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Does Time-Weighted Averaging for WBGT and Metabolic Rate Work for Work-Recovery Cycles?

by

John W. Flach

A thesis submitted in partial fulfillment
of the requirements for the degree of
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Dedication

This thesis is dedicated to my beautiful wife, Christina Flach, and amazing children, Izabella, Sophia, and Luke. Thank you for your unwavering love, support, and encouragement; without you this would not have been possible.

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List of Abbreviations & Acronyms

ACGIH®	American Conference of Governmental Industrial Hygienists
AL	Action Limit
BLS	Bureau of Labor Statistics
CAV	Clothing Adjustment Value
CDC	Centers for Disease Control and Prevention
CET	Corrected Effective Temperature
CI	Confidence Interval
HRI	Heat-Related Illness
HSMP	Heat Stress Management Program
ISO	International Organization of Standardization
NIOSH	National Institute for Occupational Safety and Health
OEL	Occupational Exposure Limit
OSHA	Occupational Safety and Health Administration
PPE	Personal Protective Equipment
RAL	Recommended Alert Limit
REL	Recommended Exposure Limit
TLV®	Threshold Limit Value
T_{re}	Rectal Temperature
TWA	Time-Weighted Average
TWA-M	Time-Weighted Average-Metabolic Rate

TWA-WBGT	Time-Weighted Average-Wet Bulb Globe Temperature
ULPZ	Upper Limit of the Prescriptive Zone
USF	University of South Florida
W	Watts
WBGT	Wet Bulb Globe Temperature

Abstract

Heat stress affects thousands of works annually by causing heat-related illnesses. Wet bulb globe temperature (WBGT) is a widely accepted metric to assess the environmental contributions to heat stress. WBGT-based occupational exposure limits (OELs) include the ACGIH TLVs and the NIOSH RELs. The OEL threshold is adjusted downward with increasing metabolic rate. Further, there is an OEL for acclimatized and non-acclimatized workers. An often-recommended intervention found within a heat stress management program is work-recovery cycles to manage exposure. To prescribe work-recovery cycles, the common practice is to use time-weighted averaging (TWA) for the WBGT and the metabolic rate. The purpose of this study was to demonstrate that TWAs for WBGT and metabolic rate are acceptable metrics for assessing exposure and prescribing work-recovery cycles.

A search of the literature found sixteen papers in which there was a protocol that could represent two different exposures. The TWA WBGT and metabolic rate were estimated from the protocol descriptions. The acclimatization state of the participants was noted. Depending on acclimatization state, the TWAs were compared to the OELs and classified as above or below the OEL. The reported physiological outcomes were classified as sustainable or unsustainable using the reported core temperatures. Sustainable was an average at or below 38°C and no individual greater than 38.5°C. Otherwise, the protocol was classified as unsustainable.

Two sets of 2x2 tables were populated from the data, one for acclimatized and one for non-acclimatized, to check for sustainability. For acclimatized participants, there were 19 protocols with a sensitivity of 1.0 and specificity of 0.58. For the non-acclimatized, the lower OEL was used to classify the 57 protocols with the resulting sensitivity of 0.71 and specificity of 0.35. Additionally, 2x2 tables classified by age group (Young, Middle, and Older) were populated with that same data to for check sustainability among acclimatized and non-acclimatized workers.

For acclimatized workers, TWA was shown to be protective with no false negatives observed. For non-acclimatized, the TWA was shown to be protective of most workers, with false negatives, which is considered not as protective. This study demonstrates the effectiveness of TWAs for work-recovery cycles as being protective of acclimatized participants, however they are less protective of non-acclimatized participants, to include Older participants.

Chapter One:

Introduction

Many industries involve performing work in hot environments, whether from the outdoor environmental conditions (i.e., agriculture or construction) or the addition of radiant heat from processes or equipment (i.e., foundries or boilers rooms). These hot environments present a heat stress (the external heat load placed on the body) among individuals while working, which causes a heat strain (individual's physiological response to heat stress) to workers.(1) Excessive heat exposure presents itself in many forms to individuals like heat stroke, heat exhaustion, heat cramps, heat rash and even death; they are the result of the cumulative effect of the heat stress in the environment, work output and risk factors for an individual.(1, 2) The U.S. Bureau of Labor and Statistics (BLS) reports in 2019 there were 43 fatalities reported to the Occupational Safety and Health Administration (OSHA) from events or exposures to environmental heat in the private industry sector.(3) Additionally, the BLS reports 2,410 reports of nonfatal occupational injuries and illnesses involving days away from work for the same sector, in the same year.(4) These figures only represent the reportable incidents; it is likely that many more unreported heat-related illnesses (HRI) occurred. In addition to the job risk factors, personal risk factors include worker demographics, predisposed medical conditions, age, gender, fitness level, and job tenure.(5) For these reasons, assessing worker exposure, risk factors that affect exposure, and mechanisms to control exposure is an integral part of any heat stress management program (HSMP).(6)

It is well established that there are three main factors that affect heat stress. These job risk factors are the environmental conditions, work demands (conveyed as metabolic rate), and clothing.(2) When assessing heat stress these factors must be considered. Over the years, much work has been done to develop guidelines, known as Occupational Exposure Limits (OEL), to manage heat stress on workers. As a result, numerous heat stress indices exist. Most notably, the ACGIH® Threshold Limit Values (TLV®) and the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limits (REL) have established mirrored guidelines that are the most widely accepted metrics to protect workers from heat stress.(7-9) OELs incorporate the environment, work demands, and a clothing factor with the goal of maintaining thermal equilibrium for sustained exposure.(7, 8) The most widely accepted metric for assessing the environmental contributions to heat stress is the wet bulb globe temperature (WBGT).(7, 8) Therefore, the OELs incorporate the WBGT, along with metabolic rate and clothing, as foundational elements when developing the guidelines. In relation to the OEL, the WBGT threshold will adjust downward with an increasing metabolic rate. It is worth noting, there are separate OELs for acclimatized and non-acclimatized workers. Both ACGIH® and NIOSH recommend, using a time-weighted average (TWA) of the WBGT and metabolic rate to assess exposures. TWAs are also used to prescribe work-recovery cycles as a key component of an effective HSMP.(6-8, 10)

In 2018, a report published by the Center for Disease Control and Prevention (CDC) documented a real-world evaluation of OELs on heat stress for outdoor workers.(10) This report evaluated 25 outdoor occupational HRIs (14 fatal and 11 nonfatal), between 2011 – 2016, that were reported to the OSHA to investigate whether the OELs were adequately protective in these incidents.(10) While the OELs were established through human experiments within a laboratory setting, this report was one of the first that documented the effectiveness of the OELs in real-life situations.(10) As such, a key finding from the report suggests the OELs as being adequately protective of the workers.(10) However, the report singles out a key issue that was identified as a major contributor to these incidents, the absence of a comprehensive HSMP to prevent HRIs when heat stress conditions are apparent or assumed to be apparent through environmental conditions or worker physiological response.(10) Other key findings point to the importance of an acclimatization process and an appropriate work-recovery regime.(10) By contrast, recent experimental data suggests that current OELs may not be protective enough of workers, particularly older workers.(9, 11, 12) Therefore, a comprehensive search of literature was used to investigate the effectiveness of work-recovery cycles in preventing overexposure to heat stress. The search garnered sixteen papers that contained protocols that could represent two separate exposures, WBGT and metabolic rate. The purpose of this study was to demonstrate that TWAs for WBGT and metabolic rate are acceptable metrics for assessing exposure and prescribing work-recovery cycles.

Chapter Two:

Literature Review

Heat stress exposure on individuals is the result from the combination of the environmental conditions, metabolic heat, and clothing; this stress presents itself through heat strain. The body's natural reaction is to thermoregulate by balancing heat gain with heat loss through several physiological responses; these include increases in heart rate, body core temperature, skin temperature, and sweat production.(8) A key indicator of unsustainable heat gain is increasing body core temperature. Therefore, body core temperature was selected as the metric in evaluating heat stress on the individual participants for this investigation, specifically rectal temperature (T_{re}).

In 1969, the World Health Organization (WHO), in the *Health Factors Involved in Working Under Conditions of Heat Stress: Report of a WHO Scientific Group*, recommended evaluating body core temperature and advised that body core temperatures should not exceed 38°C for prolonged daily heat stress exposure.(13) This has been the key core temperature metric since its establishment. While some consider it conservative, NIOSH identified 38°C as being protective of 95% of workers and established it as the accepted average limit for prolonged heat stress exposure, thus an average of 38°C for a given protocol was selected as the threshold temperature for evaluating heat stress for this study.(8) Additionally, studies have shown that individuals have commonly exceeded 39°C without noticeable physiological effects.(8, 14) Therefore, our study selected 38.5°C as the individual threshold where an exceedance would be considered unsustainable.

The total heat load on the body is the product of the environmental conditions and the metabolic heat.(7) Therefore, evaluating the environmental condition of WBGT and metabolic rate (M) are the preemptive standards used in this study to evaluate total heat load. They are firmly established through the OEL guidelines as the key metrics for managing heat stress and should play a vital role in any HSMP.

WET BULB GLOBE TEMPERATURE (WBGT)

The WBGT has been a staple for evaluating environmental conditions since 1957, when the military developed a method using the WBGT for environmental monitoring to control HRIs at basic training camps.(15) Additionally, in 1969, the WHO's scientific group also discussed utilizing the corrected effective temperature (CET), comparable metric to WBGT at the time, in their landmark report on heat stress for workers.(13) By the early 1970s, both the ACGIH®, in *Heat Stress and Strain Threshold Limit Values*, and NIOSH, in *Criteria for a Recommended Standard*, developed their respective heat stress guidelines that use WBGT and metabolic rate for developing the OELs to prevent excessive heat stress exposure.(7, 8) International standards like the International Organization for Standardization's (ISO) reference values have developed OELs that follow the ACGIH® and NIOSH guidelines for WBGT and metabolic rate.(16) Today, WBGT is the most commonly used metric for evaluating the environmental contributions to heat stress.

The WBGT is a heat stress index that has two main goals: 1) to be an indicator of whether a specific total heat stress will result in a higher risk of HRI and 2) to provide a basis for recommending additional control measures.(7, 17) There are many advantages of using the WBGT as an index for evaluating environmental conditions of heat stress because it considers four distinct thermal components that affect heat stress: air temperature, humidity, air velocity, and radiant heat.(2, 7, 8, 17) Additionally, instruments that measure WBGT require minimal skill and enable a quick and accurate assessment of the current conditions that can present a thermal exposure threat.(17) Being an index, the WBGT enables the addition of a clothing adjustment value (CAV), because clothing can alter the rate of heat exchange between a worker's skin and the ambient environmental work conditions.(7) This effect on heat stress can be significant and must be considered. Both ACGIH® and ISO utilize a CAV to equate the efficient WBGT by adding the appropriate CAV to the WBGT when developing a OEL.(7, 8) In our study, we subtracted 1°C from the OEL for semi-nude (only shorts for males and only shorts and halter-top for females) participants and the remaining studies used work clothes which is the reference clothing ensemble.

WBGT has some limitations and should be used cautiously when impermeable clothing is worn because evaporative cooling is limited.(8) Furthermore, the OELs have a small margin of safety and are based on the ability of most healthy workers to sustain exposure to heat stress and do not consider personal risk factors that can influence the body's physiological responses.(5) Nevertheless, WBGT is the most widely used and accepted index for assessing the environmental contributions to heat stress.

METABOLIC RATE

Using WBGT and a CAV are not the only factors to consider when assessing exposure to heat stress; an assessment of work demands must take place using metabolic rate. Metabolic rate (measured in Watts (W)) is the heat generated by work or activity and represents one of the key factors that contribute to thermoregulation.(17) It is more difficult to measure than the environmental conditions and depends directly on the rate and type of external work demanded by the body.(1, 2) Additionally, physiological response variations make it challenging to directly correlate personal risk factors to metabolic heat.(5)

There are numerous ways to assess metabolic heat such as: 1) direct measurement through measuring variables like oxygen consumption, 2) prediction from task analysis, 3) table look-up, 4) prediction from other physiological variables and 5) perceived exertion.(7) The table look-up method is often used for job evaluation. Table look-up is a simple method that provides quick and easy assessment of metabolic rate based on generalized categories.(2) Both ACGIH® and NIOSH provide tables in their guidelines that categorize metabolic rate; they are categorized as resting, light, moderate, heavy, and very heavy, and provide a reference metabolic rate for each.(7, 8) Based on these metabolic rates, a given OEL for WBGT can be established for the environmental conditions and vice versa, based on the OEL curve. If metabolic rate was not explicitly provided in the investigated protocols, analysis was conducted on the data provided in the protocol and a metabolic rate was determined through table look-up or equations developed for oxygen consumption.

HEAT STRESS MANAGEMENT PROGRAM

Between 2016-2018, the U. S. Army reported 13,087 HRIs that incurred a direct cost of $7.3 million.(18) This figure does not include the indirect costs associated with HRIs on production, performance, and morale. With the uncertainties of climate change, it is imperative that industries have a focused approach to heat stress management to prevent HRIs and to reduce the direct and indirect costs they produce. This begins with a comprehensive HSMP. Both ACGIH® and NIOSH discuss the important factors that should be incorporated into an HSMP. These include but are not limited to a comprehensive training program, documented heat stress industrial hygiene practices, a medical surveillance program, engineering controls, administrative controls, and personal protective equipment (PPE).(6-8) Two important controls found in an HSMP that were investigated in this study are work-recovery cycles and acclimatization state.

Occupational settings that involve performing work in environments that are above the OELs require administrative controls to limit exposure and manage to risk.(7) Because occupational exposure to heat stress may be heterogeneous or the work period naturally involves rest, an instinctive administrative control would be to implement work-recovery cycles for the workforce to limit exposure and manage risk. Additionally, work demands may fluctuate throughout a workday creating varying metabolic rates to evaluate.(1) For these reasons, the best approach to assessing the exposure is to use a TWA for WBGT (TWA-WBGT) and metabolic rate (TWA-M). Both ACGIH® and NIOSH recommend the TWA as the guiding principle to manage heat stress exposure within the bounds of the OELs and base the estimates for these OELs on a TWA.(7, 8) Furthermore, they both provide a screening criterion using TWA for managing allocations of work among a work-recovery cycle for the WBGT and metabolic rate. The current study sought to validate the use of a TWA by evaluating TWA-WBGT and TWA-M in the various protocols to determine if they are protective of workers when using work-recovery cycles.

ACCLIMATIZATION

Even though the OELs are based on the ability of most healthy, acclimatized workers to sustain heat stress exposure, they also incorporate OELs for non-acclimatized workers.(7) This is because it has been demonstrated that non-acclimatized workers are more susceptible to HRIs then acclimatized.(1, 2, 7, 8, 10) Broadly speaking, acclimatization is considered a process of becoming accustomed to new conditions.(2) For heat stress exposure, it refers to the physiological and psychological adjustments an individual undertakes when becoming more accustomed to prolonged working in the present environment, hot or cold.(1) These adjustments happen gradually over time and can aid in reducing the heat strain that may have been experienced initially, while also enhancing heat tolerance enabling a worker to worker more effectively.(1)

Acclimatization can be considered a general control for heat stress, however, implementing a standardized acclimatization program into the general controls section of a HSMP is recommended.(6-8) An acclimatization program should be designed to incorporate newly hired employees and those employees returning from extended breaks from work. Additionally, this program should have provisions for sudden changes in weather (i.e. heat waves) to ensure safety precautions are in place to monitor the environmental conditions during these times.(1) There are many resources available when developing an acclimatization program. Acclimatization was investigated in our study to determine if the OELs for work-recovery cycles are protective of both acclimatized and non-acclimatized participants.

SUSTAINABILITY

In any occupational heat stress study, the determination of what constitutes a case should be identified for analysis. In our study, we determined a case to be an unsustainable exposure to the environments presented in the protocols. While a non-case is a sustainable exposure to the same protocol environments. A sustainable exposure is an exposure at heat stress levels where thermal equilibrium can be achieved, and unsustainable exposures are those where there is a steady increase in body core temperature above desired thresholds.(14) Literature has well established an average body core temperature of less than 38°C, or any individual body core temperature less than 38.5°C, to heat stress environments as the recommended limits to minimize effects of heat stress.(2, 7, 8, 13, 14) Similar logic for both, defining a case and body core temperature, were applied in the current study. A sustainable exposure was determined to be an average body core temperature of less the 38°C and any individual temperatures less the 38.5°C. Otherwise the exposure was unsustainable and considered a case.

PROTOCOL LITERATURE

Over the past several decades much research has been completed to evaluate heat stress exposure and its effects on heat strain and physiological responses. More importantly, research that evaluated proposing limits or thresholds that can reduce excessive exposure and HRIs. In 1963, Lind's quintessential report that developed a prescriptive zone and an upper limit of the prescriptive zone (ULPZ) proved to be a starting point for developing OELs aimed to reduce heat stress risks.(19) While the study only had two subjects that completed all the protocols, the evidence clearly demonstrated that thresholds could work by illustrating that T_{re} would level off through thermoregulatory responses when working under the ULPZ or within the prescriptive zone.(19) This finding, coupled with the WHO's report on body core temperatures, are the stepping-stones for the development of work-recovery cycles and the use of a TWA to maintain heat stress exposure within the bounds of developed OELs. Over the years, varying theories and conclusions have been drawn on the effectiveness of current OELs and work-recovery cycles. Therefore, an investigation of past studies was warranted to evaluate the effectiveness of TWA-WBGT and TWA-M for work-recovery cycles in various environments based on the protocols from the studies identified. Table 1 is a representation of the literature investigated in this study.

Although Lind's previous report did not encompass work-recovery cycles, a follow-on report did. This research used three environmental conditions, based on CET, which closely resembles WBGT, and work demands over an eight-hour period to determine if the prescriptive zone and ULPZ had a similar effect on thermoregulation.(20) Subjects were monitored for three physiological responses, T_{re}, pulse rate, and sweat loss during three work protocols of sitting, intermittent work, and continuous work.(20) All three responses indicated that the perspective zone and ULPZ were protective of the subjects, while a CET above the ULPZ resulted in unsustainable heat gain.(20) This report clearly showed that there is a threshold for environmental conditions utilizing the CET and set the stage for future studies on thresholds and intermittent work.

In the late 1970s and early 1980s, a group out of the Noll Laboratory at Pennsylvania State University presented a series of studies that examined scheduling work-recovery cycles for different hot ambient conditions (hot-dry and warm-humid), with one study incorporating a radiant heat source, to test the effects on physiological responses.(21-23) While two of the studies had subjects that were acclimatized, the study with the radiant heat had non-acclimatized participants. The conclusions from the studies without a radiant heat source determined the work-recovery cycles to be adequate by keeping the average T_{re} below 38°C, however it was noted that the recovery periods for the warm-humid environments need to take place in a temperate environment to ensure T_{re} could be thermoregulated.(21-23) The protocol with the addition of radiant heat displayed similar results, however it was predicted that the average T_{re} (37.8°C) would continue to creep up and surpass 38°C for a full work shift if adequate measures are not incorporated to prevent exceedance.(22)

A more recent group of studies produced by the Human and Environmental Physiology Research Unit at the University of Ottawa published numerous papers that investigated a wide range of heat stress related concerns.(9, 11, 12, 24-30) Many of them examined heat balance for intermittent work cycles in different environmental conditions, while others also examined hydration levels, effects of age, effects of different air velocities, and effects of clothing combinations to determine if these factors effected physiological responses during intermittent work.(9, 11, 12, 24-30) While too extensive to discuss each paper in detail here, and some of the studies aimed to achieve different outcomes then sought in our study, each paper presented the requisite data needed for our study. Depending on experimental results, the conclusions also varied and raised direct questions on the effectiveness of the current OELs. Multiple papers questioned the adequacy of the OELs in protecting workers, while others concluded they were protective.(9, 11, 12) Additionally, some concluded that the projected average T_{re} would continue to rise over a full shift and exceed the 38°C threshold if measures were not taken to improve thermoregulation.(9, 11, 12)

Another group of papers examined the heat strain to determine if the OELs are protective of workers of various age groups during assessment of different work-recovery protocols and different environmental conditions. Again, the conclusions were varied and point to the OELs potentially being both protective and not protective of older workers.(25, 27-30) Because of these concerns, our study sought to investigate the effectiveness of TWA-WBGT and TWA-M to assess work-recovery cycles with regards to the OELs, but also to investigate these factors based on age group to determine the effectiveness of work-recovery cycles by age.

As previously mentioned, the CDC's case study investigated real-world HRIs and concluded that the current OELs had 100% sensitivity in identifying fatal levels of heat stress, which indicates they are adequately protective of most workers, however, measures should be implemented to protect these workers when conditions exceed the OELs.(10) Both ACGIH® and NIOSH recommend a comprehensive HSMP that incorporates work-recovery cycles and an acclimatization program.(7, 8, 10) Therefore, it was appropriate for this study to reexamine past research and investigate whether TWA-WBGT and TWA-M utilizing work-recovery cycles was adequate in protecting participants. I hypothesize that utilizing TWA-WBGT and TWA-M for constructing work-recovery cycles will be effective in protecting most workers when evaluating environmental contributions and work demands of heat stress within the bounds of the OELs.

Table 1: List of Investigated Literature

Principle Author	Article Title	Year Published
Gagnon, D.(24)	Exercise-rest cycles do not alter local and whole-body heat loss responses	2011
Graveling, R.A.(31)	Influence of intermittency and static components of work on heat stress	1995
Kaltsatou, A.(25)	Heart rate variability in older workers during work under the Threshold Limit Values for heat exposure	2020
Kamon, E.(21)	Scheduling cycles of work for hot ambient conditions	1979
Kamon, E.(22)	Scheduling work and rest for hot ambient conditions with radiant heat source	1983
Kenny, G.P.(26)	Heat balance and cumulative heat storage during intermittent bouts of exercise	2009
Krajewski, J.T.(23)	Scheduling rest for consecutive light and heavy work loads under hot ambient conditions	1979
Lamarche, D.T.(27)	The recommended Threshold Limit Values for heat exposure fail to maintain body core temperature within safe limits in older working adults	2017
Larose, J.(28)	Whole body heat loss is reduced in older males during short bouts of intermittent exercise	2013
Lind, A.R.(20)	Physiological effects of continuous or intermittent work in the heat	1963
Mairiaux, P.(32)	Prediction of strain for intermittent heat exposures	1986
Meade, R.D.(11)	Do the Threshold Limit Values for work in hot conditions adequately protect workers?	2016
Seo, Y.(9)	Heat stress assessment during intermittent work under different environmental conditions and clothing combinations of effective wet bulb globe temperature (WBGT)	2019
Stapleton, J.M.(12)	Body heat storage during intermittent work in hot-dry and warm-humid environments	2012
Wright Beatty, H.E.(29)	Increased Air Velocity Reduces Thermal and Cardiovascular Strain in Young and Older Males during Humid Exertional Heat Stress	2015
Wright, H.E.(30)	Moderate-intensity intermittent work in the heat results in similar low-level dehydration in young and older males	2014

(#) Indicates specific paper found in the References List.

Chapter Three:

Methods

The data for this study was identified through a comprehensive search of past academic literature that had incorporated the effects of heat stress on individuals using work-recovery cycles. Specifically, the search was looking for information that could represent two different exposures, the TWA-WBGT (°C) and the TWA-M (W). Additionally, this search looked for data that represented the physiological response of body core temperature from the exposure. Lastly, a detailed review of the work-recovery cycles implemented in the protocol design was performed and extracted. This search garnered sixteen papers whose data reported enough information to develop the key indicators for the current study. A database was developed from the data and protocols generated for statistical analysis (see Appendix A).

For each paper, the number of participants, age, acclimatization state, clothing worn, and total time of experimental protocols were noted. For acclimatization state, if the paper did not explicitly state that the participants were acclimatized, they were labeled as non-acclimatized. Work-recovery cycles were documented by extracting work time and recovery time for analysis and intervals presented in the study protocols so that TWA values for WBGT and metabolic rate could be computed. If WBGT was not given in the paper, the following equation (1) was utilized from data found for an exposure without direct sunlight(7):

$$(1)\ \mathrm{WBGT} = 0.7\ T_{nwb} + 0.3\ T_g$$

Where: T_{nwb} = natural wet-bulb temperature and T_g = globe temperature

If a numeric metabolic rate was not was not given in the paper, metabolic rates were estimated based on evaluation of the data provided. Additionally, if recovery metabolic rates were not given, a value of 100W was assumed for the recovery metabolic rate in our database.

The physiological response of body core temperature was extracted from the literature to determine if the mean body core temperature was greater than 38°C, or if any individual temperatures were greater than 38.5°C. This information was used to classify the outcome as unsustainable or sustainable. The total number of participants for all protocols used in this study was 558 participants, however only the mean numbers obtained from each protocol were used for analysis in this study, n = 76.

Several metrics were utilized and incorporated into our database based on the data extracted from the literature. These values are represented in Appendix A: Final Database for Study Analysis and the equations used are explained here.

The TWA-WBGT (°C) was derived from the data to analyze if a heat stress exposure was present was greater than the OEL. TWA-WBGT was determined by the following equation (2)(7):

$$(2)\ \text{TWA-WBGT} = (\text{WBGT}_W * T_W) + (\text{WBGT}_R * T_R) / T_W + T_R$$

Where: WBGT_W = Work WBGT, T_W = Work Time, WBGT_R = Recovery WBGT, and T_R = Recovery Time

The TWA-M (W) was derived from the data to determine the given metabolic workload effected on participants in the protocol. TWA-M was determined by the following equation (3)(7):

$$(3)\ \text{TWA-M} = (M_W * T_W) + (M_R * T_R) / T_W + T_R$$

Where: M_W = Work Metabolic Rate, T_W = Work Time, M_R = Recovery Metabolic Rate, and T_R = Recovery Time

The OEL for this study were set to the TLV® and Action Limit (AL) from the ACGIH®'s TLV® Heat Stress and Strain guide, which are equivalent to NIOSH's REL and Recommended Alert Limit (RAL).(7, 8) The equation for the TLV® (4) is as follows(7):

$$(4)\ \text{TLV}^{®} = 56.7 - 11.5\ \text{Log}_{10} * \text{TWA-M}$$

The equation for the AL (5) is as follows (ACGIH®)(7):

$$(5)\ \text{AL} = 59.9 - 14.1\ \text{Log}_{10} * \text{TWA-M}$$

The exposures to heat stress in our study were classified as above or below the OEL, based on acclimatization state. Acclimatized participants were referenced to the TLV® and the unacclimatized participants were referenced to the AL. These values were given a Yes, or a No, based on the value being above or below OEL. These OELs took into account a CAV, for semi-nude participants (only shorts for males and only shorts and a halter top for females) were given a -1°C CAF from the OEL. While all other clothing ensembles were woven clothing with CAV = 0. These OEL categories were analyzed against acclimatization state and sustainability.

Acclimatization state was determined by whether the paper explicitly stated that the participants were acclimatized. If not, participants were classified as non-acclimatized. These categories were labeled as A for acclimatized and NA for non-acclimatized participants.

The physiological outcomes for exposure to heat stress were placed into an unsustainable category and were classified as unsustainable or sustainable. Unsustainable was given a Yes, meaning the exposure would be unsustainable. Sustainable was given a No for not being unsustainable. This determination was based on the physiological response of increased T_{re}, where sustainable was determined by the average T_{re} for each protocol being at or below 38°C and no individual participant at or greater than 38.5°C. If either threshold was surpassed the outcome was classified as unsustainable.

As mentioned in the literature review section, the question was raised concerning the effectiveness of the current OELs with regards to age. Therefore, data was extracted from the literature to analysis the effect of the current OELs and mean age of participants against the same analysis protocol mentioned above for our study. Mean age categories were developed utilizing mean age for Young (<30 years), Middle (≥30 to <50 years), and Older (≥50 years) participants to determine if the OELs are protective of the age categories.

Statistical analysis was conducted using JMP Pro 15 Software on a Microsoft Surface laptop computer. 2X2 tables were constructed to test sensitivity and specificity for acclimatization state and sustainability versus the OELs (>TLV® and >AL). Additionally, 2X2 tables were constructed to test sensitivity and specificity for each age group category against acclimatization state and sustainability versus the OEL (>TLV® and >AL).

Chapter Four:

Results

The results presented in the 2X2 tables are the mean data extracted from each protocol found in the papers based on the total participants (558 participants). Therefore, the statistical analysis only represents the mean from each protocol (n = 76). Each table provides the sensitivity and the specificity, with the 95% confidence interval (CI), to represent the key finding from the research.

Table 2 represents acclimatized participants being measured against the ACGIH®'s TLV® to illustrate if exposure was unsustainable. A case was an unsustainable exposure, and a non-case was a sustainable exposure. The table identifies the exposure as being above or below the TLV® (indicated by >TLV®) versus an unsustainable exposure. The results produced a sensitivity of 1.00, with no false negatives, and a specificity of 0.58, with false positives.

Table 2: Acclimatized Participants

	Unsustainable				
>TLV®	Yes	No		Value:	95% CI
Yes	7	5	Sensitivity	1.00	0.59 – 1.00
No	0	7	Specificity	0.58	0.28 – 0.85

Table 3 represents non-acclimatized participants being measured against the ACGIH®'s AL to illustrate if exposure was unsustainable. A case was an unsustainable exposure, and a non-case was a sustainable exposure. The table identifies the exposure as being above or below the AL (indicated by > AL) versus an unsustainable exposure. The results produced a sensitivity of 0.71, with several false negatives, and a specificity of 0.35, with false positives.

Table 3: Non-Acclimatized Participants

	Unsustainable				
>AL	Yes	No		Value:	95% CI
Yes	12	26	Sensitivity	0.71	0.44 - 0.90
No	5	14	Specificity	0.35	0.21 - 0.52

As discussed, multiple papers conducted experiments to determine if the current OELs are adequately protective of older workers. As such, our study investigated the protocol data and generated age group categories (Young, Middle, and Older) based on the data presented in the protocols. 2X2 tables were then developed to represent the same statistical analysis performed on the acclimatized and non-acclimatized participants mentioned above, however they were categorized by age group.

Table 4 represents acclimatized participants being measured against the ACGIH®'s TLV® to illustrate if exposure was unsustainable for the Young category. A case was an unsustainable exposure, and a non-case was a sustainable exposure. The table identifies the exposure as being above or below the TLV® (indicated by > TLV®) versus an unsustainable exposure. The results produced a sensitivity of 1.00 and a specificity of 0.58.

Table 4: Acclimatized Participants: Young Category

	Unsustainable				
>TLV®	Yes	No		Value	95% CI
Yes	7	5	Sensitivity	1.00	0.59 – 1.00
No	0	7	Specificity	0.58	0.28 – 0.85

Table 5 represents non-acclimatized participants being measured against the ACGIH®'s AL to illustrate if exposure was unsustainable for the Young category. A case was an unsustainable exposure, and a non-case was a sustainable exposure. The table identifies the exposure as being above or below the AL (indicated by >AL) versus an unsustainable exposure. The results produced a sensitivity of 0.64, with several false negatives, and a specificity of 0.29, with false positives.

Table 5: Non-Acclimatized Participants: Young Category

	Unsustainable				
>AL®	Yes	No		Value	95% CI
Yes	7	24	Sensitivity	0.64	0.31 – 0.89
No	4	10	Specificity	0.29	0.15 – 0.48

Table 6 represents non-acclimatized participants being measured against the ACGIH®'s AL to illustrate if exposure was unsustainable for the Older category. A case was an unsustainable exposure, and a non-case was a sustainable exposure. The table identifies the exposure as being above or below the AL (indicated by >AL) versus an unsustainable exposure. The results produced a sensitivity of 0.83 and a specificity of 0.67.

Table 6: Non-Acclimatized Participants: Older Category

	Unsustainable				
>AL	Yes	No		Value	95% CI
Yes	5	1	Sensitivity	0.83	0.36 – 0.99
No	1	2	Specificity	0.67	0.28 – 0.85

There were no acclimatized Older participants therefore, a 2X2 table could not be constructed and statistical analysis could not be performed. Additionally. the Middle age group only had three participant variables observed which all fell into a non-acclimatized and sustainable classification, therefore a 2x2 table could not be constructed or analysis performed.

Chapter Five:

Discussion

The goal of the OELs is to maintain thermal equilibrium.(7, 8) As previously mentioned, the parameters for our study were to evaluate T_{re} to determine if average T_{re} remained below 38°C and if any individual T_{re} remained below 38.5°C. Therefore, any observed protocols above these thresholds were defined as an unsustainable exposure, and thus classified as a case. Anything below was considered a sustainable exposure and classified as a non-case. It has been established that these T_{re} thresholds are the difference between sustainable exposure, heat stress levels where thermal balance can be achieved, and unsustainable exposures, heat stress levels where a steady increase above T_{re} thresholds occur.(14)

By classifying the exposures in this manner, the current study was able analyze this data against the given exposures as being above or below the OELs; enabling an analysis to test for sensitivity and specificity. Testing for sensitivity reflects the ability to detect true unsustainable exposures, which is the characteristic of interest because it correctly classifies a case.(14) Additionally, specificity enables the ability to detect true sustainable exposures, while not as important as identifying unsustainable cases, it is important because it represents those that were correctly classified as a non-case.(14)

Table 2 shows a sensitivity of 1.00 for the acclimatized participants, with no false negatives, which is good. This indicates that all acclimatized participants were adequately protected by the OELs based on our criteria. The specificity of 0.53 indicates that there are false positives. Meaning there was exposure above the OELs, however it was a sustainable exposure, based on our criteria. This exposure is less important; however, this exposure should be monitored through a comprehensive HSMP to ensure unsustainable exposure does not occur. Based on these findings, utilizing a TWA-WBGT and TWA-M for work-recovery cycles is adequately protective for acclimatized workers within the bounds of the OELs.

Table 3 produced a sensitivity of 0.71 for non-acclimatized participants, with the potential for false negatives. Meaning the OEL is protective of most participants, however several participants were exposed below the OEL and had an unsustainable exposure. The specificity of 0.35 produced several false positive results. There were five false negative outcomes for non-acclimatized participants which points to the effectiveness of acclimatization, however other risk factors or reasoning could be linked to these unsustainable exposures. Based on the protocol data, false negatives involved protocols with older participants, the addition of radiant heat, and a near continuous work-rest cycle (60 minutes work with 60 minutes rest) which all could have contributed to these unsustainable exposures while being exposed below the OEL.(22, 24, 25)

Questions around the degree to which age effects the physiological responses and sustainability of older participants prompted our study to investigate age categories. Table 4 represents the sensitivity and specificity for the Young, acclimatized participants and produced the same results as Table 2 for acclimatized participants (1.00 and 0.58, respectively). Therefore, the outcome is the same and it can be concluded that utilizing a TWA for work-recovery cycles is adequately protective of the Young, acclimatized participants, based on this study.

Table 5 shows a sensitivity of 0.64 and specificity of 0.29 for young, non-acclimatized participants. This table has a lower sensitivity which indicates a lower probability of a true positive outcomes and reflects four of the false negatives mentioned from Table 2, minus the Older category participants. The same logic provided in Table 2 can be deduced here for understanding the potential causes for these false negatives. Therefore, the conclusion was reached that TWA for work-recovery cycles is less protective for non-acclimatized, Young participants.

It is well documented that age impacts an individual's ability to thermoregulate based on the physiological responses during heat stress.(7, 25, 27-30) Table 6 represents the data for the Older, non-acclimatized participants; there were no acclimatized participants. The resulting sensitivity was 0.83 and specificity was 0.67, both results are good outcomes, however there was one false negative result. While unable to adequately determine the definitive causative factors contributing to this false negative results, age and acclimatization stage may have contributed. Therefore, utilizing TWA for work-recovery cycles was protective of Older, non-acclimatized participants, based on our study.

Chapter Six:

Conclusion

The purpose of this study was to demonstrate that TWAs for WBGT and metabolic rate are acceptable metrics for assessing exposure and prescribing work-recovery cycles. The sixteen papers in which a work-recovery protocol was established provided heat stress exposures for which TWA-WBGT and TWA-M were computed to assess whether the exposure was above or below the OEL. This investigation also classified exposures as sustainable or unsustainable.

I hypothesized that utilizing a TWA-WBGT and TWA-M for constructing work-recovery cycles would be effective in protecting most workers when evaluating environmental contributions and work demands to heat stress within the bounds of the OELs. Based on this study, this hypothesis holds true. Just as the OELs are designed to protect most healthy, acclimatized workers to sustain heat stress exposure, this study reinforced that. Our findings indicate the TWAs for work-recovery cycles are protective of acclimatized participants, however they are less protective of non-acclimatized participants, to include Older participants. These findings illustrate the importance of incorporating TWA work-recovery cycles and an acclimatization program as integral heat stress control measures within a comprehensive HSMP.

Recommendations for future research include conducting additional studies that: 1) further test work-recovery patterns over a full 8-hour shift, 2) evaluate the effects of chronic heat stress exposure on work-recovery cycles, and 3) evaluate the effects of climate change on the current OELs and work-recovery cycles.

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Appendices

Appendix A: Table A1

Table A1: Final Database for Study Analysis

Reference Author	Protocol Description(1)	Mean Age	Age Group(2)	ACC(3)	CLO(4)	Protocol Duration (min)	TWA-WBGT (°C)(5)	TWA-M (W)(6)	TLV (°C)(7)	AL (°C)(8)	CAV (°C)(9)	>TLV	>AL	UNSUS(10)	Reasons for Sustainable Decision
Gagnon (2011)	60ER	23	Young	NA	SN	120	25	115	33	31	-1	No	No	Yes	Ave Tre > 38; Tre < 38.5
Gagnon (2011)	20ER	23	Young	NA	SN	120	25	115	33	31	-1	No	No	No	Ave Tre < 38; Tre < 38.5
Gagnon (2011)	10ER	23	Young	NA	SN	120	25	115	33	31	-1	No	No	No	Ave Tre < 38; Tre < 38.5
Gagnon (2011)	5ER	23	Young	NA	SN	120	25	115	33	31	-1	No	No	No	Ave Tre < 38; Tre < 38.5
Graveling (1995)	Exp 1-Intermittent A	29	Young	NA	SN	150	31	211	30	27	-1	Yes	Yes	No	Mean increase 0.7, +/- 0.3 SD
Graveling (1995)	Exp 1 - Intermittent B	29	Young	NA	SN	150	31	174	31	28	-1	No	Yes	No	Mean increase 0.8, +/- 0.2 SD
Graveling (1995)	Exp 4: H-H: 12.5%	29	Young	NA	SN	100	31	152	32	29	-1	No	Yes	No	Mean increase 0.68, +/- 0.43 SD
Graveling (1995)	Exp 4: H-H: 25%	29	Young	NA	SN	100	31	165	31	29	-1	No	Yes	No	Mean increase 0.49, +/- 0.19 SD
Graveling (1995)	Exp 4: H-H: 37.5%	29	Young	NA	SN	100	31	166	31	29	-1	No	Yes	No	Mean increase 0.55, +/- 0.29 SD
Graveling (1995)	Exp 4: H-H: 50%	29	Young	NA	SN	100	31	164	31	29	-1	No	Yes	No	Mean increase 0.87, +/- 0.15 SD
Graveling (1995)	Exp 4: Hot-humid: 0%	29	Young	NA	SN	100	31	178	31	28	-1	No	Yes	No	Mean increase 0.78, +/- 0.06 SD
Graveling (1995)	Exp 5: 26*/23*	29	Young	NA	SN	100	25	166	31	29	-1	No	No	No	Mean increase 0.7, +/- 0.1 SD
Graveling (1995)	Exp 5: 31*/27*	29	Young	NA	SN	100	29	166	31	29	-1	No	No	No	Mean increase 0.8, +/- 0.3 SD
Graveling (1995)	Exp 5: 35*/31*	29	Young	NA	SN	100	33	166	31	29	-1	Yes	Yes	Yes	Mean increase 1.3, +/- 0.3 SD
Kaltsatou (2020)	Inter WR 3:1 @ 29*C	58	Older	NA	SN	120	29	165	31	29	-1	No	No	Yes	Ave Tre >38
Kaltsatou (2020)	Inter WR 1:1 @ 30*C	58	Older	NA	SN	120	30	230	30	27	-1	No	Yes	Yes	Ave Tre >38

Appendix A: Table A1 (Continued)

Reference Author	Protocol Description(1)	Mean Age	Age Group(2)	ACC(3)	CLO(4)	Protocol Duration (min)	TWA-WBGT (°C)(5)	TWA-M (W)(6)	TLV (°C)(7)	AL (°C)(8)	CAV (°C)(9)	>TLV	>AL	UNSUS(10)	Reasons for Sustainable Decision
Kamon_a (1979)	WH WH	23	Young	A	WC	160	33	565	25	21	0	Yes	Yes	Yes	Ave Tre about 38.5°C; >38
Kamon_a (1979)	WH Room	23	Young	A	WC	160	26	269	29	26	0	No	Yes	No	Ave Tre <38
Kamon_a (1979)	HD HD	23	Young	A	WC	160	33	269	29	26	0	Yes	Yes	No	Ave Tre <38
Kamon_a (1979)	HD Room	23	Young	A	WC	160	26	269	29	26	0	No	Yes	No	Ave Tre <38
Kamon_a (1979)	WH Room	23	Young	A	WC	160	28	565	25	21	0	Yes	Yes	No	Ave Tre <38
Kamon_a (1979)	HD HD	23	Young	A	WC	160	33	565	25	21	0	Yes	Yes	No	Ave Tre <38
Kamon_a (1979)	HD Room	23	Young	A	WC	160	28	565	25	21	0	Yes	Yes	No	Ave Tre <38
Kamon_b (1983)	WH	23	Young	NA	WC	90	25	204	30	27	0	No	No	Yes	Extrapolated Ave Tre > 38
Kamon_b (1983)	HD	23	Young	NA	WC	90	26	204	30	27	0	No	No	Yes	Extrapolated Ave Tre > 38
Kamon_b (1983)	HH	23	Young	NA	WC	90	27	174	31	28	0	No	No	Yes	Extrapolated Ave Tre > 38
Kamon_b (1983)	WH+R	23	Young	NA	WC	90	30	277	29	25	0	Yes	Yes	Yes	Ave Tre > 38
Kamon_b (1983)	HD+R	23	Young	NA	WC	90	31	277	29	25	0	Yes	Yes	Yes	Ave Tre > 38
Kamon_b (1983)	HH+R	23	Young	NA	WC	90	33	226	30	27	0	Yes	Yes	Yes	Ave Tre > 38
Kenny_a (2009)	3 Ex X 3 R	27	Young	NA	SN	180	22	233	29	27	-1	No	No	No	Ave Tre <38; Tre <38.5; Level
Krajewski (1979)	WH WH-W	21.67	Young	A	WC	180	33	199	30	28	0	Yes	Yes	Yes	Ave Tre >38; Tre >38.5; Increasing
Krajewski (1979)	WH WH-M	26	Young	A	WC	180	33	332	28	24	0	Yes	Yes	Yes	Ave Tre >38; Tre >38.5; Increasing

Appendix A: Table A1 (Continued)

Reference Author	Protocol Description(1)	Mean Age	Age Group(2)	ACC(3)	CLO(4)	Protocol Duration (min)	TWA-WBGT (°C)(5)	TWA-M (W)(6)	TLV (°C)(7)	AL (°C)(8)	CAV (°C)(9)	>TLV	>AL	UNSUS(10)	Reasons for Sustainable Decision
Krajewski (1979)	HD HD-W	21.67	Young	A	WC	180	33	199	30	28	0	Yes	Yes	Yes	Ave Tre >38; Tre >38.5; Increasing
Krajewski (1979)	HD HD-M	26	Young	A	WC	180	33	332	28	24	0	Yes	Yes	Yes	Ave Tre >38; Tre >38.5; Increasing
Krajewski (1979)	WH Room-W	21.67	Young	A	WC	180	26	199	30	28	0	No	No	No	Ave Tre <38; Tre <38.5; Level
Krajewski (1979)	WH Room-M	26	Young	A	WC	180	26	332	28	24	0	No	Yes	No	Ave Tre <38; Tre <38.5; Level
Krajewski (1979)	HD Room-W	21.67	Young	A	WC	180	26	199	30	28	0	No	No	No	Ave Tre <38; Tre <38.5; Level
Krajewski (1979)	HD Room-M	26	Young	A	WC	180	26	332	28	24	0	No	Yes	No	Ave Tre <38; Tre <38.5; Level
Lamarche (2017)	WR3:1	58	Older	NA	WC	120	29	165	31	29	0	No	Yes	Yes	Ave Tre > 38, Tre > 38.5
Lamarche (2017)	WR1:1	58	Older	NA	WC	120	30	230	30	27	0	Yes	Yes	Yes	Ave Tre > 38, Tre > 38.5
Larose (2013)	Young (20-30 yr)	25.8	Young	NA	SN	120	25	250	29	26	-1	No	No	No	Ave Tre <38; Tre <38.5; level
Larose (2013)	Middle (40-45 yr)	43.2	Middle	NA	SN	120	25	250	29	26	-1	No	No	No	Ave Tre <38; Tre <38.5; level
Larose (2013)	Older (60-70 yrs)	63.4	Older	NA	SN	120	25	250	29	26	-1	No	No	No	Ave Tre <38; Tre <38.5; level
Lind (1963)	High	-	Young	A	SN	480	33	305	28	25	-1	Yes	Yes	Yes	Ave Tre > 38; lacking control
Lind (1963)	Low	-	Young	A	SN	480	26	305	28	25	-1	No	Yes	No	Ave Tre < 38; control ok
Lind (1963)	ULPZ	-	Young	A	SN	480	30	305	28	25	-1	Yes	Yes	No	Ave Tre < 38; control ok
Mairiaux (1986)	WH-2 ALT	21.4	Young	NA	SN	120	30	250	29	26	-1	Yes	Yes	Yes	Ave Tre > 38; lacking control
Mairiaux (1986)	WD-1 ALT	21.4	Young	NA	SN	120	28	250	29	26	-1	No	Yes	No	Tre < 38; control looked ok
Mairiaux (1986)	WD-2 ALT	21.4	Young	NA	SN	120	28	250	29	26	-1	No	Yes	No	Tre < 38; control looked ok

Appendix A: Table A1 (Continued)

Reference Author	Protocol Description(1)	Mean Age	Age Group(2)	ACC(3)	CLO(4)	Protocol Duration (min)	TWA-WBGT (°C)(5)	TWA-M (W)(6)	TLV (°C)(7)	AL (°C)(8)	CAV (°C)(9)	>TLV	>AL	UNSUS(10)	Reasons for Sustainable Decision
Mairiaux (1986)	WD-2 STEADY	21.4	Young	NA	SN	120	28	250	29	26	-1	No	Yes	No	Tre < 38; control looked ok
Mairiaux (1986)	WH-1 ALT	21.4	Young	NA	SN	120	31	250	29	26	-1	Yes	Yes	No	Ave Tre < 38; control ok
Mairiaux (1986)	WH-3 STEADY	21.4	Young	NA	SN	120	31	250	29	26	-1	Yes	Yes	No	Ave Tre < 38; control ok
Meade (2016)	WR 3:1 @ 29*	21	Young	NA	SC	120	29	165	31	29	-1	No	No	No	Ave Tre <38; Tre < 38.5; Increasing
Meade (2016)	WR 1:1 @ 30*	21	Young	NA	SC	120	30	230	30	27	-1	No	Yes	No	Ave Tre <38; Tre < 38.5; Increasing
Meade (2016)	WR 1:3 @ 31.5*	21	Young	NA	SC	120	32	295	28	25	-1	Yes	Yes	No	Ave Tre <38; Tre < 38.5; Increasing
Seo (2019)	Protective-Dry (PD)	22.1	Young	NA	PC	120	30	225	30	27	0	Yes	Yes	No	Ave Tre < 38, Tre < 38.5
Seo (2019)	Protective-Humid (PH)	22.1	Young	NA	PC	120	30	225	30	27	0	Yes	Yes	No	Ave Tre < 38, Tre < 38.5
Seo (2019)	Cotton-Dry (WD)	22.1	Young	NA	WC	120	30	225	30	27	0	Yes	Yes	No	Ave Tre < 38, Tre < 38.5
Seo (2019)	Cotton-Humid (WH)	22.1	Young	NA	WC	120	30	225	30	27	0	Yes	Yes	No	Ave Tre < 38, Tre < 38.5
Stapleton (2012)	H-D: 1 CON	22.9	Young	NA	SN	120	30	165	31	29	-1	No	Yes	No	Ave Tre < 38, Tre < 38.5
Stapleton (2012)	W-W: 1 CON	22.9	Young	NA	SN	120	29	165	31	29	-1	No	No	No	Ave Tre < 38, Tre < 38.5
Stapleton (2012)	H-D: 2 MWU	22.9	Young	NA	WC	120	30	165	31	29	0	No	Yes	No	Ave Tre < 38, Tre < 38.5
Stapleton (2012)	H-D: 3 SWU	22.9	Young	NA	WC	120	30	165	31	29	0	No	Yes	No	Ave Tre < 38, Tre < 38.5
Stapleton (2012)	W-W: 2 MWU	22.9	Young	NA	WC	120	29	165	31	29	0	No	Yes	No	Ave Tre < 38, Tre < 38.5
Stapleton (2012)	W-W: 3 SWU	22.9	Young	NA	WC	120	29	165	31	29	0	No	Yes	No	Ave Tre < 38, Tre < 38.5

Appendix A: Table A1 (Continued)

Reference Author	Protocol Description(1)	Mean Age	Age Group(2)	ACC(3)	CLO(4)	Protocol Duration (min)	TWA-WBGT (°C)(5)	TWA-M (W)(6)	TLV (°C)(7)	AL (°C)(8)	CAV (°C)(9)	>TLV	>AL	UNSUS(10)	Reasons for Sustainable Decision
Wright_a (2015)	Young Group: low velocity.	24	Young	NA	WC	135	31	250	29	26	0	Yes	Yes	Yes	Ave Tre > 38, T re > 38.5
Wright_a (2015)	Young Group: high velocity.	24	Young	NA	WC	135	31	250	29	26	0	Yes	Yes	Yes	Ave Tre > 38, T re > 38.5
Wright_a (2015)	Older Group: low velocity.	59	Older	NA	WC	135	31	250	29	26	0	Yes	Yes	Yes	Ave Tre > 38, T re > 38.5
Wright_a (2015)	Older Group: high velocity.	59	Older	NA	WC	135	31	250	29	26	0	Yes	Yes	Yes	Ave Tre > 38, T re > 38.5
Wright_b (2014)	Young Warm/Dry	25.8	Young	NA	SN	165	25	250	29	26	-1	No	No	No	Ave Tre < 38, Tre < 38.5
Wright_b (2014)	Young Warm/Humid	25.8	Young	NA	SN	165	31	250	29	26	-1	Yes	Yes	No	Ave Tre < 38, Tre < 38.5
Wright_b (2014)	Middle Warm/Dry	43.6	Middle	NA	SN	165	25	250	29	26	-1	No	No	No	Ave Tre < 38, Tre < 38.5
Wright_b (2014)	Middle Warm/Humid	43.6	Middle	NA	SN	165	31	250	29	26	-1	Yes	Yes	No	Ave Tre < 38, Tre < 38.5
Wright_b (2014)	Older Warm/Dry	57.2	Older	NA	SN	165	25	250	29	26	-1	No	No	No	Ave Tre < 38, Tre < 38.5
Wright_b (2014)	Older Warm/Humid	57.2	Older	NA	SN	165	31	250	29	26	-1	Yes	Yes	No	Ave Tre < 38, Tre < 38.5

(1) Protocol description was generated from reference protocol parameters to create an identifiable description for each protocol.

(2) Age Group was developed to differentiate age groups by Young (< 30 years), Middle (≥30 and <50 years), and Older (≥50 years).

(3) ACC = Acclimatization state; where: A = Acclimatized participants and NA = Non-Acclimatized participants.

(4) CLO = Clothing worn; where: SN=semi-nude, SC=semi-clothed, WC=work clothes, and PC=protective clothing. SN consisted of only shorts (and halter top for women). SC consisted of shorts and tee shirt (and halter top for woman, with or without tee shirt). WC consisted of shirt and trousers or coveralls of woven material. PC consisted of chemical resistant coveralls/vapor-barrier ensemble as described in the protocol.

(5) TWA-WBGT = Time-weighted average for WBGT, in °C, utilizing Equation (2) from Methods section.

(6) TWA-M = Time-weighted average for metabolic rate, in Watts (W), utilizing Equation (3) from Methods section.

(7) TLV = Threshold Limit Value, in °C, utilizing Equation (4) from Methods section.

(8) AL = Action Limit, in °C, utilizing Equation (5) from methods section.

(9) CAV = Clothing Adjustment Value, where -1°C was assessed for semi-nude participants, all others were not given a CAF.

(10) UNSUS = Unsustainable; where yes is an unsustainable exposure and no is a sustainable exposure.