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Influence of Gender on Heart Rate and Core Temperature at Critical WBGT for Five Clothing Ensembles at Three Levels of Metabolic Rate

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Influence of Gender on Heart Rate and Core Temperature at Critical WBGT for Five Clothing Ensembles at Three Levels of Metabolic Rate

by

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List of Abbreviations and Acronyms

ACGIH	American Conference of American Industrial Hygienists
ANOVA	Analysis of Variance
BPM	Beats Per Minute
HR	Heart Rate
ISO	International Organization for Standardization
IRB	Institutional Review Board
I_t	Total Clothing Insulation
NIOSH	National Institute for Occupational Safety and Health
R_{e-t}	Total evaporative resistance
R_h	Relative Humidity
T_{arm}	Arm Temperature
T_{calf}	Calf Temperature
T_{ch}	Chest Temperature
T_{db}	Dry Bulb Temperature
T_g	Globe Temperature
T_{th}	Thigh Temperature
T_{nwb}	Natural Wet Bulb Temperature
T_{re}	Core Temperature
T_{pwb}	Psychometric Wet Bulb Temperature
USF	University of South Florida

VO_{2max}	Maximum Oxygen Volume
WBGT	Wet Bulb Globe Temperature

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ABSTRACT

Three main factors that influence heat stress are clothing, work demands and environmental conditions. Gender may also influence the amount of heat stress an individual can tolerate. The purpose of this study was to examine the role of gender in heat stress limits (critical WBGT) and heat strain (heart rate and core temperature). The null hypothesis was that there was no gender difference among critical WBGT, heart rate and core temperature.

Fifteen subjects (11 men and 4 women) wore five different clothing ensembles (cotton work clothes, cotton coveralls, particle barrier Tyvek, water-barrier/vapor permeable NexGen LS417, and vapor barrier Tychem QC made by Dupont) at three levels of metabolic rate (115, 175 and 250 W m^{-2}). A treadmill was used to set the metabolic workload. A climatic chamber was used to control the environmental conditions. The participants continued to walk on the treadmill until their core temperature (T_{re}) reached a steady state. Then the air temperature and humidity were slowly increased. The point at which the core temperature increased steadily was defined as the inflection point. Environmental data as well as core temperature and heart rate

were recorded at five minute intervals. The critical conditions were noted at five minutes before the inflection point.

Metabolic rate, critical WBGT, core temperature and heart rate were analyzed by 3-way ANOVAs (participants nested by ensemble by metabolic rate) with all two way and three way interactions. Significant differences were observed between genders for metabolic rate and heart rate, but not for core temperature and critical WBGT across metabolic level and ensembles. While there were differences between genders in metabolic rate they did not affect the overall conclusions. The heart rate was significantly higher (12 bpm) for women than for men. Overall, women had the same upper limit of the prescriptive zone as men, their core temperatures were the same at this limit but women had a greater cardiovascular cost reflected in a higher heart rate.

Introduction

Among the physical agents that might be present during work, heat stress is well recognized. The job risk factors for heat stress are hot environment, heavy work demands, and protective clothing, alone or in any combination. The evaluation of heat stress is based first on exposure limits that consider the environmental conditions and the metabolic rate. A widely recognized index of environmental conditions is wet bulb globe temperature (WBGT). NIOSH (1986), ACGIH (2004) and ISO (1989) have prescribed exposure limits based on the combination of WBGT and metabolic rate, such that with increasing metabolic rate the ambient WBGT decreases. All of these occupational exposure limits are based on two goals. The first goal is to maintain the physiological responses in the work driven zone, which is a range of environmental conditions for which the body core temperature does not change for a given metabolic rate. The upper end of this range is called the Upper Limit of the Prescriptive Zone (Lind 1963). Beyond that point, the body core temperature increases with the WBGT and this range is called the environmentally driven zone. The second goal is to keep body core temperature below 38 °C, and this is accomplished if the exposure occurs in the work driven zone.

The occupational exposure limit based on WBGT depends on clothing as well as metabolic rate. To account for clothing, adjustment factors have been put forward that adjust the WBGT limit to represent the change in heat stress due to the clothing. With work clothes as a reference work ensemble, wearing particle-, liquid-, and vapor-barrier clothing ensembles have a progressive increase in the level of heat stress that can be accounted for by the adjustment factors.

There is a physiological cost to meeting the demands of heat stress and to maintain thermal equilibrium at the occupational exposure limit. These physiological costs are commonly referred to as heat strain and include heart rate, core temperature and skin temperature. There is good evidence that men and women respond to heat stress differently. This opens a question of whether men or women pay a higher physiological cost at the occupational exposure limit.

Literature Review

Work in a warm or hot environment in combination with metabolic rate and clothing requirements can bring about heat stress. For a given combination of metabolic rate and clothing, there is a limiting environmental contribution that still allows thermal balance. To achieve the thermal equilibrium, physiological systems respond to the heat stress, and this response is collectively known as heat strain. Heat strain is reflected in heart rate, core temperature and skin temperature.

Heat Stress Factors

Metabolic Rate

Metabolic rate directly affects the amount of heat stress and strain an individual experiences. For heat stress, the metabolic rate represents the internal heat generation that must be dissipated to the environment. On the heat strain side, the metabolic rate drives a need for physiological resources, especially cardiac output, that compete with the need to dissipate heat.

In order to study metabolic rate in a laboratory setting, two methods to select metabolic rate are employed; these are absolute and relative. The absolute demand has the advantage of fixing the amount of heat generation for everybody. But the absolute metabolic rate does not account for the aerobic capacity of an individual. For example if a study is conducted at 260 W, that is the target for everyone in the study. So, an individual with a low level of fitness will work relatively harder (greater physiological strain) than another individual with a greater aerobic capacity. In contrast a relative metabolic rate, matches the participants VO_{2max} or a given fraction (%) of VO_{2max} is used as the target metabolic rate. Matching or assigning a $\%VO_{2max}$ controls for the effects of fitness, but does not control for the heat generation.

Clothing

Protective clothing can alter the rate of heat dissipation via convection, radiation and evaporation. Clothing characteristics can be described by total clothing insulation (I_t) and total evaporative resistance (R_{e-t}) . In evaluating heat stress, it is important to understand insulation and permeability characteristics of clothing.

I_t is used to describe the decrease in heat flow due to clothing and air insulation. The insulative properties of clothing depend on three factors. These are the overall thickness of the clothing, the air pockets between the material and the skin, and the air pockets between the layers of clothing. The insulation affects the rate of convection and radiant heat flow.

The R_{e-t} describes the permeability characteristics. The more permeable a piece of clothing is, the more it allows sweat to evaporate and promote heat dissipation. Impermeable clothing prevents evaporation thus increasing the level of heat stress.

Convective and radiative heat loss accounts for approximately 10% of heat dissipation. The major method of heat dissipation during work is evaporation.

Therefore, R_{e-t} is the more important clothing characteristic to consider when evaluating clothing properties.

Clothing influences the upper limit of the prescriptive zone (Bernard, et al. 2005). The ACGIH (2004) has suggested clothing adjustments to be added to the ambient WBGT to account for the added heat stress burden and several others have recommended values for different clothing ensembles (Kenney 1988, O'Conner and Bernard 1999, Bernard et al 2005).

Environmental Conditions

The wet bulb globe temperature (WBGT) is used to evaluate the contribution of environmental factors to heat stress. The natural wet bulb temperature (T_{nwb}) assesses the contribution of evaporative cooling. The globe temperature (T_g) is used to evaluate convective and radiant heat. In industrial settings, the equation for WBGT is:

$$WBGT = 0.7\ T_{nwb} + 0.3\ T_g.$$

Threshold limit values established by the ACGIH prescribe a relationship between environmental conditions and work demands below which most workers can maintain thermal equilibrium when wearing ordinary work clothes. As metabolic rate increases, the ambient WBGT decreases to maintain thermal balance. The threshold can be shifted depending on the clothing requirements.

Physiological Responses to Heat Stress

Some individual variations in responses to heat stress may be accounted for by gender. The gender differences in thermoregulation become more apparent with greater thermal loads with females at a disadvantage in very hot environments. In comparison to males, females generally have 1) a greater amount of body fat which acts as insulation and increases heat storage, 2) a higher thermoregulatory set point, and 3) lower aerobic capacity which increases the relative workload of a given task (Reneau et al 1999, NIOSH 1986). Females also have a smaller blood volume and a larger surface area to mass ratio. Peripheral vasodilation results in a relatively larger amount of blood to the periphery. Generally, females rely more on convective heat loss, an advantage in hot wet environments, while males rely more on evaporative heat loss, an advantage in hot dry environments (Kenny et al. 1988, Montain et al. 1994). This is an advantage for females as decreased sweat production may slow dehydration and enhances heat dissipation in humid environments.

Acclimatization State

The amount of heat strain a worker experiences depends largely on environment, work rate and clothing as well as host factors like acclimatization state. If the worker is not acclimated to the heat, the heat strain is greater. Acclimatization can have a positive impact on heat tolerance by increasing sweat rate, increasing plasma volume, and decreasing heart rate which helps to reduce body temperature and fatigue at a given work rate.

The process of acclimatization involves exposing workers to work in a hot environment for at least two hours over sequential days. The physiological adaptations of acclimatization will occur with environmental conditions sufficient to raise body core temperature and heart rate. Acclimatization can be accomplished with exposure to a hot environment with low relative humidity (hot-dry) as well as with exposure to a warm environment with high relative humidity (warm-wet). NIOSH (NIOSH 1986) suggests that for workers with previous work experience in the heat, the acclimatization program should begin with 50% exposure on day one, 60% on day two, 80% on day three and 100% on day 4 in recognition of the increased work capacity that comes from a sound acclimatization program. NIOSH (1986) further recommends that the acclimatization program for new workers begin with 20% exposure on day one with a 20% increase in exposure each day, and is more gradual because the worker is also learning the job.

Documented physiological responses of acclimatization include improved circulatory efficiency and enhanced thermoregulation. Circulatory changes include an increase in plasma volume and decreased heart rate for a given workload (Montain et al. 1994, Moriomoto et al. 1967, Frye and Kamon 1981, Kamon et al. 1978, McLellan, 1998). In addition, there is a deceased core temperature for a given workload (Morimoto et al. 1986, Frye and Kamon, 1981, Anderson et al. 1995 Kamon et al. 1978, McLellan 1998), and a lower core temperature and skin temperature for the onset of sweating as well as a greater sweat rate (White et al. 1989, Frye and Kamon 1981, Anderson et al. 1995, McLellan, 1998). Increased core temperature is the best marker of limiting conditions for heat stress. As such, a plateau in core temperature has been suggested as the major criteria to designate complete acclimatization.

For many heat stress and strain studies, acclimated participants routinely remove acclimatization state as a potential confounder.

Heart Rate and Gender

Most research has found that men have a lower heart rate for a given level of heat stress than women (Avellini et al. 1980, Shalpiro et al. 1980, Yousef et al. 1984, Kamon et al. 1978, Mcllelan, 1998). The gender difference in heart rate in many studies was attributed to environmental conditions. Shapiro et al (1980) conducted a study under six environmental conditions including a comfortable climate (WBGT = 14.4ºC, rh = 40%), a mild-wet climate (WBGT=30.3ºC, rh = 80%), two hot-wet climates (WBGT = 34.0 and 34.5ºC, rh = 90 and 80%) and two hot-dry conditions (WBGT = 34.0 and 34.2ºC, rh = 20 and 10%). Men had lower heart rates during hot-dry conditions but not during mild-wet, comfortable or hot-wet conditions.

There are a few studies that show a greater heart rate in men than women. Avellini, Kamon and Krajewski (1980) showed that men had higher heart rates than women prior to acclimatization in hot-wet conditions. The men's heart rates were 13-25 bpm higher than the women's. Post-acclimatization, there was no difference in heart rate between men and women. Paolone, Wells and Kelly (1978) also showed higher heart rates in men in neutral, warm and hot conditions. The experimental protocol called for a metabolic rate of 50% $VO_{2\ max}$. As the authors point out, the mean exercise VO_2 of the men was 15% greater in all environments than the females.

Typically, aerobic fitness is higher in men than women. Matching participants on aerobic fitness levels the playing field. Studies that matched subjects on aerobic fitness showed no difference in heart rate between men and women (Antunano 1992, McLellan 1998). In addition, although Kamon, Avellini and Krajewski (1978) observed a greater heart rate in men, the authors point out that the difference in heart rate is proportional to the difference in $VO_{2\,max}$.

In summary, the literature suggests that there is a difference between males and females with respect to heart rate particularly under hot-dry environmental conditions.

Core Temperature and Gender

The best indicator of heat stress is core body temperature. During exercise, the increase in core body temperature is proportional to the increase in metabolic rate, heat load and may also be influenced by clothing. There are several methods to measure core body temperature, but the most common laboratory method is rectal temperature (T_{re}).

A number of researchers report a greater T_{re} in semi-nude women than in men (Yousef et al. 1984, Moran et al. 1999, Paolone et al. 1978). In addition, McLellen, (1998) also observed a greater T_{re} in men than women working in NBC clothing in a hot-dry environment. Shapiro et al. (1980) examined heat stress responses under 6 environmental conditions. Under the hot-wet conditions, men had a higher T_{re}. Under hot-dry conditions, these researchers reported a significantly greater T_{re} for women.

As previously suggested, fitness and acclimatization can have a positive effect on physiological signs of heat strain. In studies where participants were matched on aerobic capacity, the researchers (Frye and Kamon 1981, McLellan 1998) found no significant difference in T_{re} between men and women. Also, when the results of the participants in the McLellan's study (1998) were matched on aerobic capacity, gender differences in heat strain (i.e. T_{re}) disappeared.

As previously mentioned, generally men have a higher aerobic capacity than women. Using an equivalent absolute workload results in a greater relative workload for women. A number of researchers have used acclimatized subjects. For example, Avellini, Kamon, and Krajewski (1980), observed a significantly greater T_{re} in men prior to acclimatization. After acclimatization, no significant difference was noted between the genders until 90 minutes of exercise. After that point, T_{re} in males began to increase until test termination at 3 hours. At the end of the exposure, T_{re} of the men was 0.3ºC higher than the women.

Sweat Rate and Gender

During work, evaporation is the primary means of heat dissipation. Evaporation is dependent on vapor pressure gradients between the skin, air and clothing. Vapor pressure is a function of relative humidity and ambient temperature. As vapor pressure decreases, less evaporative cooling is possible. The amount of sweat evaporated is dependent on vapor pressure gradients, convection, and the amount of skin wettedness available to the environment. The amount of sweat an individual generates can have an affect on how well the body does to cool itself down.

The ability of the body to cool itself by sweating is influenced by environmental conditions. In a humid environment, the perspiration does not readily evaporate due to a low water vapor pressure gradient between the skin and air. In contrast if an individual is in a hot dry climate, the sweat easily evaporates off the skin. Morimoto (1967) observed a significant increase in sweat rates of men compared to women in both humid and dry conditions. They did observe though, that sweat rates decreased in both genders during humid conditions.

Although women have a greater number of sweat glands than men, men tend to have a higher sweat rate than women. In the literature, there is a significant difference in sweat rate between genders. Generally, the vast majority showed that men sweat much more than women (Morimoto et al. 1967, Avellini et al. 1980, Frye and Kamon 1981, Shapiro et al. 1980, Fox et al. 1969, Yousef et al. 1984, Anderson et al. 1995, Kamon et al. 1978, McLellan 1998, Paolone et al. 1978). Avellini, Kamon, and Krajewski (1980) observed that prior to acclimatization, men sweated significantly more than women. After hot humid acclimatization, the difference in sweat rate between men and women was even more significant. Sweat rate in males after acclimatization increased 35% while that of females increased 18%. In a similar study Frye and Kamon (1981) observed a greater sweat rate in men than women prior to acclimatization. After acclimatization, the sweat rate between men and women was not significantly different. Both males and females showed increased sweating after acclimatization, but in their study a significant difference between the genders did not exist.

Shapiro et al (1980) observed that acclimatized men sweated more than acclimatized women in humid environments. Under hot-wet environmental conditions men sweated 40% more than women. Under mild-wet conditions, men sweated an average of 23% more than women. In hot-dry dry conditions men sweated more than women but the difference between the sexes was not significantly different.

Fox et al (1969) and Yousef et al. (1984) studied sweat rates in hot-dry environmental conditions. They observed that females had a higher onset of sweating threshold for sweating. Females also had a lower sweat rate than males when they were exercising at the same rate. Kenny and Zeman (2002) measured sweat rate for unacclimatized males and females. They observed that males sweat significantly more than females and males had a higher evaporative rate of sweat than females.

In a study examining heat strain of subjects with equivalent aerobic capacities, Moran et al. (1999) observed equivalent sweat rates between men and women. However, there was also a third group consisting of men with a higher aerobic capacity. These subjects had a higher sweat rate than the men and women with equivalent aerobic capacities.

Skin Temperature and Gender

Skin temperature has also been used as an indication of heat stress. The majority of studies concluded that there is no significant difference in skin temperature between males and females (Avellini et al. 1980, Frye and Kamon 1981, Kamon et al 1978, Paolone et al 1978).

A few studies observed a higher skin temperature in women than men. Yousef et al (1984) and McLellan (1998) observed that women have a higher skin temperature than males. Yousef et al. (1984) attributed the higher skin temperature in the women to the lower sweat rate observed. McLellan (1998) concluded that the higher skin temperature in women was due to the NBC clothing worn during the experiment. Due to the impermeable characteristics of the clothing, there was an increase in the vapor pressure inside the suit. As suggested earlier, as women rely more on convective heat transfer, heat dissipation in humid environments is compromised. In addition, the researchers used an equivalent workload for all subjects. This may have equated to a higher relative workload for the women.

In general, the majority of studies concluded that there was no significant difference observed for skin temperature between the two sexes. The two studies that did observe a difference attributed the difference to other protocol factors.

Hypothesis

The purpose of this study was to examine the effect of gender on heart rate and core temperature at critical WBGT in five ensembles at three levels of metabolic rate. The clothing ensembles varied from cotton work clothes to those with high evaporative resistance based on past laboratory experience to represent the range of clothing used in industry. The metabolic levels were chosen to represent light, moderate and heavy work of industrial settings. The null hypothesis was that there was no gender difference among critical WBGT, heart rate and core temperature at three levels of metabolic rate and five levels of clothing ensembles.

Methods

To determine the critical conditions of men and women wearing protective clothing in heat stress at different work demands, an experimental protocol was formulated using humans subjected to three different metabolic rates wearing five clothing ensembles.

Participants

Participants (11 men and 4 women) were recruited using local printed media. A licensed physician gave each participant a physical and approved him or her for participation. Each person participating in this study signed an informed consent, which followed University of South Florida (USF) Institutional Review Board (IRB) guidelines.

Table 1 provides a summary of the physical characteristics of the participants.

Table 1. Means and standard deviations of participant age, height, weight and estimated body surface area by gender and overall.

	Number of Participants	Age (years)	Height (cm)	Weight (kg)	Body Surface Area (m^2)
Males	11	28.0 ± 9.5	176 ± 11	81.9 ±11.7	1.98 ± 0.18
Females	4	23 ± 4.7	165 ± 6	64.2 ± 18	1.70 ±0.22
All	15	26.7 ± 8.6	173 ± 11	77.2 ± 15.3	1.91 ± 0.22

Each participant was acclimatized to dry heat for five days wearing athletic shorts and a T-shirt. Chamber conditions were set to a dry bulb temperature (T_{db}) of 50°C and a relative humidity of 20%. After five days of acclimatization, each participant followed a random schedule of trials for metabolic rates and clothing ensembles.

Equipment

The experimental environment was controlled in a Forma Scientific climatic chamber where the humidity and dry bulb temperature were controlled. Environmental conditions were measured as dry bulb (T_{db}), psychrometric wet bulb (T_{pwb}), and globe temperatures (T_g) using mercury thermometers.

The work consisted of walking on a motorized treadmill. Metabolic rate was assessed every 30 minutes by measuring the volume and composition of expired air using a Douglas Bag. The percentage of oxygen in the expired air was collected in the bag and analyzed with a Beckman E-2 Oxygen Analyzer, which was calibrated before each experimental trial. The volume of expired air was measured using a Rayfield Dry Gas meter.

The core temperature (T_{re}) was measured using a flexible YSI rectal thermistor (YSI 401AC) inserted 10 cm past the anal sphincter muscle. Thermistors were calibrated before each experiment. Skin temperatures at the chest (T_{ch}), arm (T_{arm}), thigh (T_{th}) and calf (T_{calf}) were measured using a YSI skin probe taped to the body at each location. The heart rate was measured using a Polar heart monitor.

Clothing

The five different clothing ensembles worn by participants during the study were cotton work clothes (6 oz/yd^2 cotton shirt and 8 oz/yd^2 cotton pants), cotton coveralls (9 oz/yd^2), particle barrier Tyvek 1427 made by Dupont, water-barrier/vapor-permeable NexGen LS417 manufactured by Kappler, and vapor-barrier Tychem QC made by Dupont.

Experimental Procedure

Prior to beginning the experimental protocol, participants underwent an acclimatization period for 5 days. Acclimatization consisted of walking on a treadmill at a metabolic rate of approximately 160 W m^{-2} in the climatic chamber (50 ºC, 20% rh) for 2 hours. Participants wore shorts, t-shirts and/or a sports bra.

The target metabolic rates for the experimental trials were 115, 175, and 250 W m^{-2}. These rates were chosen to provide a reasonable range of work demands centered on a moderate rate of work used in previous research. Prior to the first experiment, treadmill speed and grade were adjusted for each participant to yield target metabolic rates and were used throughout the experimental trials.

The 15 combinations of metabolic rate and clothing ensemble were randomized for each participant.

The conditions for the progressive heat stress protocol began with a T_{db} of 34 °C, and a psychrometric wet bulb (T_{pwb}) at 25.5 °C (relative humidity of 50%). When a physiological steady state was achieved, as evidenced by a steady T_{re}, T_{db} was increased by 0.8 °C every five minutes and the relative humidity was held at 50%. This increased heat stress by limiting evaporative cooling and increasing the dry heat gain.

The participants were allowed to drink water or a commercial fluid replacement beverage at will throughout the experimental session.

Environmental data and participant physiological data were collected and recorded every five minutes. The experiment continued until there was loss of thermal equilibrium evidenced by at least a 0.3 °C increase in core temperature (T_{re}) within any continuous 15 minute interval, a T_{re} of 39 °C was reached, 90% of the age-estimated maximum heart rate was sustained, or the participant wished to stop the experiment.

Determination of Critical WBGT

The inflection point marks the transition from the work-driven zone to the environmentally-driven zone, which is the basis for WBGT occupational exposure limits. After the inflection point, core temperature continued to rise. Figure 1 illustrates core temperature versus time for one trial. The chamber conditions five minutes before the noted increase in core temperature was taken as the critical condition. Usually one investigator noted the critical condition, and the decisions were randomly reviewed by a second investigator. The critical WBGT in °C was computed as 0.7 (T_{pwb} + 1.0) + 0.3 T_g following the method described in O'Connor and Bernard (1999).

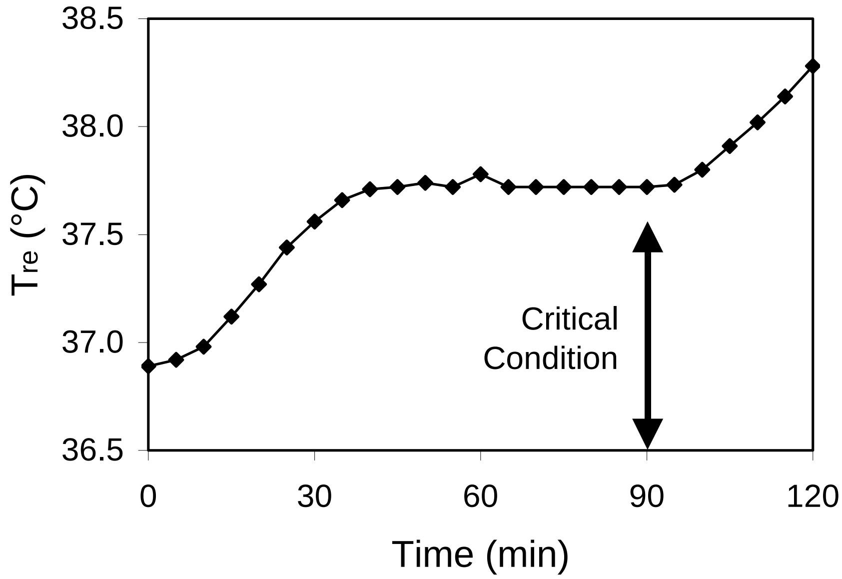

Figure 1. The time course of T_{re} for an example trial with an arrow to indicate the critical condition.

Results

The study protocol called for assessing the critical WBGT and noting the concurrent heart rate, body core temperature and average skin temperature at the critical WBGT. Data was collected across 15 combinations of clothing and metabolic rate for 11 men and 4 women, the summary of p-values is shown in Table 2.

Table 2. Summary of p-values for analyses

	p-Value			
	Metabolic Rate	Critical WBGT	Heart Rate	Core Temperature
Ensemble	0.78	<0.0001	0.059	0.18
Metabolic Level	<0.0001	<0.0001	<0.0001	<0.0001
Gender	0.0004	0.28	<0.0001	0.98
Subject	<0.0001	<0.0001	<0.0001	<0.0001
Gender/ Metabolic Level	0.84	0.10	0.12	0.39
Gender/Ensemble	0.53	0.97	0.092	0.19
Metabolic Level /Ensemble	0.37	0.63	0.43	0.94
Gender/ Metabolic Level /Ensemble	0.73	0.43	0.17	0.37

Metabolic Rate

Table 3 provides the mean metabolic rate with standard deviation for the combinations of Gender, Ensemble and Metabolic Level. Metabolic rates were compared by a 3-way ANOVA (participants nested in gender by Ensemble by Metabolic Level) with all two-way and the three-way interactions. There were significant differences, as shown in Table 2, between Genders (170 versus 184 W m^{-2} for females versus males) and among Metabolic Levels (114, 176, and 250 for Low, Moderate and High) as well as participants within Gender. .

Table 3. Means and standard deviations of metabolic rate (W/m^{-2}) by level, clothing ensemble and gender.

	Metabolic Level					
	Low		Moderate		High	
Ensemble	Female	Male	Female	Male	Female	Male
Work Clothes	110±9	125±30	162±24	178±35	247±4.8	252±37
Coveralls	117±49	118±13	158±2.3	181±12	226±21	247±52
Particle Barrier	98±11	112±16	169±15	181±19	258±34	248±37
Liquid Barrier	95±26	116±15	182±10	176±14	248±17	262±32
Vapor Barrier	100±16	120±18	162±30	181±22	232±16	255±44
Gender by Metabolic Level	104±27	118±19	167±19	179±22	242±30	253±40

The relationships for metabolic rate between Genders for the three Metabolic Levels are illustrated in Figure 2

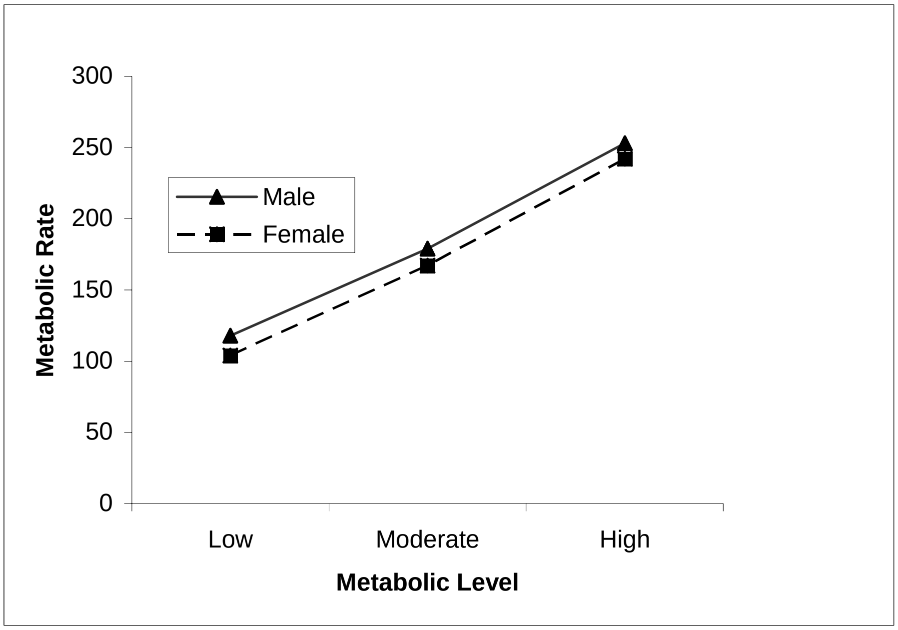

Figure 2. Average metabolic rates for males and females at each metabolic level.

Critical WBGT

Table 4 provides the critical WBGT for the combinations of Gender, Ensemble and Metabolic Level. Critical WBGTs were compared by a 3-way ANOVA (participants nested within Gender by Ensemble by Metabolic Level) with all two-way and the three-way interactions. From Table 2, there were significant differences for Ensemble and Metabolic Level as well as participants within Gender. There was no significant difference for Gender ($p = 0.28$).

Table 4. Means and standard deviations of critical WBGT (°C) by metabolic rate level, clothing ensemble and gender.

	Metabolic Level					
	Low		Moderate		High	
Ensemble	Female	Male	Female	Male	Female	Male
Work Clothes	36.9±1.0	36.5±1.2	33.4±0.9	33.7±1.6	30.5±0.6	31.3±1.8
Coveralls	35.8±1.3	35.7±1.5	34.0±1.3	33.5±1.2	30.3±1.4	31.2±1.9
Particle Barrier	36.2±0.9	35.5±1.8	33.1±0.5	33.7±1.5	29.5±2.2	31.1±1.4
Liquid Barrier	34.7±1.2	34.3±0.8	31.8±0.6	31.3±1.3	28.3±0.7	29.3±1.6
Vapor Barrier	30.9±2.0	30.7±1.6	26.4±2.5	27.5±1.6	25.0±2.0	24.4±2.2
Gender by Metabolic Level	34.9±2.6	34.5±2.5	31.7±3.2	31.9±2.8	28.7±2.6	29.5±3.2

Heart Rate

Table 5 provides the mean heart rate with standard deviation for the combinations of Gender, Ensemble and Metabolic Level. Heart rates were compared by a 3-way ANOVA (participants nested in Gender by Ensemble by Metabolic Level) with all two-way and the three-way interactions. There were significant differences for Gender and Metabolic Level as well as participants within Gender (Table 2).

Table 5. Means and standard deviations of heart rate by level, clothing ensemble and gender.

	Metabolic Level					
	Low		Moderate		High	
Ensemble	Female	Male	Female	Male	Female	Male
Work Clothes	108±20	107±12	122±5	114±19	121±61	124±21
Coveralls	117±26	103±15	122±12	112±13	150±15	121±17
Particle Barrier	118±19	108±19	127±20	114±15	144±17	123±16
Liquid Barrier	115±22	109±16	128±25	111±11	128±14	129±20
Vapor Barrier	130±30	108±15	132±18	118±17	149±24	128±13
Gender by Metabolic Level	118±23	107±15	127±16	114±15	139±30	125±17

The relationships for heart rate by Gender for the three Metabolic Levels are illustrated in Figure 3.

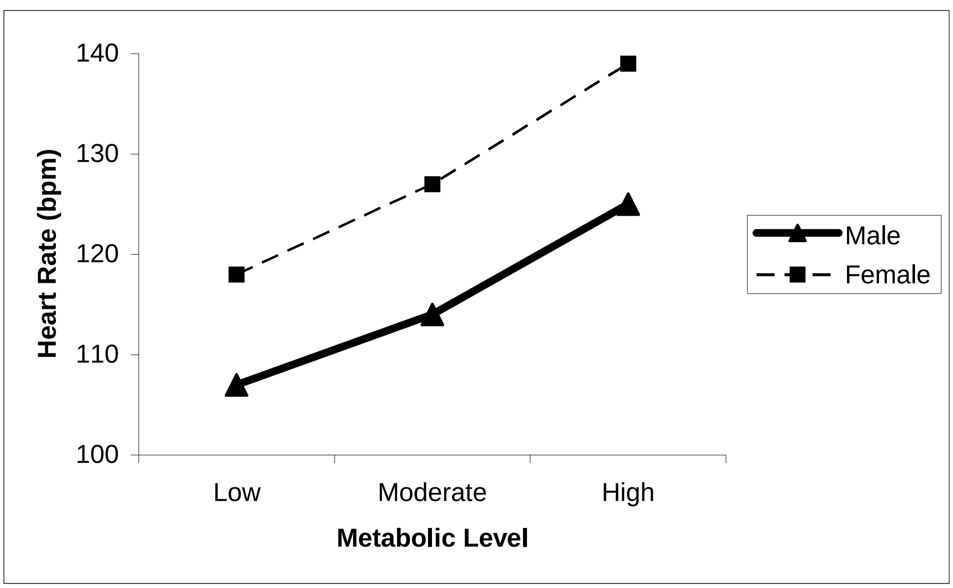

Figure 3. Average heart rates of males and females at the three metabolic levels.

Core Temperature

Table 6 provides the mean core temperature with standard deviation for the combinations of Gender, Ensemble and Metabolic Level. Core temperatures were compared by a 3-way ANOVA (participants nested in Gender by Ensemble by Metabolic Level) with all two-way and the three-way interactions. There were significant differences for Metabolic Level as well as participants within Gender (Table 2). The average core temperature for males and females was 37.75°C.

Table 6 Means and standard deviations of core temperature by level, clothing ensemble and gender.

	Metabolic Level					
	Low		Moderate		High	
Ensemble	Female	Male	Female	Male	Female	Male
Work Clothes	37.4±0.3	37.5±0.2	37.7±0.3	37.8±0.1	37.8±0.3	38.0±0.3
Coveralls	37.6±0.2	37.3±0.2	37.7±0.1	37.7±0.4	37.9±0.2	37.9±0.2
Particle Barrier	37.5±0.3	37.4±0.4	37.7±0.4	37.8±0.3	38.0±0.3	37.9±0.3
Liquid Barrier	37.4±0.4	37.6±0.2	37.9±0.4	37.7±0.2	37.7±0.2	38.1±0.4
Vapor Barrier	37.7±0.4	37.7±0.3	37.9±0.3	37.8±0.4	38.1±0.5	37.9±0.4
Gender by Metabolic Level	37.5±0.3	37.5±0.3	37.8±0.3	37.8±0.3	37.9±0.3	38.0±0.3

Discussion

To examine the possible effects of gender on the critical WBGT and physiological strain, trials were completed for 15 participants over 15 combinations of ensemble (5) and metabolic rate (3).

Metabolic Rate

There were significant differences in the three metabolic levels, which were 114, 176, and 250 W m^{-2}, and this was part of the design. The differences among participants were expected, and the effects were minimized with the factorial design of the experiment.

The difference between genders was important. Men were about 11 to 14 W m^{-2} greater than women at each level of metabolic rate. This might bias men to a lower critical WBGT and higher core temperatures and heart rates. Consequently, the interpretation of results must consider the differences in metabolic rate.

Critical WBGT

The critical WBGT was significantly different for ensemble and metabolic level as well as participants. These differences were expected. The critical WBGT values between genders was not significant, the females had an average critical WBGT of 31.9°C-WBGT while the males had an average critical WBGT of 31.7°C-WBGT. A regression of mean values for men yielded a slope of -0.037 °C-WBGT/W m^{-2}. In this study the average metabolic rate was 12 W m^{-2} greater for men which would then lower the critical WBGT by 0.4°C for men. By adding 0.4 °C, it is reasonable to adjust for this bias, which would make the critical WBGT for men 32.1°C. The adjusted difference is still the same absolute difference and therefore not significantly different.

Heart Rate and Core Temperature

With equivalent WBGTs and similar metabolic rates normalized to body surface area, a comparison of physiological strain between genders can be made. As shown in Figure 3, the heart rates for women are about 12 bpm higher than for men at each of the metabolic rate levels. In this study the men had greater normalized (and absolute) metabolic rates. A regression analysis on mean metabolic rates to mean heart rates yielded slope of 0.134 bpm/ W m^{-2}. If the normalized rates had been the same, the mean male heart rate would be 2 bpm lower. The effect is small but the differences between men and women would have been greater. Using a similar study design as the current study, Kamon, Avellini and Krajewski (1978) reported a greater HR at the critical condition in females wearing cotton work clothes. On the other hand, Frye and Kamon (1981) reported equivalent HRs for acclimatized males and females at the critical condition. Their subjects, however, were matched on aerobic capacity which would reduce differences in thermoregulation and equalize heat strain between males and females. Studies that examined the gender differences in HR in semi-nude acclimatized (Moran 2000, Shapiro et al 1980) and unacclimatized subjects (McLellan 1998, Paolone et al 1978, Yousef et al. 1984) under controlled conditions of uncompensable heat stress reported higher HRs for females than males at a specific time into the trial. In looking at gender differences in HR in response to compensable or uncompensable heat stress, the findings in the current study are in line with others in finding a higher HR response for women when there is no matching of subjects based on aerobic capacity.

Core temperature presented a different profile. There was not a significant main effect for Gender. Inspection of Table 6 shows virtually no difference in T_{re} between males and females at each Metabolic Rate Level. A regression analysis on mean metabolic rates to mean core temperature yielded slope of 0.0037°C / W m^{-2}. If the normalized rates had been the same, the mean male heart rate would be 0.04°C lower. There was no absolute difference between genders and the standard deviation was 0.3°C, a difference of 0.04°C would not likely change the statistical determination of no difference. Others report a greater T_{re} for females in hot-dry environments (Shapiro et al. 1980, Yousef et al. 1984) and a greater T_{re} for males in warm-humid environments (Avellini et al. 1980, Shapiro et al. 1980). The results of our study suggest that T_{re} was equivalent for both genders at the critical condition averaged over the Metabolic Rate Levels. Studies that evaluated T_{re} under compensable heat stress conditions similar to those in the present study reported equivalent T_{re} for males and females (Frye and Kamon 1981, Kamon et al. 1978). Frye and Kamon (1981) matched their acclimated subjects on aerobic fitness (VO_2 max = 54 and 56 ml kg^{-1} min^{-1} for females and males, respectively) and they were acclimatized. The matching removed an important difference due to gender and explained the absence of a difference in T_{re}. The lack of significance in the Kamon, Avellini and Krajewski (1978) study may have been due to the small sample size (4M and 4W). Our results differ from that of McLellan (1998) who studied unacclimatized female and male subjects wearing NBC clothing working in a hot-dry environment (40°C, 30% rh) for intermittent exercise up to 5 hours. Initial T_{re} for males and females was not significantly different, yet T_{re} was greater for females than males after 30 minutes of heat exposure. In summary, a difference was not observed in core temperature between genders; this equivalence was observed in two other studies that used a similar protocol to the current study. Studies of uncompensable heat stress did show differences.

Conclusion

The main objective of this study was to investigate if there are gender differences for critical WBGT, heart rate and core temperature at the upper limit of compensable heat stress across three levels of metabolic rate and five levels of clothing. There was no statistical difference observed between genders in critical WBGT and core temperature. The only outcome that was statistically different was heart rate. The heart rate was significantly higher (12 bpm) for women than for men. Overall, women had the same upper limit of the prescriptive zone as men, their core temperatures were the same at this limit but women had a greater cardiovascular cost reflected in a higher heart rate.

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