerance to heat strain during exercise: influence of hydration. *Journal of applied physiology, 73*(1), 368-375.

Sund-Levander, M., Forsberg, C., & Wahren, L. K. (2002). Normal oral, rectal, tympanic and axillary body temperature in adult men and women: a systematic literature review. *Scandinavian journal of caring sciences, 16*(2), 122-128.

Tanner, J. (1951). The relationships between the frequency of the heart, oral temperature and rectal temperature in man at rest. *The Journal of physiology, 115*(4), 391-409.

Tape, T. G. (2006). Interpreting diagnostic tests. *University of Nebraska Medical Center, http://gim. unmc. edu/dxtests.*

Van Marken Lichtenbelt, W. D., Daanen, H. A., Wouters, L., Fronczek, R., Raymann, R. J., Severens, N. M., & Van Someren, E. J. (2006). Evaluation of wireless determination of skin temperature using iButtons. *Physiology & Behavior, 88*(4), 489-497.

Wagner, J., Robinson, S., Tzankoff, S., & Marino, R. (1972). Heat tolerance and acclimatization to work in the heat in relation to age. *Journal of applied physiology, 33*(5), 616-622.

WHO. (1969). *Health factors involved in working under conditions of heat stress*: WHO Publications.

Williams-Steiger. (1970). *Occupational Safety and Health Act of 1970*.

Wyndham, C., Morrison, J., & Williams, C. (1965). Heat reactions of male and female Caucasians. *Journal of applied physiology, 20*(3), 357-364.